Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD)

Artificial Intelligence-enhanced Integrated Transportation Management System (AI-ITMS) Final Report 2023

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Delaware Department of Transportation

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Acronyms

Acronym	Definition
AI	Artificial Intelligence
AI-ITMS	Artificial Intelligence-enhanced Integrated Transportation Management System
AI-TOMS	AI-based Transportation Operations and Management System
API	Application Programming Interface
ATCMTD	Advanced Transportation and Congestion Management Technologies Deployment
ATSPM	Automated Traffic Signal Performance Measures
BCA	Benefit-Cost Analysis
BSM	Basic Safety Message
CAD	Computer-Aided Dispatch
CAN	Controller Area Network
CAV	Connected and Automated Vehicles
CCTV	Closed-Circuit Television
COM	Component Object Model
ConOps	Concept of Operations
COVID-19	Coronavirus Disease 2019
DE #	Delaware Route #
DelDOT	Delaware Department of Transportation
DMP	Data Management Plan
DMS	Dynamic Message Sign
DMZ	Demilitarized Zone
DSS	Decision Support System
DTC	Delaware Transit Corporation
FAST Act	Fixing America's Surface Transportation Act
FCC	Federal Communications Commission
FFS	Free-Flow Speed
FHWA	Federal Highway Administration
GHz	gigahertz
GPU	Graphical Processing Unit
GTFS	General Transit Feed Specification
GTS	Graph for Time Series
GUI	Graphical User Interface
HR	High-Resolution
I-	Interstate
ITMS	Integrated Transportation Management System
ITS	Intelligent Transportation System
Jacobs	Jacobs Engineering Group Inc.
JSON	JavaScript Object Notation
LSTM	Long Short-term Memory
ML	Machine Learning
MUTCD	Manual on Uniform Traffic Control Devices
MV	machine vision
NCHRP	National Cooperative Highway Research Program
NTCIP	National Transportation Communications for ITS Protocol
OBU	Onboard Unit

Acronym	Definition
OD	Origin-Destination
OTP	On-Time Performance
REST	Representational State Transfer
RSU	Roadside Unit
RWIS	Roadway Weather Information System
SPaT	Signal Phase and Timing
SUMO	Simulation of Urban MObility
System	Artificial Intelligence-enhanced Integrated Transportation Management System
TIS	Traveler Information System
TMC	Transportation Management Center
TRL	technology readiness level
TRPS	Traffic Responsive Plan Selection
U.S.C.	United States Code
US	United State Route
USDOT	United States Department of Transportation
VMS	Variable Message Sign
V2I	Vehicle to Infrastructure

Reference Documents

1. ATCMTD Technical Application, June 18, 2018, Delaware Department of Transportation
2. DelDOT 2022 Certified Mileage, May 30, 2023, Delaware Department of Transportation
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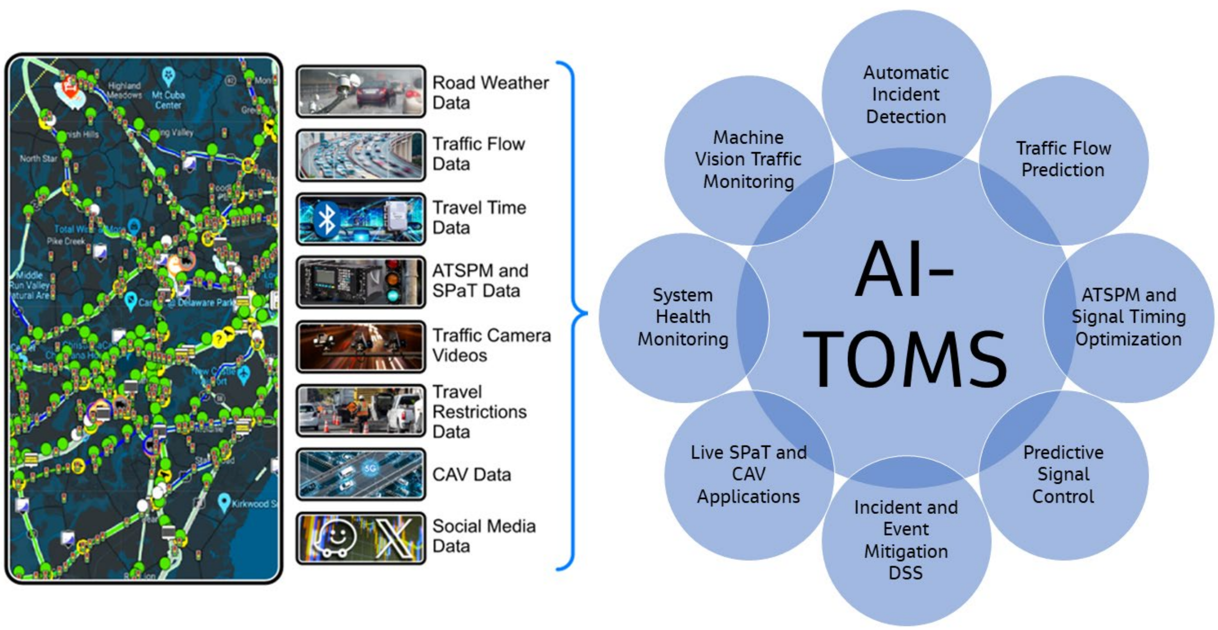
Executive Summary

Under the Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) grant program, Delaware Department of Transportation (DelDOT) is leveraging technological advances in artificial intelligence (AI) and machine learning (ML) to create an AI-enhanced integrated transportation management system (AI-ITMS); the next evolutionary step in its ever-maturing statewide integrated transportation management system (ITMS) program. While DelDOT has made significant investment in infrastructure monitoring capabilities, capable of collecting millions of data points each day, it has also come to realize that the vast amount of information is impossible for humans to constantly monitor, assess, and resourcefully respond to. Under the ATCMTD grant, the project team, led by DelDOT, has developed an AI-based Transportation Operations and Management System (AI-TOMS). This software platform will improve how the DelDOT Transportation Management Center (TMC) monitors the transportation system by predicting traffic flows; identifying anomalies and inefficiencies; and generating, evaluating, and executing response solutions to existing and predicted traffic congestion. It will be a system that goes beyond notifying technicians and the traveling public of congestion to proactively make changes that enhance mobility while continuing to evolve over time.

AI-TOMS is comprised of several key functional services based in AI and ML that pull data from all aspects of DelDOT's ITMS as shown in Figure ES 1.

Figure ES 1. Overview of AI-TOMS Inputs and Key Functional Services



ATSPM = Automated Traffic Signal Performance Measures
CAV = Connected and Automated Vehicles
DSS = Decision Support System
SPaT = Signal Phase and Timing

Under the ATCMTD grant, the project team has made impressive strides towards deploying their AI-ITMS. DelDOT has successfully integrated more than ten sources of near real-time traffic data into the system, concurrently monitoring nearly 90% of all statewide ITMS devices. With an early focus on interstate and freeway incident detection, the project team developed, tested, and integrated multiple algorithms within AI-TOMS that can detect and localize traffic anomalies, classify their severity, assess their impact, and determine alternative route choices for the traveling public. While these algorithms are still being refined and are not yet fully operationally deployed, initial evaluations show positive results. Incident detection accuracy on Interstate (I-) 95 and Delaware Route 1 (DE 1) show that AI-TOMS can identify a crash within 15 minutes of the incident on average with over 80% accuracy. These results, which DelDOT expects to improve as the system matures, are promising for improved event and incident response time.

Though interstate and freeway incidents can contribute to significant interruptions to the overall transportation network, the majority of DelDOT's roads are signalized arterials and local roads. Initial tests running select signal groups on AI-TOMS have shown promising results, with AI-TOMS making changes to the signal timing patterns based off predicted traffic and high-resolution signal data. AI-TOMS' specific ability to accurately predict traffic patterns up to one hour in advance shows great potential for DelDOT's congestion management activities.

Given the unique nature of this project, the planning, development, and implementation efforts require tasks that are different from traditional transportation/construction projects. In exploring and utilizing innovative technologies, adjustments were made to the original project scope to best meet DelDOT's needs and the overall program goals. Integrating AI and ML principles into an already existing ITMS has been a process of trial and error, notably in establishing direct communication between AI-TOMS and DelDOT's traffic signals, establishing meaningful and measurable baselines to quantify progress, and determining best use cases for various simulation models. It is the project team's ability to be adaptive and agile during this process that has gotten DelDOT's AI-ITMS to where it is today despite significant challenges.

The enhanced system is expected to reduce delays by automatically initiating efficient traffic signal timing plans before congestion starts and by rerouting traffic around incidents, making more efficient use of the existing roadway capacity and delaying the need to add new lanes. With an AI-TOMS that can communicate directly with traffic signals, technicians at DelDOT's TMC can prioritize larger incidents that require more attention and trust that AI-TOMS can automatically monitor day-to-day traffic operations and make signal timing adjustments, as necessary. Decreases in congestion rates are also expected to improve air quality, coinciding with several existing and planned DelDOT initiatives. With over 50% of delay generated from nonrecurring events, this system is designed to improve the entire process of incident management, from identification, to response, to clearance. This promotes safety and improves efficiency, allowing TMC staff to respond more quickly and efficiently to severe incidents. DelDOT has also committed to deploying advanced non-intrusive multimodal detection, such as cameras with machine vision algorithms, providing enhanced data collection capabilities and yielding greater insights into the safety and efficiency of the network.

Though the ATCMTD grant is complete, the AI-ITMS will continue to evolve as DelDOT expands its AI-ITMS infrastructure and further develops AI-TOMS to improve monitoring on their roads, keep drivers informed, improve event and incident response, and prepare for other emerging transportation technologies.

1 Introduction & Overview

1.1 Report Purpose

This document is the final report for the Advanced Transportation and Congestion Management Technologies Deployment Initiative (ATCMTD) grant program, submitted at the conclusion of the project. As it is the final report under the grant, its context provides a comprehensive look at the project period overall, dating back to when the Delaware Department of Transportation (DelDOT) was awarded the grant in 2019. This report includes a status update of the overall artificial intelligence-enhanced integrated transportation management system (AI-ITMS, or System), the System's current performance as it relates to project goals, and a complete list of challenges, scope changes, and lessons learned.

As noted in the cooperative agreement between DelDOT and the US Department of Transportation's Federal Highway Administration (FHWA), this report describes "deployment and operational costs of the project compared to the benefits and savings the project provides; and how the project has met the original expectations projected in the deployment plan submitted with the application" and fulfills the requirements stated in the 23 United States Code (U.S.C.) 503I(4)(F) described below. Additionally, the report identifies the goals of DelDOT's AI-ITMS deployment; provides updates and findings associated with research and evaluations conducted thus far; and describes innovative project elements, lessons learned, and challenges experienced while also providing recommendations to other departments of transportation who might be interested in deploying a similar system.

The document aligns with the **reporting requirement** defined below:

23 U.S.C. 503(c)(4)(F) states, *"That for each eligible entity that receives a grant under this paragraph, not later than 1 year after the entity receives the grant, and every year thereafter, the entity shall submit a report to the Secretary that describes:*

- *i. Deployment and operational costs of the project compared to the benefits and savings the project provides; and*
- *ii. how the project has met the original expectations projected in the deployment plan submitted with the application, such as—*
  - *I. data on how the project has helped reduce traffic crashes, congestion, costs, and other benefits of the deployed systems;*
  - *II. data on the effect of measuring and improving transportation system performance through the deployment of advanced technologies;*
  - *III. the effectiveness of providing real-time integrated traffic, transit, and multimodal transportation information to the public to make informed travel decisions; and lessons learned and recommendations for future deployment strategies to optimize transportation efficiency and multimodal system performance."*

1.2 Project Background

With a growing integrated transportation management system (ITMS) and millions of data points coming in each day, it is impossible for humans to constantly monitor the extensive data collected by DelDOT, focus on the most critical data, and react to the ever-changing conditions of a multimodal transportation network. DelDOT assembled a team, including Jacobs Engineering Group Inc. (Jacobs), BlueHalo (formerly Intelligent Automation Inc.), Drive Engineering Inc., and University of Delaware to develop and deploy an AI-ITMS by adopting state of the art technologies in artificial intelligence (AI) and machine learning (ML). The AI-ITMS refers to the entire AI-enhanced System, encompassing all traffic monitoring technologies; transportation infrastructure; and people involved with the planning, design, operations, and maintenance of the transportation system. The AI-based Transportation Operations and Management System (AI-TOMS) is the software platform developed as part of this project to improve how the DelDOT Transportation Management Center (TMC) monitors the transportation system by predicting traffic flows; identifying traffic anomalies and inefficiencies; and generating, evaluating, and executing response solutions to recurring and nonrecurring traffic congestion. The AI-ITMS builds on DelDOT's existing ITMS to continually monitor and more quickly detect changes in traffic demand, understand capacity at a given time, alert DelDOT personnel, provide recommended solutions, and deliver faster and more actionable traveler information. With consistent data monitoring, the System will provide more valuable outputs so technicians can better focus on specific conditions for safe and efficient response. The System can predict traffic flow in the short-term and will leverage simulation tools to predict traffic flow more accurately in the long-term. In conjunction with other applications, the System will better predict when congestion will occur using advanced traffic demand and incident detection and will be integrated with DelDOT's traffic signal control system. The AI-ITMS will provide a self-learning platform to accumulate successful expert experience and "lessons learned" to get smarter over time for transportation management and operations.

DelDOT was awarded a three-year grant from FHWA in 2019 under the ATCMTD to aid in the development and deployment of DelDOT's AI-ITMS. The original three-year project performance period was from October 2019 through October 2022. Three no-cost time extensions were issued to accommodate various project delays resulting in a revised project end date of September 5, 2023. These federal funds have been used to deploy and progress ATCMTD-targeted activities including:

- Advanced transportation management technologies
- Advanced traveler information systems
- Transportation system performance (monitoring) data collection, analysis, and dissemination

Deployment of the AI-ITMS has three components, shown in Figure 1, progressing concurrently:

- AI-ITMS-Infrastructure: Upgrade and deploy advanced sensors, video cameras, connected infrastructure, connected and automated vehicles (CAV), and transportation management system hardware and software to support the deployment of AI-ITMS.
- AI-ITMS-Operation: Development, integration, deployment, and testing of the AI-TOMS software toolkit; includes three subprojects focused on distinct transportation networks: urban, beach, and CAV. The roadways where data is being collected for AI-TOMS software in each of these areas are shown in Figure 2.
- AI-ITMS-Traveler Information System (TIS): Update the DelDOT web and mobile application to better inform the public of the travel advisories generated by AI-TOMS.

Figure 1: Components of the AI-ITMS Deployment Program

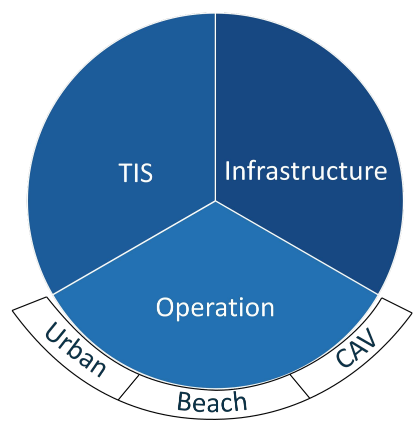
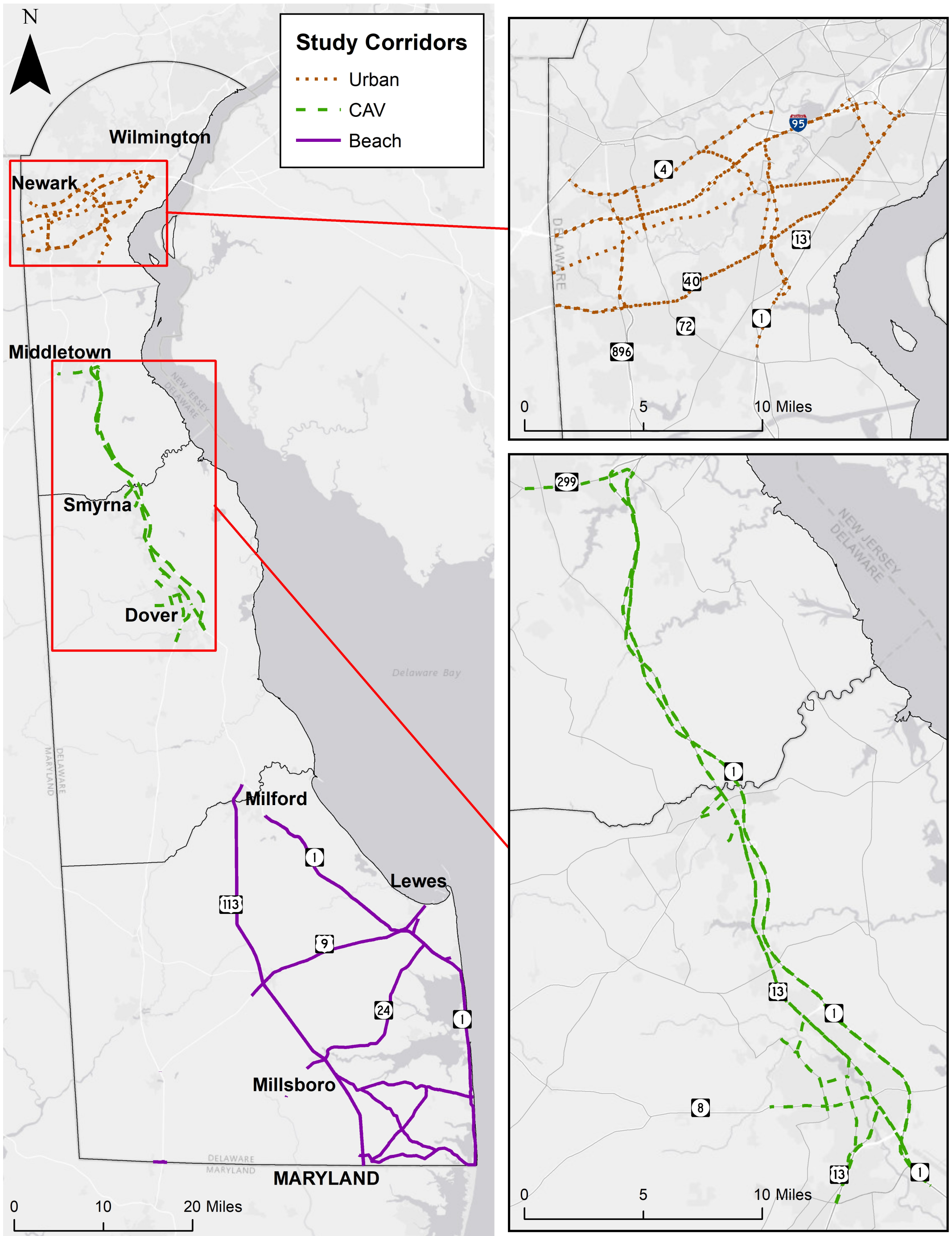


Figure 2: Urban, CAV, and Beach Study Corridors



The project team has made great strides in building a complex System throughout the three years of the ATCMTD grant and will continue deploying and refining the AI-ITMS beyond the grant.

1.3 Project Goals

DelDOT is building a system that will improve the overall safety and mobility of Delaware's transportation network. With increased monitoring and AI/ML capabilities, the System will be able to respond to actual traffic demand and roadway capacity changes, whether planned or unplanned. It will be a System that goes beyond notifying technicians and the traveling public of congestion, and makes changes that enhance mobility, like adjusting signal timings. As stated in the original ATCMTD Technical Application[1] submitted by DelDOT,

> "The vision of AI-ITMS is to automate and optimize transportation systems monitoring and operations through early and more accurate detection and identification of transportation systems anomalies and inefficiencies, reason the cause and impact of these anomaly/inefficiencies, develop corresponding solutions and provide early responses to them, resulting in improved transportation system performance and reduced traffic congestion, increased safety, improved travel time reliability and improved air quality. Furthermore, AI-ITMS will be able to handle multimodal transportation systems and services such as freeway/arterial corridors, signal systems, transit services, and Traveler Information Systems (TIS). It will also support emerging Connected and Autonomous Vehicle (CAV) technologies."

As DelDOT continues developing and deploying the System, the project team is staying adaptable and up to date on industry best practices. DelDOT plans to continue using and modifying this System as technology continues to evolve.

Development and implementation of the AI-ITMS furthers DelDOT's commitment to enhance its ITMS and align with the Department's overall vision to make **Every Trip** safe, reliable, and convenient; provide safe choices for travelers to access **Every Mode**; to seek the best value for **Every Dollar** spent for the benefit of all; and to engage **Everyone** with the respect and courtesy in delivery of services. Through the deployment of the AI-ITMS, DelDOT aims to improve the transportation network by achieving four main goals listed in Table 1. These four goals align with the objectives listed in the Fixing America's Surface Transportation (FAST) Act under 23 U.S.C. 503(c)(4)(G).

Table 1: Project Goals

AI-ITMS Project Goals	Objectives	Aligning FAST Act Goals
Increasing connectivity and data availability for multiple modes of travel	• Use AI/ML technologies to identify anomalies faster and more precisely • Increase mobility options such as alternative route choices, transit, and CAVs • Optimize transportation services to improve travel time reliability, accessibility, and reduce costs • Provide real-time travel information to the public for route choice and travel planning	• Improve mobility • Optimize multimodal performance • Provide the public with real-time integrated traffic, transit, and multimodal transportation information to make informed travel decisions • Improve access to transportation alternatives

[1] ATCMTD Technical Application, June 18, 2018, Delaware Department of Transportation

AI-ITMS Project Goals	Objectives	Aligning FAST Act Goals
Improve safety for all modes of travel	• Leverage technology to increase awareness of traffic conditions • Warn drivers about safety hazards • Track and monitor transit and public vehicles	• Reduce traffic-related fatalities and injuries • Optimize multimodal system performance
Promote environmental and economic vitality	• Streamline traffic flow to reduce delay and vehicle hours traveled • Reduce pollutant emissions with less traffic congestion and more transit ridership • Increase use of transit services for business and leisure	• Reduce traffic congestion and improved travel time reliability • Optimize multimodal system performance • Reduce transportation-related emissions • Improve access to transportation alternatives
Preparing for emerging transportation technologies (e.g., CAVs)	• Monitor and communicate with CAVs for better traffic management • Improve efficiency of operations and mobility of CAVs • Identify instances of potential AI/ML project improvements	• Reduce traffic congestion and improved travel time reliability • Optimize multimodal system performance • Provide the public with real-time integrated traffic, transit, and multimodal transportation information to make informed travel decisions

1.4 Project Team

The AI-ITMS program is led by the DelDOT Division of Transportation Solutions. This division of DelDOT is supported by the project team who performs the following tasks:

- Jacobs – program management, intelligent transportation systems (ITS) and traffic engineering services, meso and micro simulation modeling and systems engineering
- Intelligent Automation, A BlueHalo Company – technical consultants, software development, system integration
- Drive Engineering – project evaluation
- University of Delaware – research support

2 System Status

2.1 System Overview

DelDOT has focused on implementing an AI-ITMS to automate and optimize transportation systems monitoring and operations. Great strides have been made to upgrade the ITMS infrastructure and develop algorithms and software that allow DelDOT to quickly identify traffic disruptions and predict future congestion based on historical patterns. While DelDOT continues to invest in its AI-ITMS program, this section describes the programs status at the conclusion of the grant period.

AI-TOMS has been developed using a microservice-oriented architecture. Functions of AI-TOMS are encapsulated within individual microservices, which communicate using well-defined Application Programming Interfaces (APIs). The decoupled architecture provides for improved scalability, tolerance, maintenance, data availability, and security. These benefits are detailed further in Table 2.

Table 2. Benefits of Microservice-Oriented Architecture

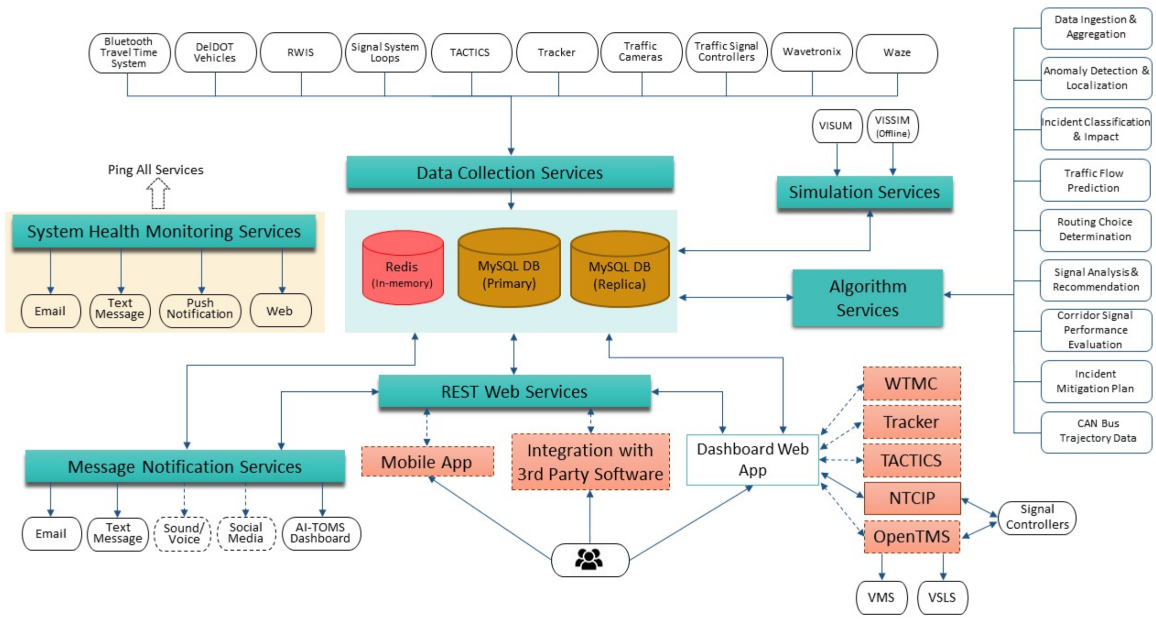
Benefit	Description
Scalability	• Services can be added and removed as needed without impacting other system functions • System can more easily accommodate increases in data volumes and user needs without the need for a costly overall or significant disruption
Fault Tolerance	• Failures in one microservice do not lead to failure of the entire system • Improved system reliability and minimized downtime
Maintenance	• Maintenance efforts are simplified • Patches are applied to individual microservices without affecting the entire system, reducing maintenance overhead
High Availability	• WebSocket communication guarantees real-time delivery of critical alerts to front-end systems • Facilitates swift decision-making and enhances efficiency • Redundancy and failover mechanisms are integrated into the architecture, allowing for switching between backup resources in case of server failures or network disruptions
Security and User Management/User Authorization	• Data and system integrity are secured with a multi-layer approach • Users have distinct privileges and access rights depending on roles and responsibilities

The interaction of microservices can be visualized using the system diagram shown in Figure 3. The system diagram shows the core system architecture where data from various types of traffic detectors and sensors are collected and ingested for near real-time traffic condition monitoring. Solid lines indicate existing inputs, algorithms, and outputs, while dashed lines represent future implementations. All the pre-processed traffic data is fed to the algorithm services for different analysis output such as data aggregation, traffic pattern anomaly detection, incident detection, traffic flow prediction, route choices, response plan development and assessment, etc. The final information output will be delivered to the web-based dashboard, mobile app interface, and through email, text message, voice/sound and social media. AI-TOMS is a part of DelDOT's overall System that encompasses the above simulation services, algorithm services, databases, and dashboard, helping to improve how the DelDOT TMC monitors the transportation network. With only 108 of Delaware's 5,486 State-maintained roadway miles classified as interstate or freeway/expressway[2], DelDOT has heavily emphasized integrating its traffic signal system, currently managed by the control

[2] DelDOT 2022 Certified Mileage, May 30, 2023, Delaware Department of Transportation

system TACTICS, into the AI-ITMS. With an AI-ITMS that can communicate directly with traffic signals and adjust signal timing automatically, traffic can move more efficiently, and TMC technicians are free to respond to incidents that may require more attention. Additional information on how the AI-ITMS enhances DelDOT TMC's operations can be found in the DelDOT "ATCMTD AI-ITMS Concept of Operations" (ConOps).[3] A larger version of Figure 3 is also available in Appendix B.

Figure 3. AI-TOMS Architecture



DB = database
NTCIP = National Transportation Communications for ITS Protocol
REST = Representational State Transfer
RWIS = Roadway Weather Information System
VMS = Variable Message Sign
VSLS = Variable Speed Limit Signs

As shown in Figure 3, AI-TOMS integrates data from a wide variety of sources, including but not limited to agency-owned traffic detector data, Automated Traffic Signal Performance Measures (ATSPM) data and live video camera feeds, as well as third-party data from connected vehicles, General Transit Feed Specification (GTFS) data originating from transit systems, social media feeds, and crowdsourced information from platforms such as Waze and Google. Using these data sources, AI-TOMS uses the power of AI and ML throughout their algorithm services to offer several key functional services to DelDOT. These key functional services functions are described in Table 3 and the algorithms and software services which support each are summarized in Appendix B.

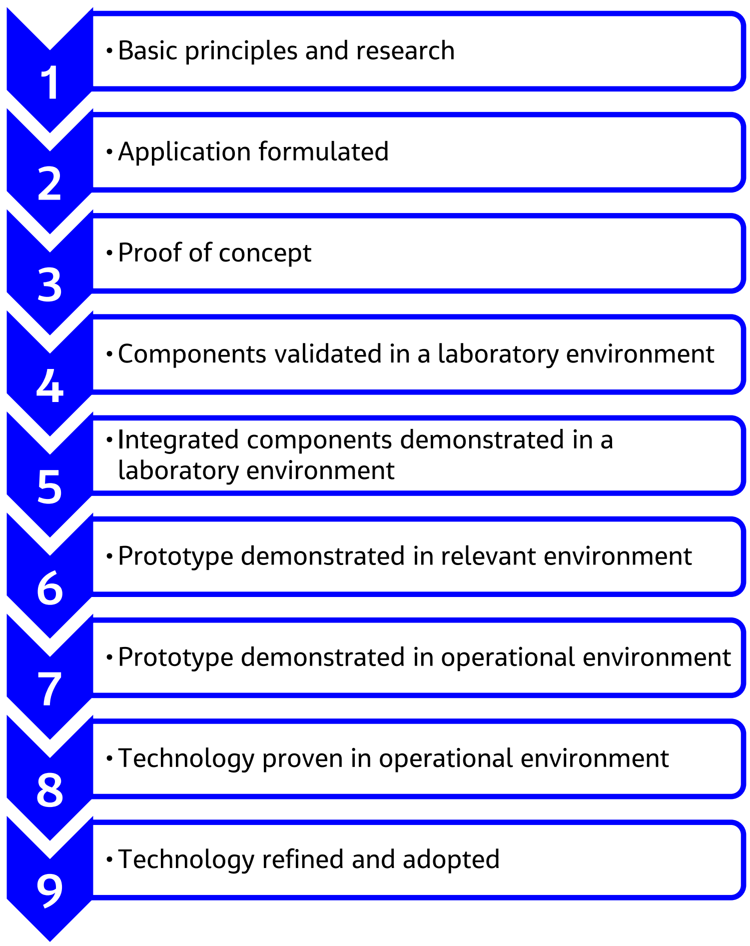
[3] ATCMTD AI-ITMS Concept of Operations, August 2020, Delaware Department of Transportation

Table 3. Summary of Key Functional Services Offered by AI-TOMS

Key Functional Service	Description
Automatic Incident Detection	• Identifies freeway and arterial traffic anomalies • Determines incident location and type • Estimates incident severity
Traffic Flow Prediction	• Uses deep learning to forecast traffic flow up to 60-minutes ahead, enabling predictive and proactive traffic flow management and signal operations • Traffic volumes are estimated within 10% and travel speeds are estimated within 3% of the true values
ATSPM and Signal Timing Optimization	• Gathers real-time traffic counts and high-resolution (HR) signal data • Produces metrics for critical movement summation and corridor synchronization • Provides live signal timing optimization using a modified Webster model and pattern recommendations
Predictive Signal Control	• Direct communication with NTCIP 1202 compliant controllers • Capable of interfacing with existing Central Traffic Signal Management System using vendor APIs • Initiates control measures based on traffic predictions, resulting in more efficient signal operations
Incident/Event Mitigation DSS	• Calculates available roadway capacity and supports rerouting decisions using VISUM and Simulation of Urban MObility (SUMO) simulations for signal strategy optimization and evaluation • Uses a digital twin approach to help visualize the outcome of mitigation plans before implementation and reduce the workload of TMC staff as they manage traffic incidents
Live Signal Phase and Timing (SPaT) and CAV Applications	• Streams real-time signal data to a cloud server to provide instant SPaT information • ML algorithm ingests CAV data to visualize vehicle trajectories, classify turning movements, measure signalized corridor synchronization, and detect traffic flow disruptions
System Health Monitoring	• Monitors detector data quality and system hardware and notifies TMC of issues with AI-TOMS tool functionality
Machine Vision Traffic Monitoring	• Ingests and processes video feeds from existing closed-circuit television (CCTV) cameras for use in traffic volume counting, travel speed and traffic density estimation, and vehicle re-identification • Machine vision module is capable of vehicle re-identification and classification • Edge computing is used in machine vision hub for vehicle detection and tracking and estimation of vehicle speeds and roadway occupancy

The AI-TOMS key functional services summarized in Table 3 have been tested across the project's Urban, CAV, and Beach study areas, and have been deployed with varying levels of maturity. In order to characterize the level of technological maturity associated with each key functional service, the project team referred to FHWA guidance found in the Technology Readiness Level Guidebook[4]. Technology readiness levels (TRLs) are assigned on a nine-point scale and are summarized by Figure 4. Additional details on each TRL can be found in the Technology Readiness Level Guidebook.

Figure 4. Technology Readiness Level Descriptions



Using these TRL definitions, the project team attributed a TRL to each benefit for each study area that the service has been deployed in to summarize their statuses. These TRLs are provided in Table 4.

[4] Technology Readiness Level Guidebook, September 2017, Federal Highway Administration

Table 4. Technology Readiness Levels for AI-TOMS Services

Function	Urban	CAV	Beach
Automatic Incident Detection	TRL-8: Freeway I-95 and DE 1	TRL-8: Freeway DE 1; TRL-7: Arterial US 13	TRL-6: DE 1 and beach network
Traffic Flow Prediction	TRL-8: Freeway I-95 and DE 1	TRL-8: Freeway DE 1 and Arterial US 13	TRL-7: arterial (zone 20) network
ATSPM and Signal Timing Optimization	TRL-6: HR data collection for US 40 network	TRL-8: ATSPM for US 13 corridor; vehicle trajectory overlay; signal timing optimization with HR data	TRL-7: ATSPM for zone 20 network
Predictive Signal Control	Not Applicable	TRL-8: NTCIP signal control based on predicted traffic demand for signal group K999 along US 13; Four operation modes available (TACTICS, AI-TOMS, manual and Time of day)	TRL-6: NTCIP signal control available, not tested yet
Incident/Event Mitigation DSS	TRL-6: Freeway incident detour scenarios and impact analysis	TRL-7: Freeway incident detour scenario modeling, mitigation plan recommendation	TRL-6: VISSIM model for Zone 20 network
Live SPaT and CAV Applications	Not Applicable	TRL-7: live SPaT for 11 intersections, less than 150 milliseconds latency	Not Applicable
System Health Monitoring	TRL-6: detector data quality; TRL-7: hardware and software health	TRL-6: detector data quality; TRL-7: hardware and software health	TRL-6: detector data quality; TRL-7: hardware and software health
Machine Vision Traffic Monitoring	TRL-6: initial MV algorithm for congestion detection on freeway I-95	TRL-8: MV hub deployed to US 13 at DE 300; MV for vehicle count, classification, and speed estimation; TR-5: Vehicle re-identification from two cameras	Not Applicable

DE = Delaware Route
I- = Interstate
MV = Machine Vision
US = United States Route

Additional information on the status of the AI-ITMS at the conclusion of the grant period is detailed by project component in Sections 2.2, 2.3, and 2.4.

2.2 Infrastructure Status

Deployment of new and upgraded infrastructure is one of three project components associated with work completed by DelDOT under the ATCMTD grant, and it is also in line with DelDOT's Integrated Transportation Management Strategic Plan[5] ("Strategic Plan"), originally created in 1997 and last updated in 2017. The Strategic Plan outlines strategies to reduce congestion and delay, improve safety and system performance, and reduce operating costs; goals that were relevant in 1997 and are still the focus of the AI-ITMS project and program today. Over the past twenty years, DelDOT has made great strides in building and expanding upon its ITMS, integrating technology, infrastructure, and people to enhance mobility and safety throughout the statewide transportation network. Throughout the three years of the project under the ATCMTD grant, DelDOT has continued to upgrade existing and deploy new traffic sensors, video cameras, connected infrastructure, CAV technology, and transportation management system-related hardware and software.

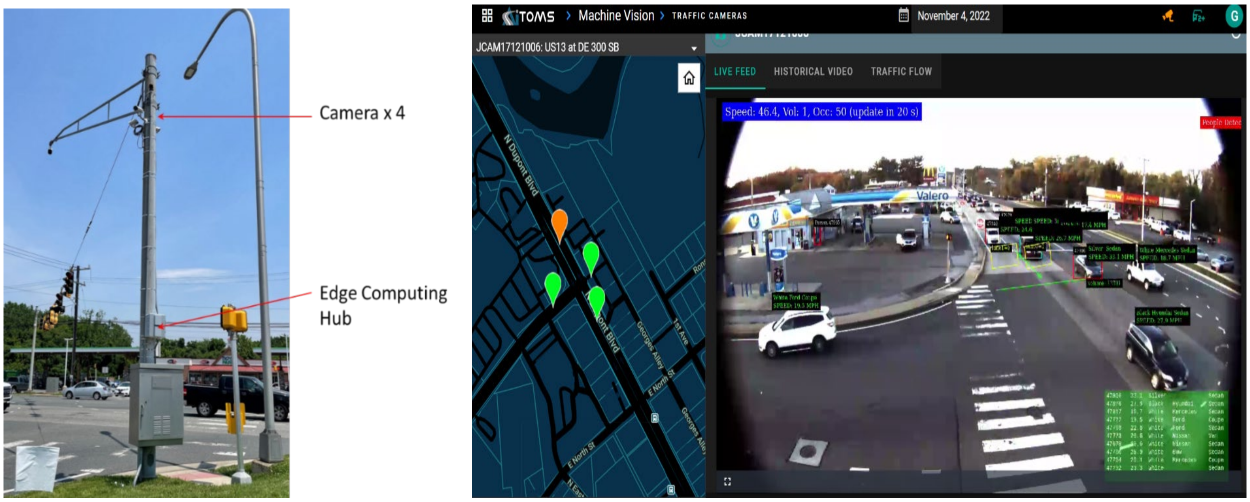
Technologies new to DelDOT's ITMS device network include enhanced signal system loop cabinet cards, controller area network (CAN) bus data dongles, machine vision and data analytics-enabled cameras, and non-machine vision-enabled cameras with machine vision processing developed by BlueHalo. These technologies provide the following benefits.

- Enhanced inductive loop amplifier cards capable of measuring vehicle signature profiles used for re-identification between detection stations for origin-destination and travel time analyses.
- CAN bus data dongles were installed into ten DelDOT vehicles that travel throughout the state. As the vehicles are used to complete regular DelDOT business, they collect and report vehicle locations, travel speeds, acceleration, and other vehicle data to the operations component of the AI-ITMS for use in evaluating corridor performance.
- Four cameras with machine vision capabilities have been installed along the CAV study corridor in Smyrna, DE. They are collecting traffic data through video analysis and are being tested for different operational functions, such as vehicle re-identification, classification, and presence detection.

Figure 5 shows the machine vision cameras BlueHalo developed for the ATCMTD grant project that have been deployed at the intersection of US-13 at DE 300 in Smyrna, Delaware. Live streaming High-Definition videos from all four channels of machine vision cameras can be accessed using one cellular modem. Vehicle detection and classification, and data processing for count, speed and occupancy are all done at the edge and the results are communicated to the server every minute.

[5] Integrated Transportation Management Strategic Plan, December 2017, Delaware Department of Transportation

Figure 5. (a) BlueHalo's Edge Computing multi-channel machine vision cameras installed at US-13 @ DE-300 in Smyrna, DE; (b) the web portal for the machine vision cameras for vehicle count, classification, and speed and occupancy estimation



(a) (b)

Figure 6a shows an example of vehicle volume data from the machine vision cameras (shown in orange) compared with vehicle volume data from signal system loops at the same intersection (shown in blue). The machine vision volume is more granular, collected every minute compared to the signal system loops' five-minute bins, but shows results very similar to the in-pavement technology. Figure 6b shows the detailed vehicle classification data collected at the same intersection by the machine vision camera, sorted into 6 tiers of vehicle classification[A].

[A] The six tiers of classification currently collected by machine vision cameras are coupe, sedan, SUV, van, large vehicle, and truck. These classifications are based on common vehicle types and are used internally within DelDOT for monitoring. They are not used for federal Highway Performance Monitoring System submittals.

Figure 6a: Vehicle counts from the machine vision cameras installed at US 13 @ DE 300 in Smyrna, DE

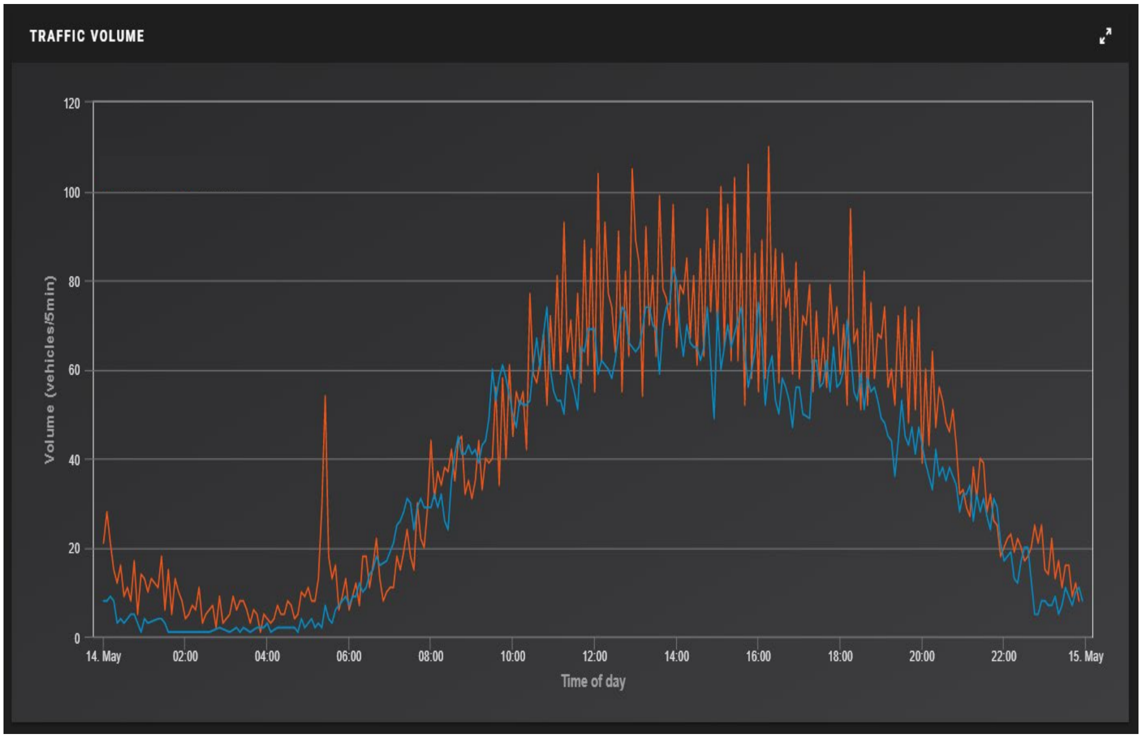
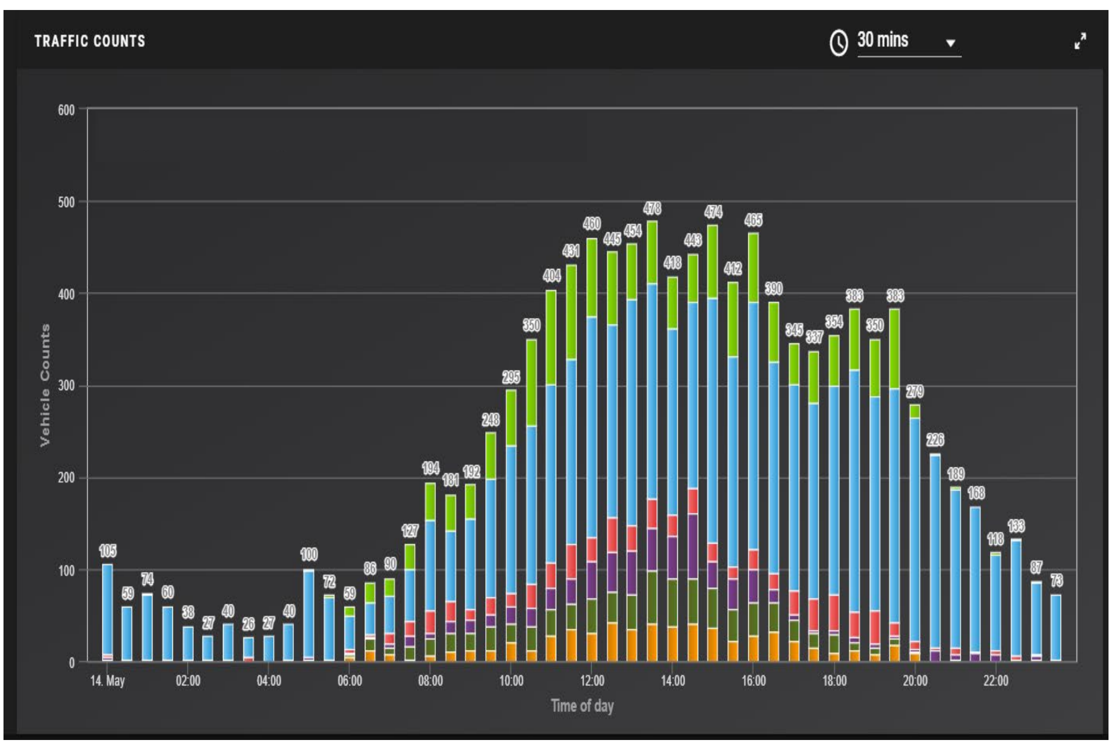


Figure 6b: Vehicle classification data from the machine vision cameras installed at US 13 @ DE 300 in Smyrna, DE



2.3 Operations Status

The operations component of the AI-ITMS project comprises all efforts relating to the development, integration, deployment, and testing of the AI-TOMS software toolkit. The AI-TOMS web interface is accessible to BlueHalo staff and approved DelDOT TMC staff and consultants.

AI-TOMS' web interface allows users to visualize all the data pulled into the System for use in algorithm services. Beyond gathering DelDOT's traffic monitoring data in a single location, several applications have been tested in the development environment demonstrating the value provided by and progress made on AI-TOMS such as anomaly and incident detection, traffic flow prediction, HR data analytics, CAV trip analysis, and machine vision functionality. The status of each function is summarized in the following subsections.

2.3.1 Algorithms Status

2.3.1.1 Data Ingestion and Aggregation Algorithm

The data ingestion and aggregation algorithm is a critical component of the overall System. It pulls DelDOT's existing ITMS data into AI-TOMS and groups it into useful, useable formats. The algorithm is developed and integrated with AI-TOMS.

Under this project, the majority of DelDOT's signal system loops, Wavetronix devices, Bluetooth sensors, weather stations, traffic cameras, variable message signs, variable speed limit signs, and hydrology stations have already been integrated into the AI-ITMS, primarily through existing JavaScript Object Notation (JSON) feeds. These feeds, a description of the data provided by each, how often they are fed into the System, their format when ingested by the System, and their data sources are shown in Table 5. As new devices are installed, they are automatically integrated into AI-ITMS operations using these data feeds. The AI-ITMS also receives information from the DelDOT signal system. Signal timing and coordination data found in TACTICS, DelDOT's current traffic signal management system, is fed into the software component of the AI-ITMS, and within the study corridors, signal controllers are being upgraded. Specific data feeds and data sources are discussed further in the DelDOT "ATCMTD AI-ITMS Data Management Plan" (DMP)[6].

Table 5: AI-TOMS Data Inputs

Data Input	Description	Pull Frequency	Format	Data Sources Included
CAN Bus Data	Provides real-time vehicle performance data including engine revolutions per minute speed, acceleration, coolant temperature, and location.	1 minutes	Binary*	• DelDOT Vehicles
HR Signal Data	Provides near-real-time data containing timestamped controller events such as changes in detector states and signal outputs.	5 minutes	Binary*	• Traffic Signal Controllers

[6] ATCMTD AI-ITMS Data Management Plan, May 2023, Delaware Department of Transportation
* Data is transformed within the System, see DMP for additional details

Data Input	Description	Pull Frequency	Format	Data Sources Included
Near Real-Time Traffic Alerts	Provides information on near-real-time travel advisories that are impacting traffic.	5 minutes	JSON	• Tracker
Restrictions for Pre-Planned Events	Provides all scheduled travel restrictions that DelDOT Public Relations knows will be impacting traffic at a scheduled time in the future. A scheduled travel restriction can be a reoccurring restriction.	60 minutes	JSON	• Tracker
Signal Groups	Provides a near-real-time history of commands that have been issued by TACTICS to individual signals and signal groups. It can be used to determine what pattern a signal or signal group should be running.	5 minutes	JSON	• TACTICS
Signal Timing Plans and Coordination Data	Provides data from TACTICS SQL Server database including green, yellow, all red, minimum and maximum green, and pedestrian clearance times for each phase of every timing plan; signal offsets; time of day plans; and signal recall statuses.	On demand	CSV*	• TACTICS
Traffic Flow per Direction	Provides near-real-time traffic metadata including volume, occupancy, speed, and direction for detectors deployed throughout the state's roadways.	5 minutes	JSON	• Wavetronix • Signal System Loops
Traffic Flow per Lane	Provides near-real-time volume data by lane for both Wavetronix and Signal loops within a 5-minute range.	5 minutes	CSV	• Wavetronix • Signal System Loops
Traffic Flow per Lane per Minute	Provides real-time Wavetronix data from a small group of detectors in 1-minute increments by lane.	1 minute	CSV	• Wavetronix

* Data is transformed within the System, see DMP for additional details

Data Input	Description	Pull Frequency	Format	Data Sources Included
Travel Times	Provides real-time travel times for defined links.	1 minute	JSON	• Bluetooth Travel Time System
Travel Time Segments	Provides a GeoJSON feature list of all defined links within the state that travel time data is collected for by DelDOT.	1 minute	JSON	• Bluetooth Travel Time System
Vehicle Positions	Provides DTC bus and paratransit vehicle locations and other related data using the GTFS file provided by a Trapeze system used by DTC.	15 seconds	JSON	• DTC Vehicles
Video Cameras	Provides camera configuration information, including the camera locations and feed URLs.	Weekly	JSON	• Traffic Cameras
Video Feed	Provides near-real-time video footage of traffic conditions.	5 minutes	MP4*	• Traffic Cameras
Waze Alerts	Provides real-time data on events and incidents that DelDOT is monitoring.	1 minute	JSON	• Waze
Weather Data	Provides near-real-time weather metadata of DelDOT's weather stations grouped by location and district yard responsibilities.	5 minutes	JSON	• RWIS
Weather Stations	Provides near-real-time weather metadata of DelDOT's weather stations which include surface temperatures at some sites.	5 minutes	JSON	• RWIS

CSV = Comma Separated Value
DTC = Delaware Transit Corporation

While the development and testing of AI-TOMS continues, all data ingested, processed, and output by the software is stored in perpetuity and managed by three databases. An in-memory Redis database stores data needed for quick data inputs, outputs, and transfers between algorithm services; and two MySQL databases serve as a production and archive database, respectively.

2.3.1.2 Anomaly Detection and Localization Algorithm

The project team has made great strides over the past three years in detecting and locating traffic anomalies based on the data input into AI-TOMS. A traffic anomaly is any deviation from the data source's established baseline, typically caused by either an increase in traffic demand or a decrease in roadway capacity. To

* Data is transformed within the System, see DMP for additional details.

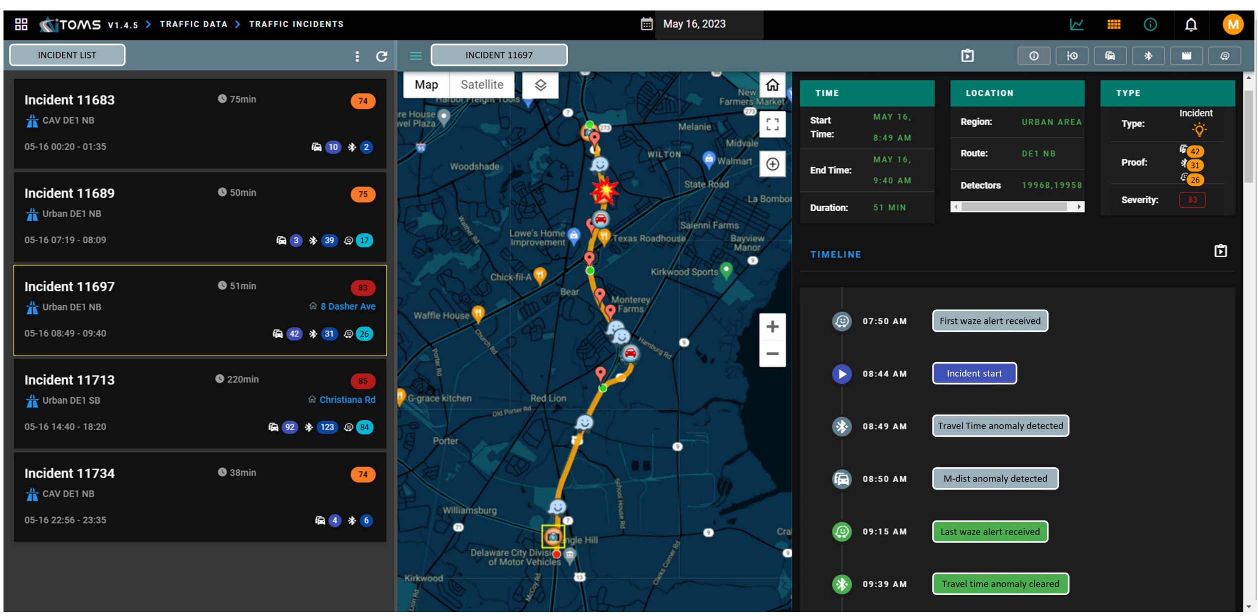
measure the transportation network's roadway capacity more accurately throughout the year, the project team first developed a free-flow speed (FFS) adjustment to account for weather impacts. The project team implemented FFS baselines using 3.5-years of weather data to analyze weather impacts on FFS and capacity in the urban and CAV areas.

The System is constantly monitoring Delaware's roadways. Traffic anomalies may occur frequently for various reasons, from debris in the roadway or a special event to a car broken down on the side of the road or a major crash that's blocking multiple lanes. Some of these anomalies are minor and will resolve quickly on their own, not all anomalies are classified as incidents by AI-TOMS. For the System to classify something as an "incident," it must detect three separate anomalies or pieces of evidence in that same area. The main components of the algorithm to detect and locate anomalies and incidents include:

- Traffic anomaly detection with data fusion comprised of Bluetooth anomaly detection, traffic flow anomaly detection, Waze anomaly detection, and DelDOT restrictions alerts
- Anomaly clustering and classification
- Data mining for travel restriction/advisory
- Incident detection and supporting evidence grouping
- Early detection by incident type

All incidents with evidence have been integrated within a single "Traffic Incidents" page on the AI-TOMS user interface, shown on Figure 7, which the user filters by day.

Figure 7: AI-TOMS Incident Page



The project team optimized the algorithm used for the video recording function to track traffic incidents, especially major incidents that cause congestion. The related video clips with incident timelines are saved in the AI-ITMS database and provide valuable information for further study on the incident impact and plan traffic mitigation in progress. Moving forward, the project team will consider combining DelDOT's ITMS data with third-party data sources to enhance automated incident detection. In order to be effective, third-party data will need to be available to DelDOT in real-time from a trusted and verifiable source as evaluated by the project team.

For anomaly and incident detection, the project team had to create distinct algorithms for both freeways and arterials. The freeway incident detection algorithms are simpler since they focus on high-speed, limited-access facilities separated by direction, resulting in fewer conflict points. Therefore, the freeway algorithms were developed first and have been integrated into AI-TOMS. The algorithm leverages travel time data from Bluetooth detectors and traffic flow data from radar detectors to facilitate quick responses to changing traffic patterns. The arterial incident algorithm is more complex due to the variable nature of arterial road networks. It is designed to detect incidents in areas with multiple intersections and variable speed limits, utilizing per-lane volume data from system detectors to detect incidents through arterial roads and travel time data from Bluetooth detectors, with the ultimate goal of minimizing congestion at critical junctions. The project team has developed an updated version of this algorithm which will be implemented soon. The project team is also evaluating integrating AI and ML components to improve the freeway and arterial incident detection algorithms.

2.3.1.3 Incident Classification and Impact Assessment

For the TMC to appropriately respond to an incident, AI-TOMS must be able to accurately classify incidents based on their severity and potential impact to the transportation network. The project team created incident severity scores based on detector data, travel time data, Waze alerts, recorded video clips, incident location, number of lanes blocked, and capacity reduction to help assess the impact of the anomaly. Users can filter the incident listings by setting a minimum severity score within AI-TOMS. Scores range from 0-100, with a severity score of 70 or higher indicating a possible need for TMC attention and possible action.

2.3.1.4 Traffic Flow Prediction Algorithm

An anticipated benefit of the AI-ITMS is the ability to make *proactive* operations management decisions rather than *reactive* ones. The traffic flow prediction algorithm anticipates what the traffic demand will look like in up to 60 minutes in the future so the TMC can start to manage congestion before it even happens. This algorithm is developed and integrated with AI-TOMS.

The project team trained new long short-term memory (LSTM) freeway detector models on I-95 and DE 1 in the urban and CAV areas. The LSTM deep learning neural network model utilizing the following input parameters for the training of traffic prediction:

- Sample data:
    - Volume
    - Speed
    - Occupancy
- Metadata (categorical):
    - Month (value 1-12)
    - Day (value 1-7)
    - Hour (value 0-23)
    - Minute (12 possible values in five-minute increments from 5-60)
    - Weather (48 varied weather conditions as defined by Yahoo weather)
    - Holiday (binary 0 or 1 depending on whether it is a holiday or not)

The overall input matrix consists of multiple sets of datapoints from the predicting sensor as well as from all the nearby sensors consisting of 20 datapoints from immediately preceding the current sample, 20 datapoints from past 20 days corresponding to the same time of day, and 20 datapoints from past 20 weeks corresponding to same time of day and same day of week. The “month” category within the metadata helps account for seasonal variations of traffic within the model. Even if the input data for prediction corresponds to a different season, the model will implicitly capture the impact of seasonal variations.

The team also trained arterial system detectors using a graph for time series algorithm (GTS model) along two major signalized corridors—the US 13 corridor in CAV area and the DE 1 corridor within the beach area.

An example showing the ability of the LSTM traffic flow prediction algorithm to accurately predict traffic volumes is shown on Figure 8.

Figure 8. Sample LSTM Volume Prediction Results using 5-Minute Prediction Increments

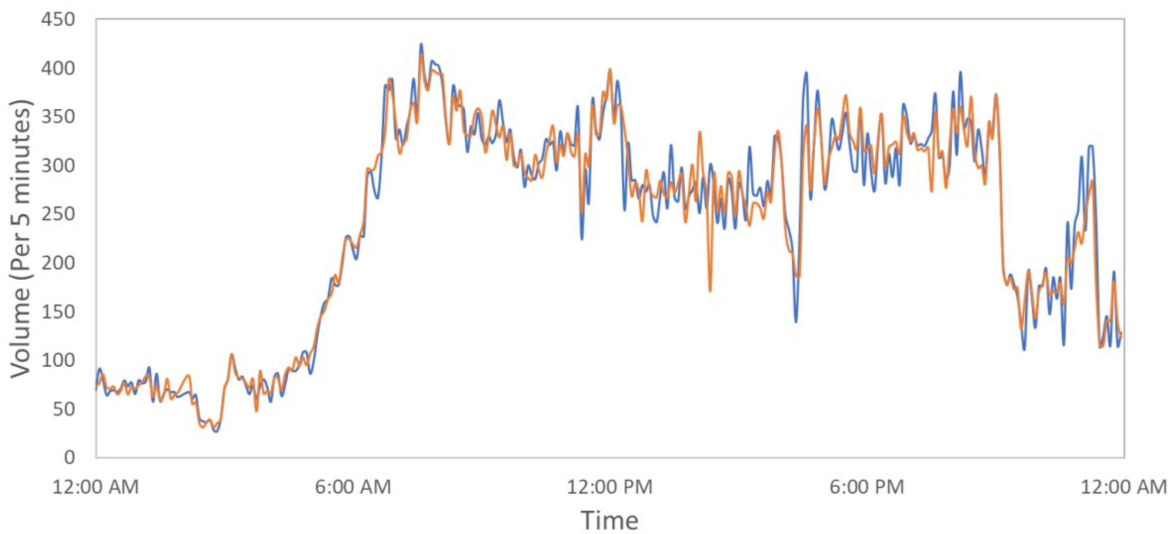


Table 6 shows example volume prediction performance for 5-, 10-, 15-, 30- and 60-minute for the same freeway detector, N19997, on I-95 using different prediction algorithms. Here “Naïve” model means using the current value as if it is the future value. The historical average is calculated based on the time of day and day of week, without considering the current datapoints. Therefore, the Mean Absolute Percent Error corresponding to historical average does not depend on the prediction horizon. This means that the prediction of volume for 5 pm on a Thursday will always be a constant regardless of whether it is predicted at 4:30 pm or at 10 am of that day or even 6 months prior to that day.

Table 6. Mean Absolute Percent Error of Traffic Volume Predictions at Detector N19997

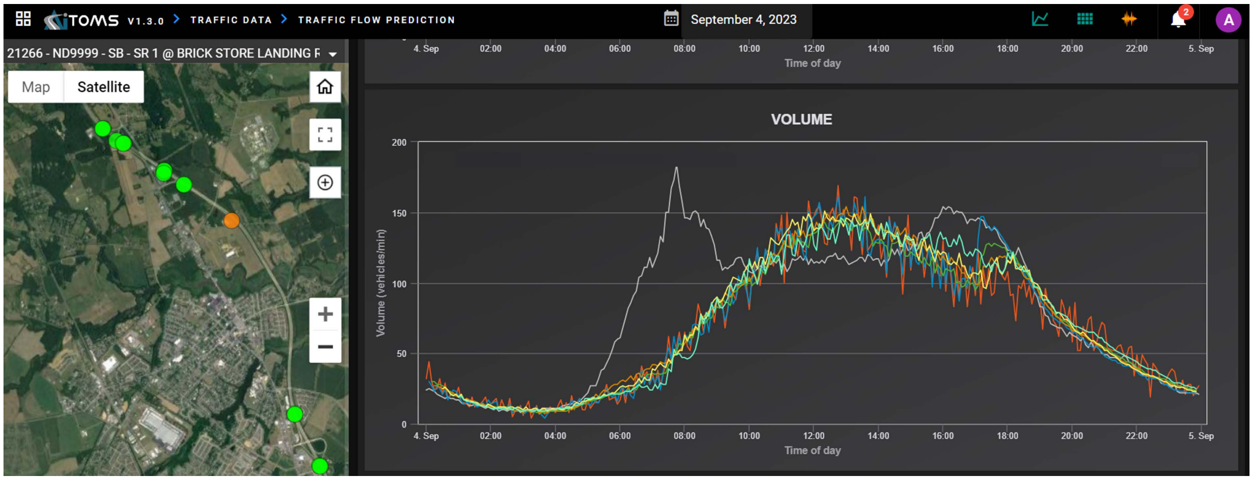
Prediction Model	5-Minute	10-Minute	15-Minute	20-Minute	60-Minute
Naïve	11.70	12.54	13.88	16.90	23.59
Historical Average	16.40	16.40	16.40	16.40	16.40
LSTM + Good Data	4.55	8.08	9.96	10.99	11.94
LSTM + 10% Random Data	32.07	28.43	19.83	18.42	19.26
Robust LSTM + Good Data	4.72	8.24	10.16	11.01	12.35
Robust LSTM + 10% Random Data	5.69	9.14	10.94	11.61	12.83

For good quality data, LSTM performs well as shown in the “LSTM + Good Data” row; however, if the data is corrupted, the regular LSTM model will perform very poorly, as shown in “LSTM+10% Random Data” row. For this project, the project team also trained the robust LSTM model based on imperfect traffic data and demonstrated that “Robust LSTM” algorithm still performs very well even when 10% of the data is corrupted, as represented by the final row of the table. The results of this comparison for additional locations may be produced upon request.

To ensure the traffic flow prediction algorithm continuously improves and adapts to seasonal traffic patterns, the project team created an automated model-updating pipeline which pulls the previous month’s data each month to assist with training prediction models. The self-learning pipeline also identifies when prediction models either degrade below a performance threshold or have noticeable improvement over the existing model based on newer data. Additionally, in the case of a short-term or a non-seasonal traffic pattern change, such as the change that one would expect from construction, manual adjustments can be made to the traffic flow prediction algorithm based on updated capacities.

Early results demonstrate AI-TOMS handles non-incident-related traffic pattern abnormalities, such as holidays, very well. Figure 9 presents an image from the AI-TOMS webpage showing actual, predicted, and baseline volumes for Labor Day, Monday, September 4, 2023. Despite baseline volumes showing typical weekday peaks in the morning and evening, AI-TOMS accurately predicted traffic volumes up to one hour ahead. This level of prediction allows DelDOT to proactively change signal timings instead of reactively as a typical traffic responsive system does.

Figure 9. AI-TOMS Traffic Prediction on Labor Day, 2023



2.3.1.5 *Signal Analysis and Recommendations*

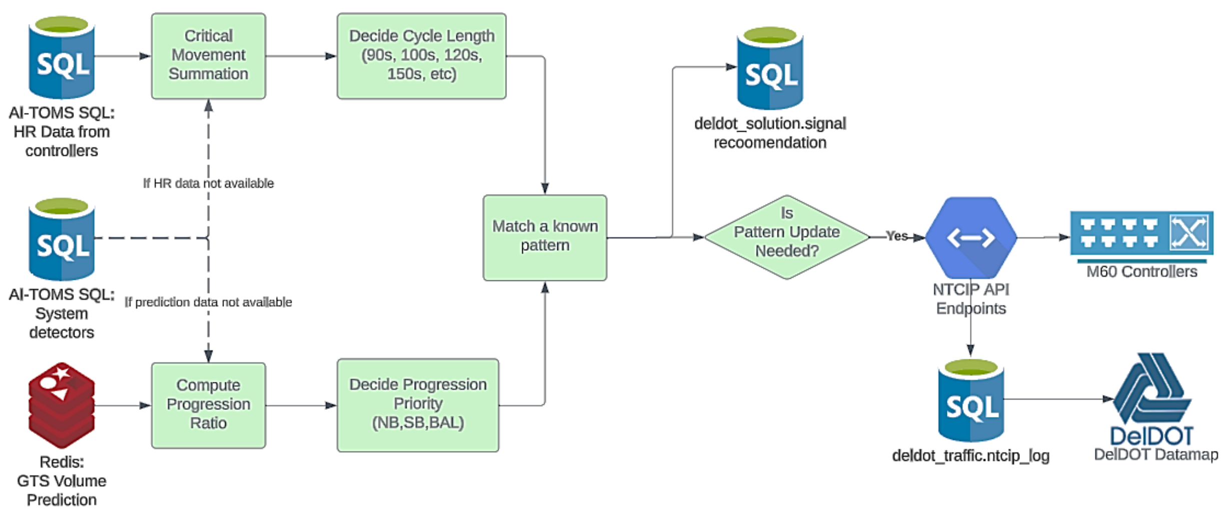
DelDOT has significantly emphasized AI and ML for traffic signal operations to keep traffic moving with and without the presence of an incident. The project team developed an algorithm that considers Critical Movement Summations in undersaturated conditions and optimizes signal timings. The project team follows National Cooperative Highway Research Program (NCHRP) 03-90 Practitioner Guidance[7] to measure two indexes based on shockwave theory: Temporal Oversaturation Severity Index and Spatial Oversaturation Severity Index. Using this guidance, the project team developed a software module in AI-TOMS to calculate the Temporal Oversaturation Severity Index and the Spatial Oversaturation Severity Index for arterial signals,

[7] NCHRP 03-90 Practitioner Guidance, Operation of Traffic Signal Systems in Oversaturated Conditions, July 2012, Kimley-Horn & Associates

two key indicators used to assess overflow queuing in traffic scenarios. the Temporal Oversaturation Severity Index measures the severity of traffic oversaturation over time (e.g., oversaturation due to insufficient green time) whereas the Spatial Oversaturation Severity Index assesses the severity of oversaturation in terms of space (e.g., oversaturation due to a downstream blockage).

Figure 10 illustrates the approach used by AI-TOMS to optimize signal timing and how it interacts with signal controllers in the field to deploy and monitor these changes. The optimization engine calculates Critical Movement Summations using HR or system detector data from the field to determine the ideal cycle length at a given intersection. Simultaneously, AI-TOMS uses its GTS traffic prediction algorithm to compute a progression ratio and determine progression priority within a signal group, allowing more green time for the direction with higher demand. AI-TOMS matches the determined cycle length and progression priority with a known signal timing pattern, typically with a cycle length ranging from 60 seconds to 240 seconds, and updates the signal timing in the field within the signal group and on DelDOT's web data map as needed. AI-TOMS also stores this recommended pattern for future use cases, allowing the System to continuously learn what works best on the roadways.

Figure 10: AI-TOMS Signal Optimization Flow



Throughout summer 2023, the signal optimization algorithm was implemented at three specific traffic signal groups. Comparing travel times along these segments when AI-TOMS was controlling signal timing vs. when TACTICS was in control showed promising results. Along a segment of road within one of these signal groups saw changes in mean travel times based on June and August 2023 Bluetooth data. Travel times along the AI-TOMS controlled segment fell within one standard deviation of the mean travel time for more than 80% of the day, an improvement over previous TACTICS-controlled days along the same segment. Travel times with less variability indicate potentially better traffic flow efficiency, but the sample size of the data was too small to make and present substantive quantitative conclusions. The project team is continuing to test the signal optimization algorithm in the field and expand the types of signal timing recommendations the System can make, including offset adjustments and split timing adjustments. With these advancements and integration of signal offsets and split timings, the System will be able to create and recommend new signal timing patterns not previously stored in TACTICS, implementing them at individual intersections as opposed to whole signal groups. The System will continue to learn what works best in the field and the project team will evaluate any new minimum or maximum cycle lengths that may need to be built into the System.

2.3.1.6 Routing Choice Determination Algorithm

This algorithm determines the possible detour route options as recommended response plans in an incident. The current version of the algorithm uses Bluetooth-based travel time data (both real-time and historical) to generate the shortest path in terms of travel time, considering the real-time capacities along the freeway and detour routes. AI-TOMS monitors and predicts the traffic demand and calculates the available capacity along the impacted roadway link. Based on the relationship between demand and available capacity, AI-TOMS will evaluate if a traffic detour is required and whether the signals along the detour route need to be adjusted to accommodate the additional detoured traffic. If a different signal plan is required, the software will use the incident mitigation plan recommendation algorithm provide an “optimal” plan with VISUM simulations and SUMO model verifications. More information on the calibration and verification of these models can be found in section 4.6.1 Calibration Criteria. A long-term model maintenance program including periodic validation and recalibration has yet to be determined and will be further investigated as part of subsequent program efforts. As development continues, the System will eventually go beyond making recommendations and will be capable of automatically making changes.

2.3.1.7 Incident Mitigation Plan Recommendation Algorithm

One of the goals of the AI-ITMS program is to create a system that can automatically provide signal timing recommendations when traffic conditions demand them. The incident mitigation plan recommendation algorithm does exactly that. When an incident impacts the capacity of a roadway significantly enough that traffic rerouting onto a parallel arterial is necessary to alleviate the resulting congestion, the arterial roadway that traffic is detoured onto experiences increases in demand. When traffic is rerouted onto a signalized roadway, this algorithm recognizes the increased demand and recommends signal timing adjustments to TMC staff. Current instances of traffic being rerouted is a manual one, typically with DelDOT setting up detour routes for long-term closures or drivers self-rerouting based on local knowledge. In the future, the System will be able to automatically determine alternative routes using simulation and modeling (fed by roadway types, travel time information, travel demand vs. capacity, etc.) and then inform drivers through TIS. The algorithm makes use of VISUM and SUMO simulations to evaluate multiple candidate signal plans, freeing TMC staff to focus more on the safety of individuals involved in the incident and clearance of obstructions to capacity. Upon reviewing the signal timing recommendations, TMC staff can initiate any timing changes using NTCIP communications.

Figure 11 presents an example from the AI-TOMS webpage of the incident mitigation plan recommendation algorithm recommending alternate signal timings along US 13 to accommodate increased demand resulting from an incident that occurred on DE 1.

Figure 11: AI-TOMS Signal Timing Recommendation for Incident Mitigation

2.3.1.8 Corridor Signal Performance Evaluation Algorithm

AI-TOMS uses speed, travel time, and delay to evaluate performance before vs. after applying mitigations to the field. AI-TOMS collects HR data from signal controllers in the field every 5 minutes and is capable of increasing the HR pull frequency to every 30 seconds. The HR data logs signal coordination diagrams, arrivals on red and green, and approach delay time and is overlayed with vehicle trajectory data for use in signal performance evaluation.

Testing of the performance evaluation algorithm has been limited as the System is in the initial stages of signal integration, but simulations have been used for testing in the CAV area.

2.3.1.9 CAN Bus Trajectory Data Algorithm

The CAN bus trajectory data algorithm was developed for calculation of the Corridor Synchronization Performance Index (CSPI) performance measure. It provides information helpful to signal synchronization such as stop frequency and travel speeds, but it is currently limited to the 10-vehicle sample set of DelDOT vehicles equipped with CAN bus data dongles.

2.3.2 Software/Systems Status

2.3.2.1 Representational State Transfer (REST) Web Services

REST software architecture helps to define the style and architecture of the AI-TOMS web server. Over the past three years, the AI-TOMS webpage has been updated based on feedback from users and reviewers on the project team. The project team merged each application's graphical user interface (GUI) into one page, resolving log-in issues in the production environment and simplifying user experience. A configuration settings tool was also integrated to allow users to set up personalized dashboards.

REST web services helped to significantly improve the playback function from the original AI-TOMS dashboard in terms of both performance and code refactoring. The playback function runs more smoothly and processes/loads data from the backend faster than before and front-end issues with loading Google Maps have been debugged. As a result, the front-end user interface performance has been improved and is currently performing as follows:

- Dashboard data loading (less than 1 second)
- Traffic data playback (less than 5 seconds)
- HR data summary page loading time (less than 1 second)

2.3.2.2 Message Notification Services

As AI-TOMS continues to learn and identify traffic patterns, it must also be able to notify the TMC and the traveling public of its findings and recommendations for the System to be useful. Currently, AI-TOMS offers a standalone notification service which provides email, SMS, and web push notifications (desktop and mobile) and updates to DelDOT's Google Cloud Platform. Currently, email notifications are sent to key TMC personnel. Once the System is fully deployed and approved, more notification services will be turned on at the discretion of DelDOT.

Messages and notifications are secured using an HTTPS encryption with a secure sockets layer (SSL) which creates an encrypted link for the AI-TOMS software.

2.3.2.3 Mobile Services and Traveler Information System (TIS)

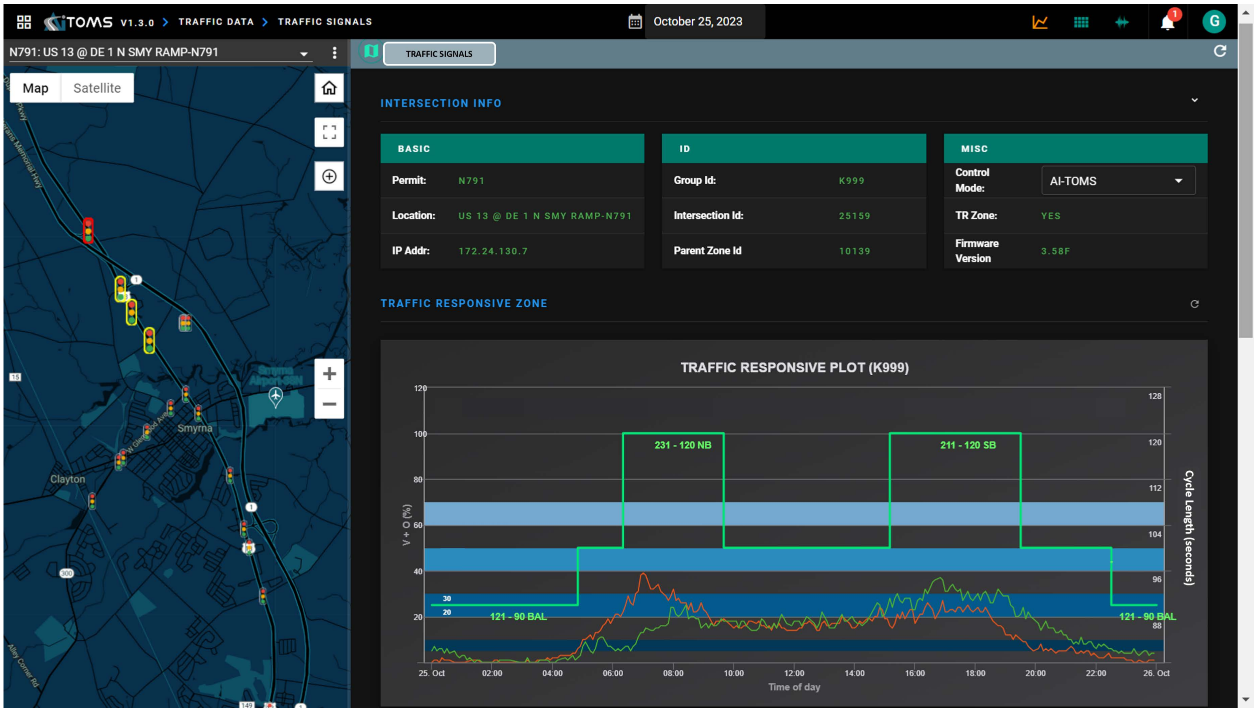
Applications and utilities are currently available on the web version of AI-TOMS, but mobile implementation of the AI-TOMS app is underway and will allow an alternative view of the data, charts, maps, and other features. Tablet and mobile support for all application interfaces have been developed, and AI-TOMS' design structure has been updated to enable easier code changes and additions in the future.

The project team also developed a concept plan for integrating AI-TOMS and AI-TMC Travel Smart (a TIS software). Integration would allow information exchange with other TMC tools, such as the TMC Data integration and Visualization Map and the DelDOT Mobile App for traveler information sharing. Looking forward, the project team plans to create an API for AI-TMC Travel Smart and other third-party software to exchange data for integration.

2.3.2.4 Signal Timing Implementation Services

Reflecting the priority placed on signal analysis and signal timing recommendations under the AI-ITMS program, the project team created a Traffic Signals page in the Traffic Data module, as shown in Figure 12. It provides users with a GUI to review current intersection signal timing information such as cycles, splits, and offsets. Adaptive traffic management strategies maintain throughput and coordination with proper cycle and offset selection and minimize delay through split optimization. The system is currently able to select and command a "best fit" timing pattern from pre-defined and pre-loaded timing plans on the controller.

Figure 12: AI-TOMS Traffic Signals Webpage



To improve user experience, the project team upgraded queries for better data load time, with Redis caching for historical data so frequently accessed data can be loaded more quickly and developed an interface within AI-TOMS to allow direct pattern selection, signal timing parameters adjustment, and signal timing implementation using NTCIP. Bench controller testing and small-scale field deployment have been completed, allowing AI-TOMS to control and operate traffic signals in northern Smyrna, Delaware (CAV area). The resulting traffic signal management strategy measures actual and predicted demand to provide more adaptive control and maintains throughput and coordination with proper cycle and offset selection.

The project team continues to test implementing timing plans on selected signals on US 13 in the CAV study area. Initial observations show that the signal group under AI-TOMS control achieves similar or slightly better performance compared to DelDOT's typical traffic responsive approach; however, a larger sample is required to quantify the impact on traffic. As testing continues and the data sample size increases, the project team will continue to evaluate AI-TOMS' effectiveness in adaptive and predictive traffic management.

2.3.2.5 System Health Monitoring Services

The system health monitoring service flags missing data and smooths data to improve the accuracy of AI and ML algorithms that are part of AI-TOMS including the incident detection, data collection, traffic flow prediction, and adaptive signal control algorithms. AI-TOMS can report and notify users of sensors with missing data and sensors with a flow status of zero. The system health monitoring services application offers a visual tool to show the System status to users with administrative access.

2.3.2.6 Simulation Services

Simulation services are used to evaluate effectiveness in the transportation network. The project team developed the VISUM simulation model for the three study areas (CAV, Urban, and Beach) using origin-destination (OD) and signal timing information. DelDOT's CUBE travel demand model and third-party location-based service and global positioning system probe data were used to provide OD information to support the initial model development. After reviewing the available OD data in the Urban Area, the team decided to utilize the existing CUBE model to produce the OD matrix for the VISUM model. Real-time traffic data from traffic flow and Bluetooth detectors are then used to calibrate trip distribution for near real-time scenarios within the Urban study area. The model framework and memorandum documents for each of the three study areas provide additional details on the approach and methodologies used.[8] [9] [10]

The project team has also developed a VISSIM model of Zone 20, which consists of 25 signals on DE 1 within the Beach study area for offline evaluation of the delay and travel times associated with the current traffic responsive plan selection (TRPS) thresholds. The project team used vehicle-actuated programming controllers to enable VISSIM to simulate programmable vehicle-actuated signal controls. During VISSIM simulation runs, vehicle-actuated programming interprets the TRPS control logic commands and generates the signal control plans for the network. Signal plans are changed based on simulated volume plus occupancy values via the VISSIM Component Object Model (COM). The users can view a graphical representation of the forecasted level of service on the map, with a forecast for every 15-minute interval. The graphical representation on the map contains an overlaid network of links that are colored to represent the level of service. The Zone 20 VISSIM model framework and memorandum documents provide additional details on the approach and methodologies used.[11]

The long-term utility of these models and related need for ongoing model maintenance program including periodic validation and recalibration has yet to be determined and will be further investigated as part of subsequent program efforts. More details on simulation services as they relate to challenges and scope changes throughout the grant can be found in Section 4.6 Simulation Challenges.

2.3.3 Data Collection Status

In addition to the data that is currently integrated into AI-TOMS, described both in the section "Data Ingestion and Aggregation Algorithm" under 2.3.1 Algorithms Status, as well as in the DMP, the project team has also evaluated other data sources, some of which are still being considered for future integration.

2.3.3.1 Loop Signature Matching

Loop signature matching allows departments of transportation to classify vehicles on roadways using existing inductive loop detectors (often referred to as "signal system loops" within DelDOT) for the purpose of classification and re-identification between upstream and downstream detector stations to measure travel times. The inductive loop card within the cabinet which typically collect vehicle volume data is upgraded to an amplifier card that measures signature profiles. These upgrades are non-intrusive and are made in the signal cabinets, providing DelDOT with additional transportation data at a lower cost than alternatives. Two loop signature matching systems were installed at DE 1 N Smyrna Ramp and Duck Creek Road on US 13. Vehicle signature data is collected from each cabinet via cellular wireless at 5-minute intervals and stored on a central server. A web interface displays the loop signature plots in real-time and a loop signature service matches the best upstream and downstream signatures of vehicles crossing both loop detectors to determine travel times. Results to date have shown an approximate 90% individual vehicle match rate.

[8] DelDOT CAV Model Framework, CAV VISSIM Model Memo, and CAV VISUM Model Memo, March 2023
[9] DelDOT Rural VISUM Model Framework and Rural VISUM Model Memo, March 2023
[10] DelDOT Urban VISUM Model Framework and Urban VISUM Model Memo, March 2023
[11] DelDOT Zone20 VISSIM Model Framework and Zone20 VISSIM Model Memo, March 2023

Match rates are sensitive to vehicle density and link distances; therefore, loop signature matching may not be effective at all locations. Future plans for this system involve additional deployment of loop signature cards, and integration into AI-TOMS algorithms to address corridor or network level vehicle trajectories, travel times and turning movement counts. DelDOT is also considering including platoon signatures to improve match rates. Though DelDOT is generally trying to move away from in-pavement technology, loop signature matching gives DelDOT the opportunity to leverage this existing infrastructure at a relatively low-cost investment.

2.3.3.2 Wejo Data

Wejo, a vendor of connected vehicle data, collects near-real-time vehicle data points and analyzes journeys across networks. The project team evaluated Wejo's data accuracy, coverage penetration, and processed Wejo data passing ten intersections in the CAV area using a one-week sample of data from Delaware. Measuring from 15,057 trips, the waypoint update frequency of the Wejo data was less than 3 seconds over 96 percent of the time. From 2016 to November 2021, penetration rates increased from an overall 1.1% overall to 4.67% as measured in the project study area. The average hourly penetration level ranged from 3.44% to 7.33%. The project team is currently looking into other data sources and options that may provide increased penetration rates.

2.3.3.3 Social Media Analytics

The project team originally planned to use data from social media sites like Twitter as another source of incident detection evidence. Under this grant, the project team completed an analysis that showed that Twitter topic modeling of multi-million tweets performed poorly due to the overwhelmingly large number of unrelated tweets with low correlation metrics between clustered topics and traffic-related labels. Additional data is needed to train a well-functioning model. DelDOT may still consider adding social media information as a data source to the System in the future but is not being actively pursued at this time.

2.3.4 Testbed Status

2.3.4.1 Machine Vision Testbed

The project team built a real-time video streaming and MV testbed on US 13, which provides constant streaming without interruption or better than every 5-minutes without interruption. The project team improved the open-source MV based vehicle tracking algorithm and speed estimation by calculating vehicle speed between two reference lines for machine vision-based traffic flow analysis. Open-source tools and the in-house developed algorithm yielded better than 95% accuracy for vehicle counting during daytime conditions and measurement of vehicle speed and roadway occupancy.

Within the testbed, the project team deployed four HR cameras with an edge computing hub at the intersection of US 13 and DE 300 in June 2022 using commercial off-the-shelf components. The MV hub provides edge computing capability to process the video images from all four cameras and generate the traffic metadata which is locally stored and forwarded to a central server. High-definition video from all four channels is live streamed at 30 frames per second and are accessed using one cellular modem. Vehicle count, speed, occupancy, and classification data are processed at the edge and results are communicated to the server every minute. The MV hub's remote access and wireless communication were tested successfully at both field and remote offices, and the upgraded MV application provides users a GUI to set up detection zones and automatically reboot the computer when the system is shut down during power outages and other unplanned events.

The project team also deployed four AI-enabled cameras on US 13 at DE 1 Ramps. Cellular communication between the four cameras and a server was set up at the field in March 2023. Users can access the cameras remotely and adjust the angle and configuration. The four cameras have been added to the remote portal for testing with object classifiers activated and settings initially trimmed for optimization.

Future work will focus on managing MV camera metadata to generate volume, speed, occupancy, travel time using object re-identification and other traffic-related information for use in transportation management applications.

2.3.4.2 Controller Area Network Bus Data Testbed

As part of the grant project, the TMC installed 10 CAN bus dongles on DelDOT public vehicles to collect vehicle location, speed, acceleration, and other CAN bus data via the onboard diagnostics II port for vehicle tracking and monitoring. The dongle logger records the CAN bus data from these vehicles in real-time and the uploads it every 5-minutes to the AI-ITMS server in the TMC. The project team completed tests for all parameters required for calculating vehicle performance including wheel-based vehicle speed, engine revolutions per minute, distance traveled, and more from the onboard diagnostics II port and vehicle location and acceleration from the geographic positioning system (GPS) and inertial measurement unit sensors. The CAV data visualization and analysis application has been upgraded in AI-TOMS and provides a beneficial tool for evaluating roadway performance under different conditions.

The project team also integrated fixed-route bus transit automated vehicle location and CAV data as overlay vehicle trajectories on the Time-Space Diagram to measure signal coordination performance. Current challenges with using existing transit automated vehicle location data and CAN bus trajectory data include:

- Sample size (number of tracked vehicles) is too small to yield an appreciable benefit
- Existence of dedicated bus lanes do not represent FFS of other general-purpose lanes
- Bus stop locations (near-side and far-side) may inaccurately reflect signal progression performance at the intersections.

DelDOT will continue to investigate equipping additional fleet vehicles and address the current challenges with using this data. The utility of vehicle trajectory data will continue to be evaluated as CAV penetration improves.

2.3.4.3 Dilemma Zone System Testbed

The dilemma zone is the area just before a traffic signal in which approaching vehicles cannot safely stop before a red light, nor can they keep driving to make it through the signal safely before the signal turns red at the speed they are going. Using radar sensors, DelDOT detects if a vehicle is entering a dilemma zone and either activates a flashing beacon to warn approaching drivers or automatically extend the green interval to allow the driver time to safely make it through the intersection.

DelDOT installed a dilemma zone system in February 2019 at the intersection of US 113 and DE 16. Under this grant, it has begun the process of installing a second dilemma zone system at the US 13 and DE 1 Ramps in Smyrna. Field equipment and infrastructure have been installed but still need to be integrated and configured before the system is operational.

2.3.4.4 Signal Phasing and Timing (SPaT) Cellular Vehicle to Everything Testbed

DelDOT installed 20 roadside units (RSU) in the CAV area early in the project prior to the Federal Communications Commission (FCC) ruling on the dedicated short-range communications 5.9 gigahertz (GHz) band spectrum reallocation. While DelDOT continues to upgrade these to dual-mode capable units to comply with the revised FCC ruling, it put its connected vehicle program on hold while it evaluates the impact of the new ruling and general direction of connected vehicle technology.

DelDOT redirected its efforts to invest in related software development to prepare for this capability. An HR data file transfer protocol (FTP) server and traffic data processing server were deployed at the TMC, and a prototype version for SPaT data collection and broadcast was developed. The SPaT data collection prototype currently shows live signal status in AI-TOMS to evaluate signal performance metrics. The average latency from the signal indication to the mobile version of AI-TOMS is less than 130 milliseconds.

A concept application using Verizon's cellular-based virtual RSU showing the potential benefits of cellular-based technology with the AI software and live SPaT data and data collection of onboard unit (OBU)-equipped vehicles will be considered in the future.

2.3.4.5 Signal Control Testbed

The project team worked with the Delaware Department of Technology and Information to set up servers and communication infrastructure which enabled signal control in the field via NTCIP. This infrastructure allows signals to operate under a variety of modes (TACTICS, AI-TOMS, time of day, and manual), and allows the user to make changes to existing patterns or create new timing plans under manual operation. To ensure the System is running smoothly without interrupting DelDOT's existing central signal control system, new computing environments have been developed to communicate between AI-TOMS and signal controllers:

- The existing operational environment is within the DelDOT intranet, currently running at the TMC with TACTICS.
- A secondary production environment in the "demilitarized zone" (DMZ) acts as a duplicate of the operational environment. Signal controllers are being copied by zone from the operational to production environment where they will run on AI-TOMS.
- A third, separate environment is used for ongoing testing and development support.

More detail on these environments is included in Section 4.4.2.

2.4 Traveler Information System (TIS) Status

The original vision for the TIS component of the AI-ITMS project incorporated all travel advisories generated by AI-TOMS with all aspects of DelDOT's existing TIS. This includes alerts through email, text message, DelDOT's web and mobile applications, and DelDOT social media accounts. Efforts integrating the TIS to date have focused on using AI-TOMS generated emails and text messages to help TMC leadership and the project team test other functions of AI-TOMS such as congestion and incident detection. Currently, these email and text alerts are sent out to select DelDOT TMC staff members. As AI-TOMS continues its migration from the development environment to the production environment and as TMC staff gain confidence in the information generated by AI-TOMS, opportunities to further integrate AI-TOMS generated alerts into the public-facing pieces of the traveler information system will grow. DelDOT intends to implement varied levels of TIS notifications, differentiating between internal and public-facing notifications. Public-facing messaging will be on a need-to-know basis, using non-technical language to inform travelers of things like travel times to key destinations and hazards on the roadway ahead

3 System Performance

3.1 Evaluation Scope

The ATCMTD grant requires that DelDOT perform an evaluation of its AI-ITMS program at the conclusion of the grant period. While development, testing, and implementation of the AI-ITMS program is ongoing and will continue beyond the conclusion of the grant, this evaluation presents a snapshot of how the AI-ITMS currently performs when measured against the project goals and performance measures outlined in the *AI-ITMS Evaluation Plan* (Evaluation Plan)[12].

These results refer to both analysis of AI-ITMS and analysis of the AI-TOMS. In these cases, mentions of AI-ITMS refer to the entire AI-enhanced ITMS; encompassing all traffic monitoring technologies; transportation infrastructure; and people involved with the planning, design, operations, and maintenance of the transportation system. AI-TOMS refers specifically to the software developed to provide the existing DelDOT ITMS with AI-enhanced capabilities.

The Evaluation Plan outlines the goals, objectives, guiding questions, and performance measures used in this evaluation. These goals, objectives, and guiding questions are outlined in Table 7 broken down by the goals set by the project team for the AI-ITMS. This information was then used as a foundation to develop the performance measures shown in Table 8.

It is important to note that the performance measures outlined in Table 8 are reflective of the primary project goals at the time that the Evaluation Plan was written. Over the past couple of years, the AI-ITMS program's focus has shifted considerably towards progressing the elements of the AI-ITMS that relate to signal operations. With this shift, several of the project's software components remain in the pre-deployment stage and have not yet been approved for deployment by DelDOT. Since the Evaluation Plan did not set performance measures for the pre-deployment stage, this evaluation focuses on evaluating the project using only the performance measures established for the deployment stage where appropriate. The performance measures established for post-deployment can be found in Appendix B and should be reevaluated as work continues beyond this grant.

Table 7. Project Goals, Objectives, and Guiding Questions

ID	Goal	Objectives	Evaluation Questions
1	**Increase transportation system monitoring speed and accuracy**	• Use AI/ML technologies to identify anomalies faster and more precisely • Leverage new sensor technologies to detect changing traffic conditions • Track and monitor transit and public vehicles	• What is the average AI-ITMS incident detection time for both freeway and arterial roads? • How accurately does AI-TOMS detect traffic incidents? • How frequently and precisely does AI-TOMS monitor and update transportation system conditions (tracking vehicles, monitoring signal systems etc.)?

[12] AI-ITMS Evaluation Plan, July 16, 2020, Delaware Department of Transportation

ID	Goal	Objectives	Evaluation Questions
2	**Automate transportation system information analysis and traveler information sharing**	• Extract transportation system performance measures and predict impacts automatically • Provide real-time travel information to the public for route choice and travel planning • Increase mobility options such as alternate route choices, transit, and CAVs • Warn drivers about transportation safety hazards	• How efficiently can AI-ITMS update traffic/detour notifications onto VMS/Dynamic Message Sign (DMS), the DelDOT website and mobile application ("platforms")? • How well does AI-TOMS meet the expectations of the traveling public, DelDOT TMC employees, and stakeholders? • Following AI-ITMS public outreach, what is the increase in usage for the DelDOT website and mobile application?
3	**Improve event/incident response through advanced control of ITS devices**	• Streamline traffic flow to reduce delay and vehicle hours traveled • Improve transit schedule adherence • Optimize transportation services to reduce costs and improve travel time reliability and accessibility • Automate transportation management response decisions and procedures for TMCs	• What is the reduction in congestion volume and duration resulting from AI-ITMS deployment? • How many ITS devices does AI-TOMS simultaneously monitor and control? • How cost-effective is AI-TOMS? • How long does it take AI-TOMS to formulate mitigation suggestions for confirmed traffic incidents (signal timings, detours, lane closure, dispatch, etc.)?
4	**Prepare for emerging transportation technologies**	• Monitor and communicate with CAVs for better traffic management • Improve efficiency of operations and mobility of CAVs • Identify instances of potential AI/ML project improvements	• How well does AI-TOMS interface with CAVs and other emerging technologies? • What Lessons Learned did the project support team identify to assist in facilitating future AI-ITMS deployments?

Table 8. Evaluation Performance Measures

Name	Deployment Stage Performance Measures	Evaluation Period
Incident Detection Time	Freeway: Incident detection time[B] $\leq$ **10 minutes** Arterial: Incident detection time $\leq$ **15 minutes**	Freeway: July 1, 2022, to May 31, 2023 Arterial: March 1, 2023 to May 31, 2023
Incident[13] Detection Accuracy	Major Incident[14]: ≥ **90%** detection accuracy, Medium Incident: ≥ **85%** detection accuracy Minor Incident: ≥ **75%** detection accuracy	Freeway: July 1, 2022, to May 31, 2023 Arterial: March 1, 2023 to May 31, 2023
Transportation System Condition Updates	Provide automatic road anomalies/congestion updates every **7 minutes**	As of June 30, 2023
Notification Update Speed[C]	**≤ 3 minutes** following incident detection	March 1, 2023 to May 31, 2023
Notification Update Accuracy[D]	**≥ 95%** accuracy following incident detection	March 1, 2023 to May 31, 2023
AI-ITMS Approval Rating	***Evaluated Post Deployment only.***	N/A
Public Participation	***Evaluated Post Deployment only.***	N/A
Average Delay Time	No decrease in roadway segment average delay time	Not evaluated. See section 3.11 for more details.
Concurrent Monitoring Capabilities	AI-ITMS simultaneously monitors of **50%** of the DelDOT ITS and internal networks	As of June 30, 2023
Benefit-Cost Ratio	Positive ratio of AI-ITMS benefits to cost for specific deployment	Qualitative assessment as of June 30, 2023
Incident Mitigation Suggestions	Suggestions for incident mitigation are offered in **≤ 5 minutes** following incident detection	Not evaluated. See section 3.14 for more details.

[B]: Timestamp associated with detection of a traffic incident by AI-TOMS.
[C]: The length of time AI-TOMS takes to update traffic/detour notifications across all platforms.
[D]: The word for word message accuracy AI-TOMS achieves when updating traffic/detour notifications across all platforms.

[13]: The *Highway Capacity Manual 6th Edition* defines an incident as any occurrence on a roadway, such as crashes, stalled cars, and debris in the roadway, that impedes normal traffic flow.

[14]: Project team defined major, medium, and minor incidents using *Manual on Uniform Traffic Control Devices* (MUTCD). Major incidents are defined as having a duration longer than 2 hours, medium incidents are defined as having a duration between 30 minutes and 2 hours, and minor incidents are defined as having a duration of less than 30 minutes.

Name	Deployment Stage Performance Measures	Evaluation Period
Transit Schedule Adherence	**4-5%** improvement in on-time performance (OTP)	Not evaluated. See section 3.15 for more details.
Preparation for Emerging CAV Technology	Accurately determine the penetration rate of OBU-equipped vehicles broadcasting vehicle to infrastructure (V2I) basic safety messages (BSM) from **30%** of the DelDOT RSU-equipped intersections	Not evaluated. See section 3.16 for more details.
Lessons Learned	List of lessons learned per AI-ITMS deployment phase	As of June 30, 2023

This is the first formal evaluation of the AI-ITMS (System). As DelDOT continues deployment, the performance metrics above are used as benchmarks of success for the System. As work continues beyond the ATCMTD grant program, additional evaluations may be completed to help DelDOT track the System's growth and accuracy. DelDOT is aware there may be times when the System does not exceed the standards set by the performance measures above but still offers an improvement over a previous practice. DelDOT views these scenarios as a successful step toward its ultimate goals.

3.2 Evaluation Team Roles and Responsibilities

This evaluation was completed by the evaluation team, described in Table 9. The roles and responsibilities of evaluation team members were assigned to provide an independent analysis of the progress made on the project while leveraging the knowledge of project team members. All project team members and their roles are summarized in Table 10.

Table 9. Evaluation Team Members and Roles

Team Member	Role and Responsibility
DelDOT Division of Transportation Solutions	• Program lead and managing agency
Drive Engineering	• Analysis lead
Jacobs Engineering Group	• Analysis support and quality assurance/quality control • Report lead
BlueHalo	• Provider of data gathered and produced by AI-ITMS
University of Delaware	• Quality assurance and quality control

Table 10. Project Team Members and Roles

Team Member	Role and Responsibility
DelDOT Division of Transportation Solutions	• Program lead and managing agency
Jacobs Engineering Group	• Program management • ITS and traffic engineering services

Team Member	Role and Responsibility
	• Systems engineering
BlueHalo	• Technical consultants • Software development and system integration
Drive Engineering	• Project evaluation
University of Delaware	• Research support

3.3 Evaluation Procedure Overview

While the Evaluation Plan outlines the performance measures that are used in this evaluation, it does not specify the specific procedures for calculating and measuring them. Therefore, specific procedures were developed for the during-deployment performance measures using the three-step framework outlined below.

1. Reviewed the *AI-ITMS Evaluation Plan* for goals/objectives, evaluation questions, and performance measures.
2. Determined which performance measures could be tested given the status of the System and the available data sources for use in evaluation.
3. Identified hardware, software, and deployment location requirements.

Depending on the characteristics of each performance measure, procedures include either quantitative or qualitative evaluations, or a combination of both. The detailed methodologies for evaluating the AI-ITMS and the results of the evaluation are broken down by performance measure in the following sections.

3.4 Incident Detection Time

3.4.1 Incident Detection Time Approach

The Evaluation Plan set the following performance measures for System incident detection time during deployment.

- Freeway: Incident detection time **≤ 10 minutes**
- Arterial: Incident detection time **≤ 15 minutes**

The evaluation team used a combination of Tracker to identify incidents that occurred within the study area and computer-aided dispatch (CAD), the software used to dispatch first responders to the scene of an incident, to estimate a ground truth of when the incident occurred. AI-TOMS incident start times were then compared with the CAD incident start times of incidents that appeared in Tracker.

It is noteworthy that Tracker and CAD log traffic incidents such as crashes, car breakdowns, and roadway obstructions whereas AI-TOMS is designed to log all traffic events, including severe congestion unrelated to the kinds of incidents that are logged in Tracker and CAD. As a result, the results of the incident analysis presented in subsequent sections should be interpreted as a reflection of AI-TOMS ability to capture the kinds of incidents that are logged in both Tracker and CAD rather than AI-TOMS ability to diagnose traffic anomalies.

3.4.2 Incident Detection Time Analysis Period Selection and Bounds

The evaluation team first consulted with BlueHalo to determine the analysis period based on when the incident detection algorithms were more fully developed. Based on these conversations, an analysis period of July 1, 2022, to May 31, 2023, was selected for freeway incident detection, and March 1, 2023 to May 31, 2023 was selected for arterial incident detection. While the evaluation team would have preferred to use analysis periods of equal lengths, the arterial incident detection algorithm was not advanced enough to have its performance evaluated until March 2023, and the evaluation team decided to maximize the freeway analysis period to collect a larger sample size rather than shorten it to match the arterial analysis.

BlueHalo also provided input on the appropriate geographic bounds for the evaluation. While the AI-ITMS has been developed and tested on roadways within parts of each of Delaware's counties, the freeway and arterial incident detection algorithms have been primarily tested along three facilities in New Castle County and Kent County within the Urban and CAV project study areas, summarized in Table 11.

Table 11. Incident Detection Study Bounds

Study Area	Route	Section	Classification
Urban	I-95	Maryland line to I-495	Freeway
	DE 1	DE 72 to I-95	Freeway
CAV	DE 1	DE 299 to DE 10	Freeway
	US 13	DE 299 to DE 10	Arterial

Additionally, since the freeway incident detection algorithm was carefully calibrated to monitor freeway traffic flow conditions, incidents that occurred on freeway exit and entrance ramps were determined to be outside of the area of interest for this evaluation. The evaluation team acknowledges that successful statewide deployment will require incident detection along freeway ramps as well, but it believes a fair assessment of the incident detection algorithms should exclude freeway ramps at this time while acknowledging this limitation.

3.4.3 Incident Matching Methodology

While incident start times from CAD were used in the evaluation of AI-TOMS incident detection times, the evaluation team had to first establish a methodology for matching incidents from Tracker to incidents from AI-TOMS. Consultant members of evaluation team had permission to review incident data entered into Tracker but did not have permission to review incident data from the CAD database. Therefore, incidents from Tracker were first matched with incidents from AI-TOMS. Incidents from Tracker that had potential pairs in AI-TOMS were then matched to their corresponding CAD entries by DelDOT TMC employees. This process is detailed further below.

1. Plotting of incidents logged in Tracker that occurred within the study periods and study bounds to identify the location of each crash.
2. Review of the Tracker incident data and provision of CAD incident start times by DelDOT TMC employees.
3. Review of AI-TOMS detected incidents for potential matches. AI-TOMS detected incidents were selected for review if they occurred along the same roadway, in the same direction, and had an event start time that was within either 30 minutes prior to or 2 hours after the incident start time logged in Tracker. Exceptions were made in cases when additional supporting evidence such as volume, speed, and video logs from AI-TOMS could confirm that an event outside of that time bound was a match.

4. Review of supporting volume, speed, video, and incident playback data within AI-TOMS as available and as necessary to confirm or reject potential matches.
5. Logging of AI-TOMS incident identification numbers and start times for use in analysis.

In total, 168 incidents from Tracker occurred within the study periods and study areas. 160 incidents logged in Tracker could be confidently tied to an incident logged in CAD. Two potential reasons for the discrepancy are that the 911 call taker may have coded the incident as something that did not transfer to DelDOT in the CAD system and that the call location entered into CAD may have been entered incorrectly. For example, the location could have been entered as Main Street in Newark, Delaware, but the incident actually occurred and was responded to on Main Street in Middletown, Delaware. Out of the 160 incidents that could be tied to the CAD data, 108 could be matched to anomalies detected by AI-TOMS. This data set is included as Appendix A.

Of the 168 incidents from Tracker and 160 incidents that could be matched to an incident logged in CAD, just eight incidents occurred on US 13. A sample size of eight incidents is too few to constitute an adequate sample for an analysis of the arterial incident detection algorithm. Therefore, the evaluation team has deferred further analysis of arterial incident detection until a larger incident sample has been gathered. This reduces the sample size to 160 incidents from Tracker and 152 incidents that could be matched to an incident logged in CAD. Of the 152 incidents with entries in CAD, there were105 incident pairs for analysis from AI-TOMS.

3.4.4 Incident Detection Time Comparison and Results

Using the 105 incident pairs that appeared in Tracker, CAD, and AI-TOMS along I-95 and DE 1, the evaluation team calculated the average difference in detection time between the CAD and AI-TOMS. This average was calculated for both freeways combined, by study area, and by facility using Equation 1. Results of this calculation are shown in Table 12.

Equation 1. Average Detection Time Difference Formula

$$Average\ Detection\ Time\ Difference = \frac{\sum(AI\ TOMS\ Event\ Start\ Time - CAD\ Incident\ Start\ Time)}{Number\ of\ CAD\ Incidents}$$

Table 12. Average Detection Time Differences (minutes:seconds)

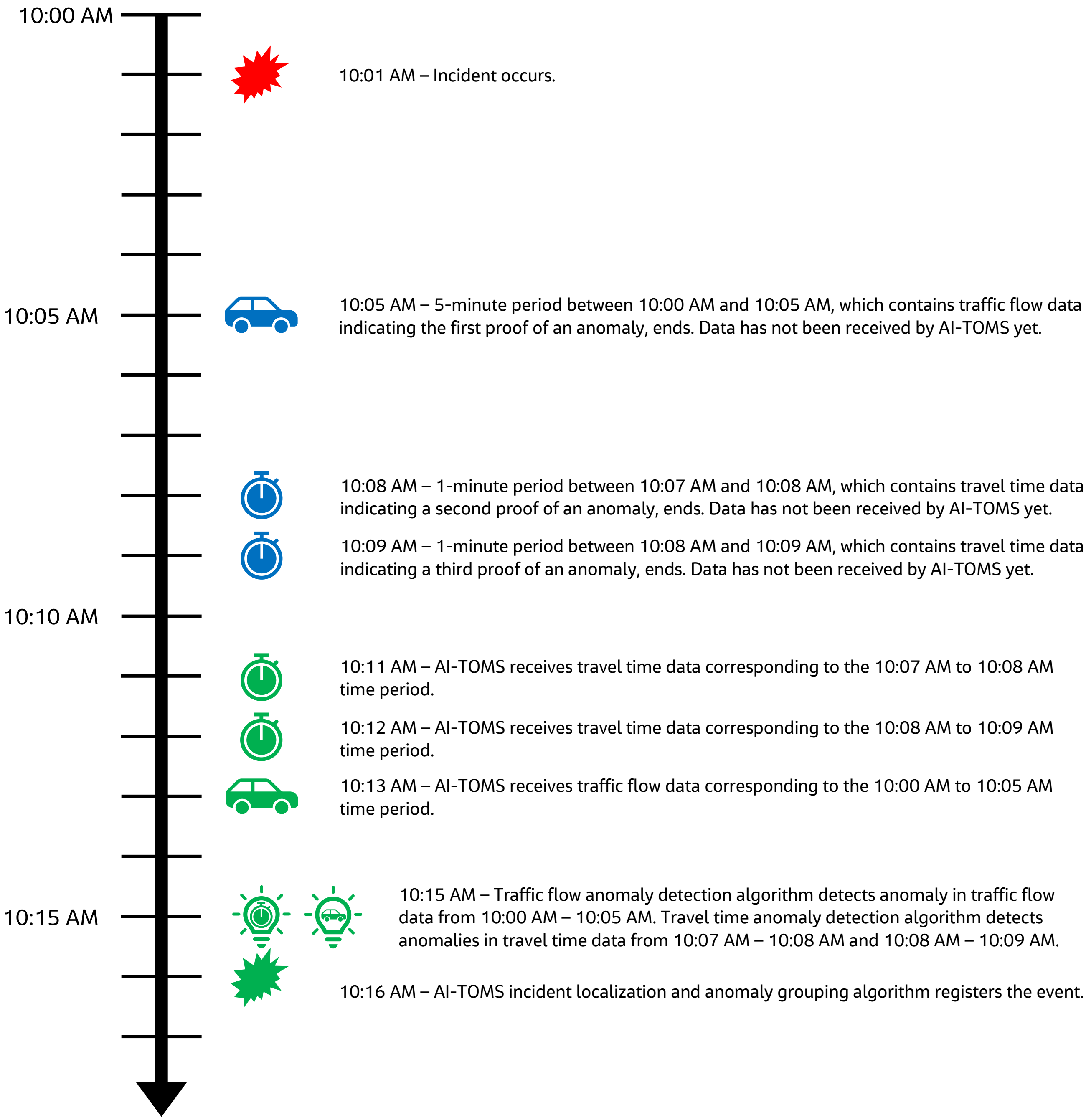
Study Area	I-95	DE 1	All (I-95 & DE 1)
Urban	12:49	19:23	14:59
CAV	-	13:03	13:03
Both	12:49	16:16	14:33

On average, the AI-TOMS freeway anomaly detection algorithms detect incidents 14 minutes and 33 seconds after they occur on freeways as measured by CAD. Therefore, AI-TOMS does not currently meet the thresholds set for incident detection times on freeways.

With that being said, the results are also nuanced. Incident detection times were lowest on I-95 where DelDOT has a higher density of Wavetronix and Bluetooth detectors. This indicates that performance of AI-TOMS' anomaly detection algorithms may be tied to monitoring device density and that it may be possible to lower freeway incident detection times closer to the 10-minute threshold set by the Evaluation Plan by installing additional Wavetronix and Bluetooth detectors. Furthermore, discussions with DelDOT and

BlueHalo revealed that most of the delay seen in the average incident detection times is due to latencies within DelDOT's existing system rather than within AI-TOMS. For example, traffic flow data is collected by roadside radar detectors in 5-minute increments. At the end of each five-minute period, the device pushes the data it collects to DelDOT TMC. This means if an incident occurs immediately after the device pushes the data to DelDOT TMC, the traffic flow data impacted by the incident will not be received by DelDOT TMC's existing monitoring systems for just under 5-minutes. Additionally, since AI-TOMS currently exists within a DMZ separate from DelDOT TMC's other systems, the data DelDOT receives from the field must then be pushed to the server where AI-TOMS resides. This process takes between 6 and 8 minutes. Figure 13 illustrates the role that delays due to the existing system play in lengthening the average incident detection times with an incident detection timeline for a hypothetical incident. Figure 13 also shows AI-TOMS works quickly to identify travel time and traffic flow anomalies, and register incidents once it receives the necessary data.

Figure 13. Timeline for Incident Detection Following a Hypothetical Incident



As DelDOT continues to develop its AI-ITMS program, the evaluation team recommends additional attention be given to reducing the latencies within DelDOT's existing system and further testing and development of the arterial incident detection algorithm.

3.5 Incident Detection Accuracy

3.5.1 Incident Detection Accuracy Approach and Methodology

The Evaluation Plan set the following thresholds for incident detection accuracy during deployment.

- Major Incident: ≥ 90% of major incidents detected by AI-TOMS
- Medium Incident: ≥ 85% of medium incidents detected by AI-TOMS
- Minor Incident ≥ 75% of minor incidents detected by AI-TOMS

Note that to meet the above detection accuracy thresholds, AI-TOMS only needs to have detected the specified percentage of the total number of major, medium, and minor incidents as logged by DelDOT.

Incident severity was tied to *Manual for Uniform Traffic Control Devices* (MUTCD) definitions which set incident duration thresholds of less than 30 minutes for minor incidents, 30 minutes to 2 hours for medium incidents, and over 2 hours for major incidents.

Unfortunately, the evaluation team was unable to identify a reliable source of data containing incident clearance times for use in classifying incidents by severity. Therefore, detection accuracy was evaluated for all incident severities combined.

To maintain consistency with the incident detection time analysis, the incident detection accuracy analysis made use of the same incident data set consisting of 152 crashes logged in Tracker with CAD entries that occurred on I-95 and DE 1 between July 1, 2022 and May 31, 2023 and the 105 corresponding incident-anomaly pairs with AI-TOMS which were identified using the manual matching process outlined in Section 3.4.3.

The incident detection accuracy analysis then became a three-step process.

1. Identify the number of incidents across the study areas and study periods for all facilities combined, as well as by individual study area and facility using CAD incident start times and Tracker incident end times.
2. Repeat step 1 for incidents with matches from AI-TOMS.
3. Calculate the incident detection accuracy using Equation 2.

Equation 2. Aggregate Incident Detection Accuracy

$$Incident\ Detection\ Accuracy = 100\% \times \frac{\sum AI\ TOMS\ Incidents}{\sum CAD\ Incidents}$$

3.5.2 Incident Detection Accuracy Results

The results of the incident detection accuracy analysis are shown in Table 13, Table 14, and Table 15. Table 13 and Table 14 show the number of incidents logged in Tracker and CAD and the number of incident pairs identified from AI-TOMS. Table 15 shows the detection accuracy broken down by facility and study area.

Table 13. Incidents Logged in Tracker and CAD

Study Area	I-95	DE 1	All (I-95 & DE 1)
Urban	63	36	99

Study Area	I-95	DE 1	All (I-95 & DE 1)
CAV	Not applicable	53	53
Both	63	89	152

Table 14. Incident-Anomaly Pairs from AI-TOMS

Study Area	I-95	DE 1	All (I-95 & DE 1)
Urban	55	27	82
CAV	Not applicable	23	23
Both	55	50	105

Table 15. AI-TOMS Incident Detection Accuracy

Study Area	I-95	DE 1	All (I-95 & DE 1)
Urban	87%	75%	83%
CAV	Not applicable	43%	43%
Both	87%	56%	69%

As shown in Table 15, the AI-TOMS anomaly detection software component detected the highest percentage of Tracker/CAD incidents along I-95, at 87%. Along DE 1, there is a notable difference between the ability of the anomaly detection algorithm to detect incidents in the Urban and CAV study areas. As with the incident detection time analysis, the evaluation team believes this to be the result of higher densities of ITS devices being in use along I-95 and within the Urban study area than in the CAV study area.

While these results do not demonstrate that the incident detection algorithms are currently meeting the accuracy standards across the board, they do demonstrate the potential for increased future success along freeways as additional ITS devices are installed and as the algorithms continue to mature. Furthermore, it is worth noting that AI-TOMS is specifically designed to detect incidents that are impacting traffic flow. This means that incidents which appear in Tracker and CAD are less likely to be detected by AI-TOMS during nighttime hours when an incident may not restrict capacity enough to cause congestion that impacts traffic flows and travel times and when another incident is already ongoing along the same section of roadway. Additionally, it is also important to emphasize that these results reflect AI-TOMS' ability to detect incidents that are entered into Tracker and CAD, not a reflection of AI-TOMS' ability to diagnose traffic anomalies. A separate analysis outside the scope of the performance measures established by the Evaluation Plan may provide insights into how accurately AI-TOMS identifies all traffic flow anomalies.

3.6 Transportation System Condition Updates

The Evaluation Plan sets a threshold of every 7-minutes for how frequently AI-TOMS should provide transportation system condition updates during the deployment phase of the project. The speed with which AI-TOMS can provide these updates is dependent on two things, how frequently data inputs are pulled by

AI-TOMS and how frequently the AI-TOMS traffic monitoring algorithms run. AI-TOMS can only meet the 7-minute threshold for transportation system condition updates if both all data inputs are pulled and if all traffic monitoring algorithms are run more frequently than every 7-minutes.

BlueHalo provided the update frequencies for all real-time data inputs to the AI-ITMS as shown in Table 16 and all algorithms being run as part of AI-TOMS as shown in Table 17. Additional information on data inputs into AI-TOMS can be found in the AI-ITMS DMP.

Table 16. Data Input Update Frequencies

Name	Description	Update Frequency
CAN Bus Data	Provides real-time vehicle performance data including engine revolutions per minute, speed, acceleration, coolant temperature, and location.	1 minute
High-Resolution Signal Data	Provides near-real-time data containing timestamped controller events such as changes in detector states and signal outputs.	5 minutes
Near Real-Time Traffic Alerts	Provides information on near-real-time travel advisories that are impacting traffic.	5 minutes
Signal Groups	Provides a near-real-time history of commands that have been issued by TACTICS to individual signals and signal groups. It can be used to determine what pattern a signal or signal group should be running.	5 minutes
Traffic Flow per Direction	Provides near-real-time traffic metadata including volume, occupancy, speed, and direction for detectors deployed throughout the state's roadways.	5 minutes
Traffic Flow per Lane	Provides near-real-time volume data by lane for both Wavetronix and Signal loops within a 5-minute range.	5 minutes
Traffic Flow per Lane per Minute	Provides real-time Wavetronix data from a small group of detectors in 1-minute increments by lane.	1 minute
Travel Times	Provides real-time travel times for defined links.	1 minute
Vehicle Positions	Provides DTC bus and paratransit vehicle locations and other related data using the GTFS file provided by a Trapeze system used by Delaware Transit Corporation.	15 seconds
Video Feed	Provides near-real-time video footage of traffic conditions.	5 minutes
Waze Alerts	Provides real-time data on events and incidents that DelDOT is monitoring.	1 minute
Weather Data	Provides near-real-time weather metadata of DelDOT's weather stations grouped by location and district yard responsibilities.	5 minutes
Weather Stations	Provides near-real-time weather metadata of DelDOT's weather stations which include surface temperatures at some sites.	5 minutes

Table 17. AI-TOMS Algorithm Update Frequencies

Name	Description	Update Frequency (minutes)
M-dist Anomaly Detection	Detects traffic flow anomalies using traffic volume and traffic speed data.	5

Name	Description	Update Frequency (minutes)
Bluetooth Anomaly Detection	Detects traffic flow anomalies using Bluetooth travel time data.	1
Waze Alert Mapping	Filters and maps Waze events and incidents that DelDOT is monitoring.	5
Restriction Data Mapping	Maps travel restrictions that impact transportation system operations.	5
Incident Detection	Determines which traffic anomalies detected by the M-dist anomaly and Bluetooth anomaly detection algorithms rise to the level of a traffic incident and monitor incidents through their completion.	1

Each of the 13 data inputs to and five algorithms run by AI-TOMS are ingested and run a maximum of every 5 minutes, meaning the AI-ITMS is successfully providing transportation system condition updates under the 7-minute threshold set for the deployment phase.

3.7 Notification Update Speed

The Evaluation Plan set a threshold for incident notification update speeds during deployment of less than or equal to 3-minutes following incident detection by AI-TOMS. Note that there is an important difference between 3-minutes following an incident and 3 minutes following incident detection. This measure is intended to compare notification timestamps against the timestamps associated with when AI-TOMS registers the incident using the incident detection algorithm. Additionally, this measure was defined with the goal of AI-TOMS being capable of producing incident notifications across all components of DelDOT's TIS, including DelDOT's email alert system for DelDOT employees, social media accounts, the DelDOT mobile app, and VMS/DMS boards across the state.

At this stage of the AI-ITMS project, AI-TOMS has not been configured to communicate notifications to the public-facing components of the DelDOT TIS. Therefore, the evaluation team is not able to evaluate AI-TOMS incident notification update speeds to DelDOT's social media accounts, the DelDOT mobile app, or DelDOT's VMS/DMS boards. However, testing of AI-TOMS incident notification capabilities via DelDOT's email alert system is possible. Therefore, this evaluation presents the results of an analysis focusing on the DelDOT email alert component of the TIS. As DelDOT continues development of the AI-ITMS, it should evaluate the incident notification capabilities of AI-TOMS as they reach maturity.

3.7.1 Notification Update Speed Approach and Methodology

This analysis of AI-TOMS incident notification speeds focuses on the email alerts produced by AI-TOMS and sent to subscribed DelDOT employees when an incident is detected using either the freeway or arterial incident detection algorithm and consisted of a three-step process.

1. Select the study bounds and study period for the analysis. I-95, DE 1, and US 13 within the Urban and CAV study areas were chosen as the study area because the evaluation team already had the incident detection data for these sections of roadway. March 2023 – May 2023 was selected as the study period. Unlike the incident detection analyses, this analysis did not require the evaluation team to identify matching incidents between Tracker and AI-TOMS, so the evaluation team used a narrower study period while increasing the sample size for analysis.

2. Request AI-TOMS incident notification email data from BlueHalo. This data set was formatted as a comma-separated-value file containing a row for each incident notification email sent during the study period with columns for the text included in the body of each email and the subject line. The data for each notification email contains three key items for this analysis: the incident ID, whether the email is an email alerting the start or end of an incident, and the date and time that the email notification was sent. Figure 14 provides an example from the incident notification email data.

Figure 14. Incident Notification Email Data Example

Body	Subject
INCIDENT CLEARED NB US13 from Walnut Shade to DE10 Incident Id: 13476 Status: INCIDENT CLEARED Location: NB US13 from Walnut Shade to DE10 Start Time: 2023-06-28 17:24:43.808 End Time: 2023-06-28 17:47:03.28 Severity: 64 Evidences: Travel Time Detectors: Explanation: Bluetooth indicates congestion. See incident details <https://usg02.safelinks.protection.office365.us/?url=https%3A%2F%2Faitoms.net%2Fin%2F13476&data=05%7C01%7Cxiaoliang.zhao%40bluehalo.com%7Cece190c2801d417eb68c08db78242016%7C10c0370427c34ea18c2b2d9417d7ae50%7C0%7C0%7C638235868815109851%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000%7C%7C%7C&sdata=e0rrMGF3A0IGJ%2FfU3BzmAjnWkjRNJCO3FZCi4%2F%2FUhOA%3D&reserved=0> Wed Jun 28 18:07:48 EDT 2023	*INCIDENT CLEARED* NB US13 from Walnut Shade to DE10

3. Calculate the average incident notification update speeds for AI-TOMS generated email alerts for both incident starts and incident ends using Equation 3 and Equation 4, respectively. Incident IDs were used to pair the times at which AI-TOMS detects an incident and detects an incident as being cleared with the incident detection and incident clearance notification email times. A total of 1,278 incident start pairs and 1,325 incident end pairs were considered.

Equation 3. Average Incident Start Notification Speed Formula

$$Incident\ Start\ Notification\ Speed = \frac{\sum Incident\ Start\ Email\ Notification\ Time - Incident\ Detection\ Start\ Time}{Number\ of\ Incidents}$$

Equation 4. Average Incident End Notification Speed Formula

$$Incident\ End\ Notification\ Speed = \frac{\sum Incident\ End\ Email\ Notification\ Time - Incident\ Detection\ End\ Time}{Number\ of\ Incidents}$$

3.7.2 Notification Update Speed Results

Using Equation 3 and Equation 4, the evaluation team calculated the average time difference between incident notification emails and incident detection start and end times. The results of these calculations are shown in Table 18.

Table 18. Average Incident Email Notification Speeds (minutes:seconds)

Incident Start Notification Speed	Incident End Notification Speed
-0:04.46	-0:04.38

The negative numbers in Table 18 indicate that email notifications are actuated and sent out several seconds before AI-TOMS registers the incident within its database. While notification emails being sent out prior to the registering of an incident within the AI-TOMS database does technically mean emails are sent out in less than three minutes after an incident is registered, it is unclear how long it takes for a notification email to be sent from the moment that the AI-TOMS algorithm concludes that an incident is present. Discussions with BlueHalo confirmed that this point in time is not currently measured and cannot be more accurately measured than it is using the time when an incident is registered by the database unless the incident detection algorithm were to be altered to register incidents prior to actuating incident notification emails.

Given the results of the notification update speed analysis, the evaluation team believes the spirit of the notification update speed measure has been met for email notifications since incident notification emails are actuated directly by the incident detection algorithms and clearly sent out in a manner that enables consumers of the information to react and respond to the incident, as necessary.

As notification capabilities expand to include other aspects of DelDOT's TIS such as social media, consideration should be given to the current order of operations associated with registering incidents and generating incident notifications if their inclusion adds additional latencies to the incident logging process within the AI-TOMS database.

3.8 Notification Update Accuracy

The notification update accuracy measure outlined in the Evaluation Plan states that incident notifications should be **≥ 95%** accurate descriptions of the incident following its detection during the deployment phase. Once again, because AI-TOMS has only been integrated with the email alert component of DelDOT's TIS, the evaluation team is limited to evaluating only AI-TOMS incident email alerts. Figure 15 shows an example of one such alert generated by AI-TOMS.

Figure 15. AI-TOMS Incident Notification Email

***INCIDENT CLEARED* SR 1 @ SR 273**

Incident Id:	10551
Status:	INCIDENT CLEARED
Location:	SR 1 @ SR 273
Start Time:	2023-06-12 13:56:05.457
End Time:	2023-06-12 19:04:41.176
Severity:	90
Evidences:	Traffic Flow, Travel Time, Waze Alerts
Detectors:	ND0038, ND0039
Explanation:	The following lanes are congested: (19958:0/2/1).

See incident details

As shown on Figure 15, AI-TOMS generated incident notification emails pull queried information directly from the AI-TOMS incident database. In this way, the notification emails are 100% accurate because they provide the exact information stored about an incident by the incident database. However, the information provided by AI-TOMS generated incident notification emails is not specific enough for a reader that is not an expert user of the system to understand the full details of the incident. For example, if an operator receives a notification like the one shown on Figure 15, it is not immediately clear on which leg of the DE 1 at DE 273 intersection the incident occurred, which approach lane the incident has occurred in, which approach lanes have been affected, and what the anticipated impact to traffic flow is. Furthermore, a member of the public would have even less of an idea how to interpret this incident alert.

The evaluation team acknowledges that different syntax and diction are required when providing internal and public-facing incident notifications, and the level of detail shown is appropriate for the current level of maturity of AI-TOMS' incident notification capabilities. However, because the emails do not provide actionable information, the evaluation team does not believe the incident notification email capabilities are mature enough to be evaluated using the standard set by the Evaluation Plan for the deployment stage. Therefore, DelDOT should revisit evaluation of notification update accuracy in the future.

Note that as DelDOT continues to develop AI-TOMS' incident notification capabilities, notifications to each component of the TIS will be designed to provide the intended audience with the level of information each requires to make educated decisions about use and management of Delaware's transportation system. Posts to social media will be geared towards the public and should provide readers with the information they need to make educated travel decisions. Notifications to TMC operators will be similarly geared towards providing the key information they need to make decisions about how to manage incidents and congestion.

3.9 AI-ITMS Approval Rating

The Evaluation Plan states that the AI-ITMS approval rating will only be evaluated after deployment is complete. Since the deployment phase of the project has not been completed, the evaluation team did not attempt to quantify the approval rating of the AI-ITMS amongst the public, TMC employees, or stakeholders. Qualitatively, DelDOT is pleased with the progress that has been made by members of the project team and is committed to continuing to develop, improve, and expand the capabilities and reach of the AI-ITMS.

3.10 Public Participation

The Evaluation Plan outlines that public participation with the AI-ITMS will be measured using DelDOT webpage usage and DelDOT mobile app downloads following the completion of the deployment phase. Therefore, the evaluation team did not review public participation data as part of this evaluation.

3.11 Average Delay Time

The Evaluation Plan does not set a threshold for changes in average delay time during the deployment phase. Since there is no delay threshold to compare against during deployment, and because AI-TOMS is in the early stages of deployment, the evaluation team did not attempt to quantify any impacts of deployment of the AI-ITMS on average delay times. As DelDOT looks forward to its evaluation of average delay time post-deployment, it can leverage the historical travel time analyses completed as part of its Transportation Operations Management Program[15] and the signal delay metrics collected and calculated by AI-TOMS to establish travel time baselines.

3.12 Concurrent Monitoring Capabilities

The Evaluation Plan set a goal for the AI-ITMS to simultaneously monitor 50% of DelDOT's ITS and internal networks during the deployment phase. However, it does not define what it means for AI-ITMS to "monitor" an ITS device. Monitoring can take on a spectrum of meanings from simply collecting data from to analyzing the data to produce insights.

This evaluation measures the concurrent monitoring capabilities of the AI-ITMS for each device type individually and combined as of the end of the grant period, June 30, 2023. It does so by calculating the percentage of DelDOT's ITS devices that AI-TOMS ingests data from and classifies the device types as being actively or passively monitored. Devices which currently feed data into AI-TOMS algorithms are actively monitored and devices whose data have not been integrated into AI-TOMS algorithms are considered to be passively monitored. The evaluation team accomplished this by comparing the number of permanent devices available to AI-TOMS and the number of permanent devices listed using DelDOT TMC's Electronic Operations software and by interviewing BlueHalo to determine which data sources are actively being used by AI-TOMS. Note that DelDOT's hydrology water-level gauges were excluded from this analysis because DelDOT never intended to integrate that aspect of its flood monitoring system into AI-TOMS as part of this project. Integrating hydrology water-level gauges is currently planned as part of future AI-ITMS program efforts. Additionally, devices that were invested in as part of project testing such as CAN Bus data dongles and machine vision capable cameras were also excluded from this calculation because it is known that AI-TOMS is collecting data from 100% of those devices. Results of the concurrent monitoring capabilities analysis are presented in Table 19.

[15] https://deldot.gov/Programs/itms/index.shtml?dc=tomp

Table 19. AI-ITMS Concurrent Monitoring Capabilities

Network	Monitoring Level	Location Count	Locations Monitored	Percent Monitored (%)
Bluetooth Travel Time System	Active	256	245	96
Traffic Signal System [E]	Active	1152	904	78
Wavetronix Detector	Active	233	229	98
Signal System Loop Volume Detector [F]	Active	538	529	98
Railroad Crossing Status	Passive	21	21	100
Drawbridge Status	Passive	2	2	100
Water on Road Signage	Passive	6	6	100
Variable Message Signs	Passive	20	19	95
Variable Speed Limit Signage	Passive	12	12	100
Roadway Weather Information System	Active	35	33	94
CCTV Cameras	Active	250	246	98
Total	Not applicable	2,525	2,246	89

As shown in Table 19, the concurrent monitoring capabilities of the AI-ITMS exceed the threshold of 50% set by the Evaluation Plan for performance during deployment.

3.13 Benefit-Cost Ratio

3.13.1 Benefit-Cost Ratio Initial Approach

Evaluating the ratio of benefits experienced by DelDOT from the AI-ITMS project to the costs required to implement it is one of the most critical aspects of the evaluation. The Evaluation Plan set a goal of achieving a positive ratio of AI-ITMS benefits to cost for specific deployments during the deployment phase of the project. In other words, the benefits should outweigh the costs. The *AI-ITMS Benefit-Cost Analysis Procedure*[16] document outlines the methodology for measuring the benefit-cost ratio.

[E] Only intersection traffic signals, high-intensity activated crosswalk beacon signals, and fire signals are included in this analysis.
[F] Each location refers to a single intersection which may include multiple in-pavement loops across multiple approaches.
[16] AI-ITMS Benefit-Cost Analysis Procedure, September 22, 2020, Delaware Department of Transportation

The AI-ITMS project's software components have not yet been approved for the deployment phase, with integration into signal operations ongoing and traffic anomaly and incident detection only just beginning to be implemented at DelDOT TMC. Additionally, calculating and projecting benefits first requires the establishment of evaluation baselines. However, Coronavirus Disease 2019 (COVID-19) brought about major changes to baseline travel patterns throughout the project, especially during 2020 and 2021, and delayed the evaluation team's ability to establish a quality baseline for comparison. Given these challenges, the evaluation team does not have an adequate sample period to pull data from for a full quantitative benefit-cost analysis, nor does the evaluation team have enough information to meaningfully project quantitative benefit-cost analysis for the deployment phase of the project. Therefore, the evaluation team concluded that they did not have the scale of data necessary to complete the quantitative benefit-cost analysis that was initially scoped. As DelDOT continues to develop the AI-ITMS, it will establish firm baselines for use in quantifying benefits and will determine the benefit-cost ratios of project components once adequate sample sizes are available.

3.13.2 Benefit-Cost Ratio Qualitative Assessment

Due to the importance of understanding the benefit-cost ratio of developing and deploying an AI-enhanced ITMS, the evaluation team instead presents a qualitative summary of the benefits that are expected during deployment. The results of this qualitative analysis are presented in Table 20. Note that benefits and costs are broken down by the goals originally presented in Section 1.3. Project Goals. Therefore, several of the benefits and costs are repeated across project goals.

Table 20. Qualitative Benefit-Cost Analysis Results

Project Goal	Benefits	Costs
Increase transportation system monitoring speed and accuracy	+ Automated ITS device network monitoring + Faster freeway congestion and incident identification + Faster arterial congestion and incident identification (anticipated) + Automated congestion and incident response recommendations (anticipated) + Enables proactive decision-making in place of reactive decision-making (anticipated) + Predictive signal system operations (anticipated)	– ITS device installation, maintenance, replacement, and calibration – DelDOT staff training on new technology and associated procedures – Software development and maintenance – Server installation and maintenance – Data storage – Signal cabinet upgrades
Automate transportation system information analysis and traveler information sharing	+ Automated traveler notifications using VMS/DMS, social media, and DelDOT website (anticipated) + Reduced delays and increased safety due to more informed road users (anticipated)	– Installation, maintenance, and replacement of VMS/DMS – Software development and maintenance

Project Goal	Benefits	Costs
Improve event/incident response through advanced control of ITS devices	+ Automated event and incident response (anticipated) + Reduced delays, emissions, and improved safety (anticipated) + Incident playback capabilities allow DelDOT to learn from and improve with each incident	– DelDOT staff training on new technology and associated procedures – Software development and maintenance – Server installation and maintenance – Data storage – Signal cabinet upgrades
Prepare for emerging transportation technologies	+ V2I communications resulting in improved system learning (anticipated) + Reduced delays, emissions, and improved safety (anticipated) + Creates a forward-looking and adaptive monitoring system (anticipated)	– RSU installation and maintenance – Communications infrastructure upgrades

3.14 Incident Mitigation Suggestions

The performance benchmark set for incident mitigation suggestions during deployment is that incident mitigation suggestions should be offered by the AI-ITMS in less than 5 minutes following incident detection. Note that the intended meaning of this measure is not that AI-TOMS should be able to generate a full incident response plan within 5-minutes of detecting an incident, rather it is intended to mean that AI-TOMS should be capable of searching an incident case library and determining which incident management steps ought to be initiated using case-based reasoning. At the time of this evaluation, incident mitigation suggestions are only offered within the CAV study area, and due to the limited sample of incidents requiring mitigation, it was determined that an analysis of AI-TOMS' capabilities would not provide meaningful results.

3.15 Transit Schedule Adherence

While the Evaluation Plan defines a performance threshold of a 4-5% improvement in on-time performance for transit schedule adherence, the project team removed the transit schedule adherence criteria from the evaluation metrics during year 2 of the project as noted in the AI-ITMS Annual Report 2021[17] submitted to FHWA in February 2022. This decision was made after determining that transit schedule data would not be incorporated into the algorithms being designed for the project. Therefore, the evaluation team did not attempt to evaluate transit schedule on-time performance as part of this evaluation.

3.16 Preparation for Emerging CAV Technology

The original vision of the AI-ITMS project included planning for CAV technology. This planning effort included equipping intersections with RSU capable of capturing BSM from OBU-equipped vehicles. As a

[17] ATCMTD AI-ITMS Annual Report 2021, February 2022. Delaware Department of Transportation.

result, the Evaluation Plan included a performance measure stating that the evaluation team would accurately determine the penetration rate of OBU-equipped vehicles broadcasting V2I BSMs from 30% of DelDOT RSU-equipped intersections.

DelDOT always looks to position itself to adapt to and incorporate emerging technologies; however, during early stages of the project's development, changes in FCC rules for the 5.9 GHz spectrum changed DelDOT's near-term goals for what it would accomplish within the grant period. The FCC issued these new rules on November 18, 2020, and they re-assigned portions of the 5.9 GHz spectrum originally allocated for dedicated short-range communications service. After the announcement, DelDOT placed this portion of their connected vehicle program on hold so that it could evaluate the impact of the new ruling on RSU deployments within the state. As a result, the project team determined that resources would be best spent on advancing other aspects of software development. A proof of concept was developed to show the potential of benefits of CAV technology within the AI software, but it has not been integrated into AI-TOMS. Integration of V2I information from OBU-equipped vehicles remains part of DelDOT's long-term vision for the AI-ITMS, but no set plans are currently in place. Therefore, this evaluation does not attempt to determine the penetration rate of OBU-equipped vehicles broadcasting V2I BSMs from any DelDOT RSU-equipped intersections.

That is not to say that DelDOT has not advanced efforts to prepare for emerging CAV technologies under this grant. DelDOT has advanced parallel efforts that are not captured by the performance measure outlined in the Evaluation Plan to continue preparing for CAV. These efforts include upgrading existing RSUs to support dual-mode cellular vehicle to everything connections, researching use cases of third-party commercial data sources, and equipping 10 DelDOT vehicles with cellular-based OBU equipment which provides real-time location, speed, and heading information to AI-TOMS. AI-TOMS uses the data it ingests from these 10 DelDOT vehicles to test measurements of corridor traffic signal progressions. Research and development continue in each of these areas despite DelDOT shifting immediate priorities away from new RSU deployments.

3.17 Evaluation Summary

The evaluation team believes this evaluation demonstrates positive results for DelDOT's AI-ITMS program despite deferring evaluation of six performance measures – AI-ITMS Approval Rating, Public Participation, Benefit-Cost Ratio (partial-deferment), Incident Mitigation Suggestions, Transit Schedule Adherence, and Preparation for Emerging CAV Technology – due to challenges that the project team faced during development and changes to the scope of the program. As DelDOT continues to develop its AI-ITMS program, it will need to consider how to best approach meeting the thresholds set for each of these performance measures during both the deployment and post-deployment phases of the program.

Of the performance measures that the evaluation team was able to consider quantifiably, the results were encouraging and represent meaningful progress having been made by the project team. While the Incident Detection Time and Incident Detection Accuracy measures could not be measured against a true ground truth, the comparisons produced against Tracker and CAD demonstrate that with enough monitoring device density, AI-TOMS can quickly and accurately identify incidents. Additionally, AI-TOMS easily cleared the thresholds set for Transportation System Condition Updates, and Concurrent Monitoring Capabilities. This was made possible due to the pre-existing ITMS made up of DelDOT owned and operated devices that DelDOT has been building and expanding for decades, providing confidence to the evaluation team that the program goals and objectives which have not yet been achieved remain squarely in the sights of DelDOT management and the project team. The results of the evaluation team's analysis are included in Table 21.

Table 21. Summary of Evaluation Results

Name	Deployment Stage Performance Measures	Results
Incident Detection Time	Freeway: Incident detection time ≤ **10 minutes** Arterial: Incident detection time ≤ **15 minutes**	• The average AI-TOMS freeway incident detection time is 14 minutes and 33 seconds
Incident Detection Accuracy	Major Incident: ≥ **90%** detection accuracy, Medium Incident: ≥ **85%** detection accuracy Minor Incident: ≥ **75%** detection accuracy	• Unable to assess by incident severity • 87% of incidents on I-95, 75% of incidents on DE 1 in the Urban study area, and 43% of incidents on DE 1 in the CAV study area were detected • Detection accuracy was highest on I-95 and areas with a higher density of ITS devices
Transportation System Condition Updates	Provide automatic road anomalies/congestion updates every **7 minutes**	• Full system updates are provided every 5 minutes • Bluetooth anomaly and incident detection updates are provided every minute
Notification Update Speed	**≤ 3 minutes** following incident detection	• Notifications are being sent out via email by the incident detection algorithm prior to incidents being registered in the AI-TOMS database • Automated notifications to other pieces of the TIS are not operational yet
Notification Update Accuracy	**≥ 95%** accuracy following incident detection	• Incident email alerts are 100% accurate, but do not provide actionable information
AI-ITMS Approval Rating	***Evaluated Post Deployment only.***	***Evaluated Post Deployment only.***
Public Participation	***Evaluated Post Deployment only.***	***Evaluated Post Deployment only.***
Average Delay Time	No decrease in roadway segment average delay time	• No analysis required at this time
Concurrent Monitoring Capabilities	AI-ITMS simultaneously monitors of **50%** of the DelDOT ITS and internal networks	• 89% of DelDOT's statewide permanent ITS device network is simultaneously monitored
Benefit-Cost Ratio	Positive ratio of AI-ITMS benefits to cost for specific deployment	• Quantitative analysis deferred until post-deployment
Incident Mitigation Suggestions	Suggestions for incident mitigation are offered in **≤ 5 minutes** following incident detection	• Automated incident mitigation suggestions are only offered within the CAV study area and there is not a large enough sample of incidents requiring mitigation to analyze

Name	Deployment Stage Performance Measures	Results
Transit Schedule Adherence	**4-5%** improvement in on-time performance (OTP)	• Year 2 scope change steered the project away from incorporating transit schedule data and evaluation of project impacts on OTP
Preparation for Emerging CAV Technology	Accurately determine the penetration rate of OBU-equipped vehicles broadcasting V2I BSM from **30%** of the DelDOT RSU-equipped intersections	• Analysis deferred due to FCC rule changes resulting in shift in project priorities • DelDOT is pursuing parallel efforts to prepare for emerging CAV technologies
Lessons Learned	List of Lessons Learned per AI-ITMS deployment phase	• Lessons learned included within Section 4

4 Challenges and Lessons Learned

Given the unique nature of this project, planning, development, and implementation efforts required tasks that are different from traditional transportation/construction projects. In exploring and utilizing innovative technologies, adjustments were made to the original project scope to best meet DelDOT's needs and the overall program goals. The nature of utilizing leading edge technologies is the need for flexibility to adjust methods and approaches as the project progresses. All scope deviations were communicated with FHWA throughout the three years of the project in quarterly and annual reports to gain feedback and ensure that the project is moving forward within the ATCMTD program requirements. Now at the end of the grant, these challenges and corresponding lessons learned are summarized below.

4.1 Institutional

The automation component of the system requires continuous vigilance to understand what is happening and why the system is doing what it does. This represents a shift in how the future TMC will operate. The project's focus was development of a software-based tool to automate many different functions while providing a clear picture as to why decisions are being made. As the TMC operational focus shifts towards greater automation and as the System continues to be deployed, the required knowledge, skills, and abilities of DelDOT staff will need to be evaluated and developed.

The availability and maturity of an in-house software development and information technology group are also proving to be important components to a successful systems integration effort. Using an agile software development approach with continuous and frequent feedback from end users proved invaluable in helping guide future development. This tight feedback loop was important not only to keep the project on schedule but also to make decisions and change direction along the way.

Future considerations include putting in place a sustainable funding and contracting mechanism to retain ongoing specialized AI and ML software development services. This is not a "set it and forget it" commercial-off-the-shelf product, rather it is a continuously evolving capability that gets updated as we learn by doing and as technology advances, especially in the areas of data science and algorithm development. The old model of procure once and maintain does not address the dynamic needs of these more advanced systems.

4.2 AI and ML Technology

The science behind AI and ML is continuously evolving with improvements in algorithm development and experience in different application environments. The project team began with LSTM freeway detector models to develop the 5-to-60-minute traffic prediction time horizons, but quickly determined that the same models would be too resource intensive to apply to the larger number of arterial detectors. It then switched to using GTS for arterial traffic flow prediction. Continuing data collection, model training, and evaluation may reveal and inform additional future adjustments.

The AI models have an automated retraining process setup to account for drifting statistical models. The models are reusable from site to site and is a matter of remapping the data streams and any specific logic that operators want custom for their facilities. The models also require significant training time using the site-specific data.

Graphical Processing Units (GPUs) are often required to accelerate the computations for deep learning model training. High-end GPUs can be costly, and a limited number of GPU cards were available for on-premise deployment. Therefore, resource optimization and planning needed to be carefully conducted to ensure the size of the network and accuracy of prediction models were optimized.

Additionally, weather and lighting conditions still present challenges to machine vision algorithm performance. Improved image and video quality under non-ideal conditions can certainly improve the performance of vehicle detection and tracking algorithms.

Data quality also plays a key factor in AI and ML model performance. Enhancing and ensuring AI and ML model usefulness requires consideration of data quality monitoring, including redundancies and backup data sources for instances when the primary data source is not available or has been corrupted, and training models with tolerance of missing and corrupted data.

4.3 Data Reliability and Standardization

Part of the data ingestion and curation pipeline includes data quality assessment, data smoothing and filling in missing data when ITS subsystems are offline or individual components are unavailable. For example, the project team experienced regular weekly rebooting of the TACTICS central traffic signal system which resulted in missing system detector data. This data is needed for predictive traffic flow measures, congestion, and incident detection. The algorithms were adjusted to fill in with historical data, but this may need to be revisited to provide more contextual data substitution. Other accuracy measures may also be investigated to improve front-end data quality as DelDOT investigates future detection needs and use of smart detection technologies.

While the AI-ITMS depends on good quality data, it can also detect erroneous data inputs and automatically shift to alternative sources. Understanding which detectors are driving which decisions is an important part of providing insight to system behavior. The criticality of the sensor device and the impact of its failure is therefore situationally based on the algorithms used and availability of redundant systems. For example, there may be several other system detectors available to measure flow data along a particular roadway segment, or flow data on neighboring segments may help inform the affected segment. This would limit the impact of the failure compared to the impact if there were no redundancy available. Future work to better understand these relationships, dependencies, and related impacts may be used to help prioritize future maintenance management activities.

Furthermore, operations management and incident response often require quick action, adjusting to congestion as soon as it happens (or even before with the use of traffic flow prediction algorithms). While the evaluation team found that AI-TOMS is currently sending out an incident notification alerts within one minute of incident detection, there is a current latency within DelDOT's existing ITMS as indicated in section 3.7

Notification Update Speed that causes delays in AI-TOMS receiving traffic information from the ITMS devices. In the future, DelDOT may consider more frequent pull rates from the devices and explore ways to cut down on the time it takes for traffic data to travel from the device to the TMC.

Non-standard traffic signal controller field cabinet wiring was a challenge associated with HR data collection. DelDOT uses older style National Electrical Manufacturers Association (NEMA) TS1 signal cabinets which have limited input/output (I/O) facilities to support all system detection needs. With HR data collection differences between system detection needed to be accommodated within the data collection software. Standardization in detection layout and associated cabinet wiring standards, or at least reducing the variability, would simplify the software design efforts. Design standardization could also lead to better operational understanding and easier troubleshooting as this capability scales. Advanced smart detection and newer cabinet standards may also help with this issue.

4.4 Deployment Challenges

One of the major challenges in the deployment of this project is the unique nature of the AI-ITMS. AI and ML are novel technologies, especially in the transportation industry. United States Department of Transportation (USDOT) has indicated their view of AI as a promising strategy to help improve safety and encourage innovation within transportation, and they support activities related to research, adoption, and deployment of AI. Although USDOT is making concerted efforts to establish AI as a transportation improvement strategy, there are still unknowns associated with this as a tool. Applying AI and ML methods to a transportation management system requires a non-traditional approach to data collection, deployment, and evaluation techniques. The project team is working to keep up to date with federal efforts related to AI in transportation and continues to investigate methods to establish processes for applying traditional project tasks to this non-traditional program.

4.4.1 TMC System Integration

During the project, the AI-TOMS software has been primarily developed and tested within two environments. The development environment continues to support all software development, initial integration testing, and performance validation. The DelDOT AI-TOMS deployment environment is established in a special DMZ subnetwork isolated by a firewall from the other TMC systems, as directed by Delaware Department of Technology and Information. As new versions of AI-TOMS software are ready for deployment, they are installed in the DMZ. Integrating AI-TOMS with other TMC and external systems outside of the DMZ presents a challenge. TACTICS, traffic signal controllers, and other legacy software that AI-TOMS communicates with are located on the DelDOT intranet. Because DelDOT needs to use TACTICS for daily operations while AI-TOMS is under development, a second version of TACTICS was created within the DMZ allowing AI-TOMS to communicate with the software as well. This is not a long-term solution, but it has given DelDOT the ability to continue testing and developing AI-TOMS without impacting operations. Changes to the DMZ firewall rules are an ongoing challenge as the system matures and new services are made available. Firewall rule changes follow a formal request, approval, and implementation cycle that can significantly slow the deployment of new capabilities.

As the system is prepared for operation, DelDOT is planning to deploy multiple environments to better support system redundancy and provide a more controlled method of deployment, testing, and validation. A complete standalone and redundant production environment including TACTICS and AI-TOMS is being deployed within the DMZ. A separate test and integration environment will be developed within a separate a protected subnetwork with access to similar TMC systems from which new software versions may be deployed and tested prior to commitment to production. Establishing these environments, coordinating, and migrating systems will result in some additional delay but will better prepare DelDOT for the future.

The long-term computing architecture will require further evaluation to determine the best mix between on-premises and possible cloud-enabled capabilities. The potential amount of data storage needs and the computing needs of the AI/ML, MV, modeling, and simulation components as the system scales may require more cost-effective edge and cloud capabilities. The evaluation will need to strike a balance between system performance, reliability, availability, and cost.

The COVID-19 pandemic also presented challenges to integration due to travel restrictions and limited access to the TMC. Members of the project team were sometimes unable to physically meet at the TMC to implement software, update servers, and test hardware/system performance. Despite fewer overall restrictions, as recently as February 2023 the TMC had to be locked down due to a COVID-19 outbreak. Security, safety, and health of its employees is a top priority for DelDOT. The project team continues to work with DelDOT's software and information technology teams to overcome this challenge.

4.4.2 Signal Control Integration

A key component of the AI-ITMS is the ability to communicate with the traffic signals to change timings in response to demand. Traffic signal operations have historically been managed by the Siemens (Yunex) TACTICS centralized signal control system. The original project vision was for AI-TOMS to integrate directly with TACTICS, issuing timing pattern change requests and retrieving real-time data, while allowing TACTICS to maintain control of all the signals. Ongoing discussions with Yunex throughout the project revealed that a suitable API to support the desired methods was not available, and there were not any plans to provide such an interface. The project team has since changed the traffic signal control design to communicate directly between AI-TOMS and the traffic signal controllers using the NTCIP standard. This change in approach has added significant development delays. This delay has been partially responsible for the delayed integration with field traffic signal controllers. While deployment has been delayed, the new approach does demonstrate the power of interoperability through open standards and provides a more sustainable and vendor-neutral solution. The following challenges have been experienced:

- Traffic signal controllers need to be upgraded to a more current version of the SEPAC firmware supporting NTCIP. Under TACTICS management, the controllers had been communicating using the proprietary ECOM protocol. This represents a step increase of several software versions for many of the signals which also presents other challenges. In addition to many new application features, the NTCIP database changes how patterns and some other parameters are represented. These changes require a methodical upgrade process to properly transfer the database and validate the controller operation before field deployment. The additional coordination and time required to perform these upgrades has delayed implementation of the intersection control component of the AI-TOMS software.
- Built-in safety features available in TACTICS are currently not available within AI-TOMS. Currently, AI-TOMS selects from pre-existing patterns within the controller which have been developed, checked, and downloaded from TACTICS. As AI-TOMS evolves to dynamically change pattern and other signal data in the future, additional methods must be considered to validate this data before transmitting to the signal controller.
- Traffic signal controllers are now talking with two different masters, TACTICS and AI-TOMS, requiring some additional coordination. TACTICS continues to be responsible for time synchronization, controller database management, status polling, backup operations, and timing plan management. AI-TOMS is responsible for issuing operational timing plan changes in response to real-time demand. TMC technicians need to first place a TACTICS signal control group (zone) into ACSLite mode to relinquish command responsibility from TACTICS before AI-TOMS can take over.

A more automated or seamless signal management solution will need to be developed to improve this operation as the system scales.

- AI-TOMS' scalability to support over 1,200 statewide traffic signals is still to be determined.
- The need to advance SEPAC controllers to the latest version also required DelDOT to upgrade TACTICS to the latest version. TACTICS is being deployed as a single instance within a virtualized environment. The optimum architecture and the number and type of servers needed to support over 1,200 traffic signal controllers will need to be monitored and evaluated as system cutover continues. Delays resulting from the database migration and upgrade process significantly impacted subsequent controller deployment.

4.4.3 Supply Chain Delays

Like traditional transportation and construction projects, timelines associated with equipment procurement are also proving to be a deployment challenge. Device installations have required additional effort and installation procedures have caused unpredictable delays in deployment. Many of these delays were experienced as a result of shipping delays, increased costs, and long backorders due to COVID-19. For example, MV camera installation was delayed until the proper poles could be installed to support the cameras. The project team has learned to take these potential delays into account when planning project tasks.

4.5 Evaluation Challenges

4.5.1 Establishing Metrics and Baselines

The role of the TMC is always to monitor, control, and communicate. This has not changed since the beginning of this grant, however the transportation system DelDOT monitors has experienced many significant changes during this time, the most impactful being the effects on travel patterns due to COVID-19. With the adjustments in mandates and travel restrictions related to the pandemic, patterns are changing more frequently, especially during 2020 and 2021. The traffic-related impacts of COVID-19 on the transportation network delayed the project team's ability to establish a baseline to evaluate system performance against. Many months of unpredictability and uncertainty in travel patterns made it difficult for the software team to determine what was an anomaly based on a true incident versus a change in travel patterns based on mandates and travel restrictions. The software development team continues to improve adjustable baselines for software and deep learning algorithms based on continuously collected data. As the system continues to develop and travel patterns have been re-established, the System's self-learning mechanisms allow it to adjust to changes more easily and become "smarter" over time.

As the AI-ITMS matures, it is DelDOT's intention to establish a true baseline based on existing conditions now that travel patterns have restabilized. This baseline may be used to complete a more comprehensive system evaluation, including a quantitative benefit-cost analysis. The baseline methodology should consider whether the performance measures for the project are quantifiable, how the performance of each task will be measured, and if the expected time and cost goals were met. Some metrics are more challenging to define baselines for, including improved travel time and delay. Starting with a small number of affected segments, the evaluation team may evaluate the variables that impact delay and adjust to better understand the benefits directly stemming from the System in a defined area. The project team continues to consider these metrics and how a baseline can be determined to evaluate and establish performance levels for the system. Adjusting these metrics and baselines will be a priority as we gain experience with the System.

4.5.2 Incident Detection and Classification

Throughout the project, the project team had ongoing discussions regarding the definition of an incident, how the system will identify different levels of an incident and how that differs from how incident severity was defined for the purposes of the evaluation, and how to optimize incident detection on freeways and arterials.

First, we must consider defining what qualifies as an incident. Definitions of what an incident is vary between occurrence when traffic flow diverges away from a pre-established baseline and events like crashes or roadway obstructions, regardless of their impact on traffic. To meet DelDOT TMC's needs, the freeway and arterial incident detection algorithms used by AI-TOMS consider an incident to be any situation that causes traffic flows and travel speeds to vary from pre-determined baselines. In this way, DelDOT TMC ensures it is responding appropriately to situations that are impacting traffic flow and reduce delays for roadway users. Note that this differs from how incidents that are entered into Tracker are defined, which are considered crashes or roadway obstructions that have variable impacts on traffic flow.

To match the AI-TOMS-identified incidents with Tracker/CAD-identified incidents, the evaluation team first attempted to match incidents from Tracker and incidents from AI-TOMS using a Python algorithm. This automated process matched incidents based on geographic proximity and incident start times. However, initial results showed that this method had several limitations. First, incident information is entered manually into Tracker, leaving it susceptible to human error and delays if employees are handling other tasks more crucial to incident response. Additionally, incident location coordinates from AI-TOMS are currently estimated based on the Bluetooth segment where travel time anomalies are detected and Wavetronix sensors where volume and spot speed anomalies are detected, meaning their locations reflect where traffic flow is impacted and do not always match exactly with the locations of incidents in Tracker. These limitations do not impact DelDOT's ability to identify and respond to incidents in real-time, but their combination makes it challenging to accurately identify matching incidents using the original Python algorithm. Once again, defining a process that considers engineering judgement offered potential for accounting for this challenge. Therefore, the evaluation team shifted its approach to a manual process to allow engineering judgement help resolve potential discrepancies.

To assess the System's ability to detect incidents within specific timeframes, it is necessary to know when the incident occurred on the roadway. However, even though DelDOT employs an extensive network of ITS devices, the only way for anyone to truly know the exact time of an incident is for a DelDOT employee to watch the incident occur on CCTV camera and log the incident start time. This presents an obvious challenge, and forced the project and evaluation teams to consider methods of approximating incident start times.

Due to the difficulty associated with measuring the time an incident occurred, when creating the incident detection time performance measure at the start of the project, the project team intended to use traffic microsimulation models to simulate real-world conditions. These models would be built as part of the larger project for use in real-time decision-making and would be used offline as part of the evaluation. Within the model, an incident would be simulated, and AI-TOMS would be employed to test the average delay time for AI-TOMS to detect an incident on freeways and arterials.

Although the project team has developed microsimulation models as described in the section of this report on Simulation Services, the project team found it challenging to produce microsimulation models that were both large enough to include the entirety of each of the study areas and efficient enough to be used in real-time operations decision-making.

Since the evaluation team could not follow the approach that was initially intended to be used in this evaluation, it evaluated other means of estimating a baseline for comparison. Two additional sources of incident data were identified and subsequently ruled out as true baselines; DelDOT's incident tracking software, Tracker; and Waze.

Based on conversations with DelDOT TMC about incident response, the evaluation team determined incident start times entered into Tracker were not reliable measure of when incidents occur. This is because incident information is entered manually into Tracker when they are available, leaving it susceptible to human error and delays when employees are handling other tasks more crucial to incident response. Using Waze as a baseline for incident start times is also flawed because it relies on crowdsourced data collected from motorists that have inherent reporting time variability.

Based on the data available, Tracker and CAD were selected for use in the incident detection time and incident detection accuracy comparisons. However, Tracker and CAD define incidents differently from AI-TOMS, offering a potential source of discrepancy in this analysis. Additionally, since AI-TOMS classifies an incident as any instance when traffic flow is diverging away from the pre-established baseline patterns, it logs many more incidents than Tracker. If users don't consider the context surrounding both tools, they may wrongly be led to believe that the automated incident detection algorithms are overreporting the number of incidents on Delaware's roads by an order of magnitude.

Next, the project team had to consider incident severity identification. Understanding the severity of an incident as it develops is necessary to enable DelDOT TMC to understand how to properly respond. For example, a minor incident may not require a detour, but a severe incident on I-95 may require a detour and even collaboration with neighboring state operations centers. For the purposes of the evaluation, the evaluation team hoped to define the severity of incidents based on their durations as outlined in the MUTCD. However, accurate incident end times were not accessible to the project team.

Furthermore, the approach outlined by the MUTCD for classifying the severity of incidents is acceptable when reviewing AI-TOMS' ability to detect an incident that we retroactively know to have been minor, medium, or major, but a separate approach is needed for responding to incidents in real-time. Therefore, the project team collaborated with FHWA to identify a method that aligned not only with federal requirements, but also with DelDOT operations in a realistic way. The method that the project team arrived on calculates incident severity scores from multiple sources of incident evidence data, including traffic flow and Bluetooth travel time anomalies, Waze alerts, weather data and more.

Finally, the project team needed to consider the unique challenges to incident detection on freeway and arterial roadways. DelDOT TMC manages a large and diverse network of ITS devices that provide traffic volumes, travel speeds, and Bluetooth travel time data. However, as demonstrated by the results of the incident detection time and incident detection accuracy analyses included in the evaluation, timely and accurate incident detection was typically most accurate along I-95 and the sections of DE 1 within the urban study area, indicating that the performance of the incident detection algorithms relies heavily on the density of ITS devices being used to monitor these roadways. The project team also quickly learned that incident detection on arterial roads presents its own set of challenges. The "heartbeat" of arterial traffic flow is impacted by factors that uninterrupted flow facilities like I-95 do not experience such as traffic signals, pedestrians, bus stops, mid-block business and residential driveways, and increased lane changes. The challenges associated with arterial incident detection are clearly reflected in the slower incident detection times and lower incident detection accuracies calculated along US 13 as part of the evaluation. Improving arterial incident detection will be a focus point for DelDOT as it continues efforts to build and implement its AI-ITMS.

4.5.3 Benefit-Cost Analysis

As stated in DelDOT's vision statement, the department "seeks the best value for every dollar spent for the benefit of all" which is a value carried throughout deployment of the AI-ITMS. DelDOT continues to make extensive investments in technology, including its fiber-optic system, telecommunications system, detection, and traffic signal control system. This project, in parallel with other ongoing efforts, sets the foundation for a predictive and adaptive system. As stated in previous reports, transportation management and advanced technology provide greater returns on investment than physical roadwork and construction. As physical alterations are made on roadways, traffic increases, and traffic flow management becomes increasingly important. DelDOT aims to get the most out of the available capacity as possible using technology and management methods. When DelDOT does perform physical construction, ITMS devices and communication are built into the project development process. The department has integrated the need for ITMS infrastructure into their philosophy as a transportation agency to prepare for the future.

Using this ITMS infrastructure, DelDOT collects extensive amounts of data from sensors and devices throughout the transportation network. This data is made readily available to users and provides an invaluable tool that can be used in real-time as well as for planning for future enhancements. In addition to investments in infrastructure, DelDOT has also invested in a dedicated software development team that created and continues to maintain DelDOT's data map site and mobile application to share the data collected statewide with road users. DelDOT has made significant investments in infrastructure as well as in people to continue to enhance their statewide ITMS. AI and ML is the next step in enhancing the system. By integrating advanced software tools, DelDOT continues their commitment to enhance the system and build on the foundation and investments they have established. The AI-ITMS will provide an immediate return on investment as a rapid deployment solution to mitigate congestion and improve DelDOT's road network safety. This investment will provide greater system efficiency and continued improvement in anomaly detection and transportation management control.

Throughout project development, the project team has identified a number of benefits that are expected to outweigh the costs as part of the analysis. For example, the system is expected to reduce delay in project areas which will have a major impact on congestion levels. Decrease in congestion rates will improve air quality and coincide with a number of existing/planned DelDOT initiatives to do so. Emissions reduction calculations will be performed in alignment with other DelDOT projects and strategies to mitigate congestion and improve air quality. Additionally, reduction in incident detection time will allow for improvement in incident clearance times, saving TMC staff time and resources. Over 50% of delay is nonrecurring – this system is designed to identify and detect unexpected incidents sooner so that TMC staff can respond more quickly and efficiently. The entire process of incident management will be improved, from identification, to response, to clearance. This benefit is invaluable as it promotes safety as well as efficiency. DelDOT is also committed to deploying non-intrusive detection, such as MV through this project. By utilizing new and innovative detection solutions, DelDOT will save on costs and will continue to maintain the integrity of their roadways.

The AI-ITMS Benefit-Cost Analysis (BCA) Procedures document has been developed in conjunction with the USDOT's Volpe Center. The document describes the analysis process, the tools used to complete the BCA, the detailed methodology, including objectives and associated benefits/costs, as well as the analysis procedure for during and post deployment. As noted in Section 4.5.1, a baseline for some performance measures could not be defined within this grant period, and it is DelDOT's priority moving forward to establish such measures. The BCA will be revised to include the establishment of a baseline as enabled by the AI-ITMS to provide a measure of the total impact of the System once it is in production. These revisions will clarify how the baseline will be determined. Regarding the sensitivity analysis for CAV deployment, further consideration will be given to this area of the BCA and will be relayed to FHWA. Local cost data will be included in the budget documentation where possible within the BCA. Additional consideration will be given to future projections made through the BCA.

4.6 Simulation Challenges

4.6.1 Calibration Criteria

Simulation services are used to perform measure of effectiveness evaluation with incident events to support the assessment and mitigation of those events in the network. The modeling team came across a challenge as calibration procedures were identified and defined. At the start of the project development, FHWA provided criteria[18] for simulation modeling and calibration. As the project continued, FHWA's calibration criteria were updated to a new version[19] which included varying requirements for calibrating simulation models. The updates required the modeling team to update their calibration procedure and collect and analyze more data than expected initially. As work continues beyond the end of this grant, the modeling team will continue to analyze additional data and work with FHWA to update the project's model calibration process to operate within project limits to meet the latest FHWA requirements successfully.

4.6.2 Use of Simulation Modeling Software

The project team built a simulation server at BlueHalo lab and completed the simulation models, using various modeling software including SYNCHRO, SUMO, VISSIM, and CUBE to extract the base network geometry and OD data and VISUM for the CAV, Urban, and Beach study areas as defined in the program scope.

SYNCHRO is a traffic analysis and simulation software that allows users to model various traffic scenarios. It is widely used for various aspects of traffic analysis and signal timing optimization in DelDOT. In this project, SYNCHRO was used to integrate all existing models developed by DelDOT and then transfer them as base models for use in VISUM, VISSIM, and SUMO. Since SYNCHRO does not provide users with APIs, it was not integrated with AI-TOMS at the current phase.

SUMO is a free, open-source microscopic traffic simulation software designed to simulate road traffic in urban areas. Since SUMO provides user-friendly APIs for developers to integrate with other software, researchers widely recommend it to model and analyze traffic flow, congestion, and mobility patterns in complex urban environments. However, the progress of building a model is time-consuming, the simulation speed for a regional network is slow, and the software support is lacking compared to other available simulation modeling software. The project team tested SUMO on US 13 in the CAV area with 11 traffic signals to evaluate the feasibility.

VISSIM is a commercial microscopic traffic simulation software developed by PTV Group. Transportation engineers, urban planners, and researchers widely use it to model and analyze traffic flow, congestion, and mobility in both urban and rural environments. VISSIM is known for its high detail and accuracy, making it suitable for studying complex traffic scenarios and optimizing transportation systems and tends to be VISSIM is more user friendly and reliable since it's a commercial software. PTV provides professional services and software version iterations with more functions. The project team found VISSIM simulations for a large regional network, such as the study areas in the project scope, become extremely slow and may not meet the requirements of the TMC for use in real-time operation applications. For the Zone 20 signal group in the Beach study area, VISSIM was used offline to compare the TRPS module in TACTICS with AI-TOMS' signal

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[18] Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software, 2004, Federal Highway Administration

[19] Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software, 2019, Federal Highway Administration

optimization algorithm applied to the zone.

VISUM is being used as a sandbox to evaluate and test the recommended plans from AI-TOMS, with functions developed to optimize signal timings based on real-time conditions. VISUM is a commercial transportation planning software developed by PTV Group. Similar to VISSIM, it provides a COM interface for developers to integrate with other software and external scripts. VISUM is designed for macroscopic traffic modeling and transportation planning, and it complements the capabilities of VISSIM. VISUM allows users to model transportation networks at a high-level, focusing on the overall flow of traffic and travel patterns. It is beneficial for regional transportation networks with its fast simulation. This project uses VISUM models to identify optimal signal patterns when incidents occur, providing the optimal splits and offsets. The project team has integrated VISUM into AI-TOMS for the CAV area for incident mitigation and will expand to the beach and urban network in future development.

The models focus on vehicle performance without transit, bike, pedestrian, and other multimodal inputs. While beneficial for the initial development, a mature system should incorporate all transportation users. However, the currently available data collection services do not provide sufficient data from transit, bike, and pedestrian users. This lack of data from public transportation and vulnerable road user groups causes the traffic mitigation solutions generated by the AI engine to ignore particular road user groups. Future efforts will investigate improving data collection from public transportation and non-vehicle road users to further train the AI engine to generate comprehensive transportation management solutions. Additionally, input will be gathered from users and stakeholders to provide valuable insights, report discrepancies, and suggest improvements that can enhance the accuracy of models.

5 Conclusion

5.1 Research, Educational, and Workforce Development

Insights, feedback, and data from the project were pivotal in introducing novel AI methodologies for traffic management. These resources enabled research that holds both theoretical significance and practical value, forging a valuable tool set for scholars and practitioners. Furthermore, such contributions amplify the impact of the project, setting a trajectory for future developments in AI-enhanced traffic management. Throughout the project's duration, a substantial body of literature was produced, providing valuable resources for both industry practitioners and academics. The work done on this project had a broad influence, accelerating and enabling research within this space. The data and insights gathered by the project team were critical in developing methodologies for the 12 peer-reviewed articles, listed below, published in prestigious journals and highly competitive conference proceedings. The peer-reviewed research outcomes and publications that acknowledged the project are predominantly categorized into two main groups: research on near real-time traffic prediction, and networking and applications in ITS.

[1] M. Shaygan, C. Meese, W. Li, X. G. Zhao, and M. Nejad, "Traffic Prediction using Artificial Intelligence: Review of Recent Advances and Emerging Opportunities," *Transportation Research Part C: Emerging Technologies,* 2023.

[2] C. Meese, D. Lee, H. Chen, and M. Nejad, "vLOFT: Variable Learning Rate for Online Federated Traffic Prediction," in *26th IEEE International Conference on Intelligent Transportation Systems (ITSC)*, Bilbao, Spain, 2023.

[3] C. Meese, H. Shen, G. Hao, W. Li, and M. Nejad, "Dynamic Traffic Prediction at the ITS Edge with Online Models and Blockchain-based Federated Learning," *IEEE Transactions on Intelligent*

Transportation Systems, vol. 24, pp. 1-14, 2023.

[4] C. Meese, H. Chen, S. A. Asif, W. Li, C.-C. Shen, and M. Nejad, "BFRT: Blockchained Federated Learning for Real-time Traffic Flow Prediction," in *2022 22nd IEEE International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*, 2022: IEEE, pp. 317-326.

[5] H. Guo, C. Meese, W. Li, and M. Nejad, "B2SFL: A Bi-level Blockchained Architecture for Secure Federated Learning-based Traffic Prediction," *IEEE Transactions on Services Computing,* 2023.

[6] W. Li, C. Meese, H. Guo, and M. Nejad, "Aggregated Zero-Knowledge Proof and Blockchain-Empowered Authentication for Autonomous Truck Platooning," *IEEE Transactions on Intelligent Transportation Systems,* vol. 24, no. 4, pp. 1-15, 2023.

[7] Z. Zhong, M. Nejad, and E. E. Lee, "Autonomous and Semiautonomous Intersection Management: A Survey," *IEEE Intelligent Transportation Systems Magazine,* vol. 13, no. 2, pp. 53-70, 2020.

[8] H. Guo, W. Li, M. Nejad, and C.-C. Shen, "Proof-of-event recording system for autonomous vehicles: A blockchain-based solution," *IEEE Access,* vol. 8, pp. 182776-182786, 2020.

[9] W. Li, H. Guo, M. Nejad, and C.-C. Shen, "Privacy-preserving traffic management: A blockchain and zero-knowledge proof inspired approach," *IEEE Access,* vol. 8, pp. 181733-181743, 2020.

[10] T. Ma, R. Zhang, and M. Nejad, "Secure Connected Vehicle-based Traffic Signal Systems Against Data Spoofing Attacks," in *2021 IEEE Wireless Communications and Networking Conference (WCNC)*, 2021: IEEE, pp. 1-7.

[11] W. Li, C. Meese, H. Guo, and M. Nejad, "Blockchain-enabled Identity Verification for Safe Ridesharing Leveraging Zero-Knowledge Proof," in *2020 3rd International Conference on Hot Information-Centric Networking (HotICN)*, 2020: IEEE, pp. 18-24.

[12] W. Li, M. Nejad, and R. Zhang, "A blockchain-based architecture for traffic signal control systems," in *2019 IEEE International Congress on Internet of Things (ICIOT)*, 2019: IEEE, pp. 33-40

The reference [1] collaborative paper titled "Traffic Prediction using Artificial Intelligence: Review of Recent Advances and Emerging Opportunities," co-authored by University of Delaware and BlueHalo researchers and published in "Transportation Research Part C: Emerging Technologies," serves as a key resource for both graduate students and transportation engineers keen on exploring this domain.

Furthermore, the depth and versatile nature of the research is evidenced by the more than 150 citations these publications have garnered in a relatively short period. Additionally, several publications received prestigious recognitions, further underscoring the global academic relevance of this work. Two noteworthy recognitions are:

- The 2022 IEEE Intelligent Transportation Systems Society (ITSS) Best Dissertation Award - Second Prize
- Best Paper Award, IEEE Connected and Automated Vehicles Symposium (CAVS)

Beyond recognition in writing, the project partially supported and guided four graduate and many undergraduate researchers at the University of Delaware, all specializing in Transportation Engineering. One of the graduate students is now an assistant professor, and another is a transportation engineering professional. Close to 30 undergraduate researchers were exposed to the groundbreaking findings of the project. Additionally, these students benefited from firsthand experiences during their visits to the DelDOT TMC, further enriching their comprehension of AI-enhanced traffic management.

5.2 Outreach

The Project team participated in multiple outreach opportunities primarily thorough conferences to support broad industry-wide exposure and collaboration in this innovative field. Copies of these presentations may be available from DelDOT upon request.

[1] ITS America Annual Conference, Charlotte, NC, December 8, 2021 – the project team presented a technical paper, Leveraging Delaware's Existing ITMS Components for AI Deployment, as part of a conference panel discussion.

[2] Transportation Research Board Annual Meeting, Washington, DC, January 9-11, 2022 – BlueHalo software team demonstrated the AI-TOMS software as an exhibitor.

[3] USDOT ITS-JPO, Washington, DC, January 26, 2022 – the project team presented a comprehsive review of the project progress as part of the DelDOT's ATCMTD Traffic Prediction and Traveler Information Using AI Project Update meeting.

[4] NCHRP 23-16: Implementing and Leveraging ML at State Departments of Transpotation, June 2022 – May 2023. DelDOT supported developing case studies applicable to agencies that are ready for near-term deployment of AI/ML. The objective of this research is to advance the understanding and use of ML tools and techniques at state departments of transportation and other transportation agencies by creating resources that capture ML best practices.

[5] ITS Maryland Legislative Technology Fair, Annapolis, MD, March 9, 2023 – BlueHalo software team provided a live demonstration of the AI-TOMS platform. This is an educational outreach event for Maryland state congressional staff.

[6] Transportation Research Board Annual Meeting, Washington, DC, January 8-12, 2023 – BlueHalo software team presented, Data Collection and Processing to Support AI Enhanced Traffic Operation and Management, AED50 Committee meeting on Artificial Intelligence and Advanced Computing. The presentation showcased how the teams collect, process, and generate insights for DelDOT's AI-ITMS.

[7] ITE Mid-Colonial District Annual Meeting, Pittsburg, PA, April 19, 2023 – BlueHalo software team presented, Data Collection and Processing to Support AI Enhanced Traffic Operation and Management. The presentation showcased how the teams collect, process, and generate insights for DelDOT's AI-ITMS.

[8] ITE Mid-Colonial District Annual Meeting, Pittsburg, PA, April 19, 2023 – Jacobs modeling team presented, AI-based Dynamic Arterial Signal Management – A Case Study. The presentation focused on the VISSIM model evaluation of the Zone 20 arterial beach route.

[9] ITS America Annual Conference, Dallas, TX, April 24-27, 2023 – BlueHalo software team presented a technical paper – Applying AI to Enhance DelDOT's AI-ITMS Program. The presentation and demonstration highlighted the AI-TOMS software capabilities supporting DelDOT's AI-ITMS program.

[10] Missouri DOT AI/ML Roundtable Discussion, St. Louis, MO, June 27-28, 2023 – Gene Donaldson/DelDOT presented the AI-TOMS software and DelDOT's AI-ITMS program in a discussion with several other DOTs pursuing other AI work.

5.3 Recommendations

Through the development of the AI-ITMS, the project team has documented important actions that have proved helpful and developed recommendations regarding future deployment strategies for departments of transportation.

When developing simulation models for use in an AI system, it is recommended that they be created and calibrated based on existing models if possible. Software development requires accurate ground truth data for calibration and algorithm development. This will ensure the AI and ML algorithms are able to operate successfully. It is imperative for the project team to continue working closely with TMC operations staff to better understand the measures taken as events occur and the optimal response to develop an innovative methodology to train the system and verify ground truth details within AI-TOMS. Focusing on a single location for testing and calibration of the system is recommended before building out the system and extending operation.

During the planning and development stages of a project, it is recommended that the project team consider timelines and potential delays related to device procurement and installation. The project team should be aware of any potential delay during the process, either during plan review, device procurement, or delivery, and plan accordingly to ensure the project progresses. Understanding the level of integration that is needed for device installations and if any existing contracts are in place with the agency may help mitigate any delay related to device procurement. Similarly, there is currently no existing contracting mechanism to procure innovative technologies. As emerging technology in transportation continues to become more prevalent for departments of transportation, an expedited process to procure this kind of equipment would greatly benefit agencies who often experience challenges and time delays when it comes to innovative technology procurement.

To align with national guidelines, the project team has been working to develop an extensive ITS Architecture. Creating and maintaining an architecture that uses common language to allow for planning, defining, and integrating ITS will help not only with the development of this project as it relates to ITS device procurement and installation but will be extremely helpful as DelDOT continues to invest in technology deployment to enhance its transportation system in line with the national standards. For a system as complex as DelDOT's, it is recommended to have an ITS architecture to clearly define the components and the ITS devices and how they communicate so that project teams and third-party providers can understand how integration can occur.

5.4 Summary

The project team, led by DelDOT, has made impressive strides towards deploying an AI-ITMS throughout this grant period. DelDOT has successfully integrated more than ten sources of near-real-time traffic data into the System, concurrently monitoring nearly 90% of ITMS devices statewide.

With an early focus on incident detection on Interstates and freeways, the project team developed, tested, and integrated multiple algorithms within AI-TOMS that can detect and localize traffic anomalies, classify their severity and assess their impact, and determine alternative route choices for the traveling public. While these algorithms are still being refined and are not yet operationally deployed, initial evaluations show positive results for a System still under deployment. Incident detection and accuracy on I-95 and DE 1 show that AI-TOMS can identify a crash within 15 minutes of the incident on average with over 80% accuracy. These results, which DelDOT expects to improve as the System becomes more advanced, are promising for improved event and incident response time through advanced control of ITS devices.

Though Interstate and freeway incidents can contribute to significant interruptions to the overall transportation network, the majority of DelDOT's roads are signalized arterials and local roads. With an AI-TOMS that can communicate with traffic signals, technicians at DelDOT's TMC can prioritize larger incidents that require more attention and trust that AI-TOMS can monitor day-to-day traffic operations and make signal timing adjustments as necessary to keep traffic moving. One key element is the signal system integration where AI-TOMS can make optimal signal plan recommendations given the current and predicted traffic demand, and then communicate these signal plan changes to the field using NTCIP. This change from the original planned approach of communicating directly between AI-TOMS and the TACTICS centralized signal control system added significant development delay, which has been partly responsible for the delayed integration with field traffic signal controllers. Despite this delay, the new approach does demonstrate the power of interoperability through open standards and does provide a more vendor-neutral solution, giving DelDOT greater flexibility in the future. With communication now possible, initial tests of running select signal groups on AI-TOMS have shown promising results, with AI-TOMS making changes to the signal timing patterns based off predicted traffic and HR data. AI-TOMS specific ability to accurately predict traffic patterns up to an hour in advance shows great potential for DelDOT's congestion management.

The varied functions of the System and their TRLs are shown in Table 22. Across the three different study areas, each function ranges from TRL 6, "prototype demonstrated in relevant environment" to TRL 8, "technology proven in operational environment" showing that DelDOT is well on its way to a fully refined AI-ITMS.

Table 22: Technology Readiness Levels for AI-TOMS Services

Function	Urban	CAV	Beach
Automatic Incident Detection	TRL-8: Freeway I-95 and DE 1	TRL-8: Freeway DE 1; TRL-7: Arterial US 13	TRL-6: DE 1 and beach network
Traffic Flow Prediction	TRL-8: Freeway I-95 and DE 1	TRL-8: Freeway DE 1 and Arterial US 13	TRL-7: arterial (zone 20) network
ATSPM and Signal Timing Optimization	TRL-6: HR data collection for US 40 network	TRL-8: ATSPM for US 13 corridor; vehicle trajectory overlay; signal timing optimization with HR data	TRL-7: ATSPM for zone 20 network
Predictive Signal Control	Not Applicable	TRL-8: NTCIP signal control based on predicted traffic demand for signal group K999 along US 13; Four operation modes available (TACTICS, AI-TOMS, manual and Time of day)	TRL-6: NTCIP signal control available, not tested yet

Function	Urban	CAV	Beach
Incident/Event Mitigation DSS	TRL-6: Freeway incident detour scenarios and impact analysis	TRL-7: Freeway incident detour scenario modeling, mitigation plan recommendation	TRL-6: VISSIM model for Zone 20 network
Live SPaT and CAV Applications	Not Applicable	TRL-7: live SPaT for 11 intersections, less than 150 milliseconds latency	Not Applicable
System Health Monitoring	TRL-6: detector data quality; TRL-7: hardware and software health	TRL-6: detector data quality; TRL-7: hardware and software health	TRL-6: detector data quality; TRL-7: hardware and software health
Machine Vision Traffic Monitoring	TRL-6: initial MV algorithm for congestion detection on freeway I-95	TRL-8: MV hub deployed to US 13 at DE 300; MV for vehicle count, classification, and speed estimation; TR-5: Vehicle re-identification from two cameras	Not Applicable

Moving forward, the project team will continue its work moving forward with a focus on signal integration and day-to-day traffic operations, enhancing AI-TOMS ability to make offset adjustments and split timing adjustments. AI can monitor a transportation network better than any group of human technicians can, and DelDOT sees this as a great opportunity. DelDOT intends to reevaluate the System's performance measures, with an emphasis on establishing consistent baseline and ground truth data to better measure improvements in the System, track signal performance success, and incorporate the lessons learned from the initial evaluation completed during the ATCMTD grant.

It is the project team's ability to be adaptive and agile during this process that has gotten DelDOT's AI-ITMS to where it is today despite significant challenges. DelDOT is looking forward to continuing the development of its AI-ITMS to increase monitoring on their roads, keep drivers informed, improve event and incident response, and prepare for other emerging transportation technologies.

6 Appendix A. Incident Data

READ ME	
Tracker Start Time	Incident start time logged in Tracker by DelDOT staff
AI TOMS Incident	Incident ID number of the AI TOMS incident that was matched to the Tracker incident
AI-TOMS Incident Start Time	Incident start time logged by AI-TOMS anomaly detection algorithm
Corridor	Study area the incident occurred in (Urban or CAV)
Route Type	Notes whether the incident occurred on a freeway or arterial
CAD Date and Time	Incident start time logged by computer-aided dispatch

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
12/05/22 12:22:35	8378	12/5/22 12:17	Urban	Freeway	I- 95	12/5/2022 12:08
12/07/22 15:27:50	8410	12/7/22 15:09	Urban	Freeway	I- 95	12/7/2022 15:06
12/09/22 09:59:31	8422	12/9/22 10:00	Urban	Freeway	I- 95	12/9/2022 9:52
12/10/22 01:57:42	0	#N/A	CAV	Freeway	DE- 1	12/10/2022 1:10
12/11/22 19:18:44	8435	12/11/22 17:20	Urban	Freeway	I- 95	12/11/2022 17:23
12/21/22 01:07:15	0	#N/A	CAV	Freeway	DE- 1	12/21/2022 0:40
12/22/22 22:11:59	0	#N/A	CAV	Freeway	DE- 1	12/22/2022 21:47
12/22/22 07:54:40	0	#N/A	CAV	Freeway	DE- 1	12/22/2022 7:42
12/25/22 17:09:16	8623	12/25/22 17:10	Urban	Freeway	I- 95	12/25/2022 16:55
12/30/22 09:15:32	8673	12/30/22 9:31	Urban	Freeway	I- 95	12/30/2022 8:25
1/03/23 21:29:40	0	#N/A	Urban	Freeway	I- 95	1/3/2023 21:17
1/04/23 08:41:34	8724	1/4/23 8:30	Urban	Freeway	I- 95	1/4/2023 8:38
1/08/23 11:02:22	8756	1/8/23 11:50	Urban	Freeway	I- 95	1/8/2023 10:30
1/09/23 03:56:10	8760	1/9/23 4:01	Urban	Freeway	I- 95	1/9/2023 3:46
1/19/23 04:24:22	8801	1/19/23 4:17	Urban	Freeway	I- 95	1/19/2023 4:19
1/22/23 06:35:59	0	#N/A	CAV	Freeway	DE- 1	1/22/2023 6:26

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
1/22/23 05:08:12	8825	1/22/23 5:05	Urban	Freeway	I- 95	1/22/2023 4:50
1/29/23 11:58:12	8920	1/29/23 11:52	Urban	Freeway	I- 95	1/29/2023 11:47
2/01/23 19:35:29	8967	2/1/23 19:07	Urban	Freeway	I- 95	2/1/2023 18:58
2/03/23 22:35:11	9000	2/3/23 22:25	Urban	Freeway	I- 95	2/3/2023 22:17
2/04/23 13:26:12	9001	2/4/23 14:05	Urban	Freeway	I- 95	2/4/2023 13:17
2/05/23 00:28:49	0	#N/A	Urban	Freeway	I- 95	2/4/2023 23:35
2/05/23 06:03:24	0	#N/A	CAV	Freeway	DE- 1	2/5/2023 5:46
2/08/23 05:37:13	9028	2/8/23 5:56	Urban	Freeway	I- 95	2/8/2023 5:20
2/09/23 06:36:32	9036	2/9/23 6:45	CAV	Freeway	DE- 1	2/9/2023 6:27
2/14/23 18:48:28	9058	2/14/23 18:48	Urban	Freeway	I- 95	2/14/2023 18:50
2/15/23 09:05:57	9067	2/15/23 8:45	Urban	Freeway	I- 95	2/15/2023 6:56
2/17/23 07:42:37	0	#N/A	CAV	Freeway	DE- 1	2/17/2023 7:35
2/17/23 12:43:35	9089	2/17/23 12:34	Urban	Freeway	I- 95	2/17/2023 12:37
2/26/23 02:21:01	9146	2/26/23 1:45	Urban	Freeway	I- 95	2/26/2023 1:41
2/28/23 08:58:52	9169	2/28/23 8:50	Urban	Freeway	I- 95	2/28/2023 8:38
3/01/23 07:23:37	9179	3/1/23 7:22	CAV	Freeway	DE- 1	3/1/2023 7:06
3/01/23 08:04:59	9181	3/1/23 8:25	Urban	Freeway	DE- 1	3/1/2023 7:54
3/02/23 06:55:38	0	#N/A	CAV	Arterial	US- 13	3/2/2023 6:34
3/03/23 14:58:02	9196	3/3/23 14:43	Urban	Freeway	I- 95	3/3/2023 14:36
3/06/23 07:37:05	9214	3/6/23 7:30	Urban	Freeway	DE- 1	3/6/2023 7:22
3/08/23 10:34:19	0	#N/A	CAV	Freeway	DE- 1	3/8/2023 10:23

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
3/13/23 14:19:51	9355	3/13/23 14:01	Urban	Freeway	DE- 1	3/13/2023 13:48
3/15/23 16:35:05	9426	3/15/23 16:41	CAV	Arterial	US- 13	3/15/2023 16:35
3/17/23 13:47:49	0	#N/A	CAV	Arterial	US- 13	3/17/2023 13:42
3/19/23 06:06:28	0	#N/A	Urban	Freeway	I- 95	3/19/2023 5:57
3/19/23 19:51:59	0	#N/A	CAV	Freeway	DE- 1	3/19/2023 19:36
3/23/23 17:27:59	9712	3/23/23 16:45	CAV	Freeway	DE- 1	3/23/2023 16:24
3/25/23 11:48:58	9777	3/25/23 11:51	CAV	Freeway	DE- 1	3/25/2023 11:49
4/04/23 07:58:00	10113	4/4/23 7:51	Urban	Freeway	I- 95	4/4/2023 7:47
4/04/23 20:45:06	10136	4/4/23 20:05	Urban	Freeway	I- 95	4/4/2023 20:06
4/05/23 16:30:42	10180	4/5/23 16:34	CAV	Arterial	US- 13	4/5/2023 16:20
4/05/23 02:19:34	10141	4/5/23 2:05	Urban	Freeway	I- 95	4/5/2023 2:01
4/08/23 01:52:10	10281	4/8/23 1:45	Urban	Freeway	I- 95	4/8/2023 1:26
4/08/23 18:28:38	0	#N/A	CAV	Arterial	US- 13	4/8/2023 18:13
4/08/23 18:27:48	0	#N/A	CAV	Arterial	US- 13	4/8/2023 18:13
4/10/23 16:47:45	10362	4/10/23 16:35	CAV	Freeway	DE- 1	4/10/2023 16:12
4/11/23 01:55:49	0	#N/A	Urban	Freeway	I- 95	4/11/2023 1:40
4/16/23 12:15:56	10551	4/16/23 12:20	Urban	Freeway	DE- 1	4/16/2023 11:42
4/16/23 01:36:19	0	#N/A	Urban	Freeway	I- 95	4/16/2023 1:14
4/21/23 19:19:29	10722	4/21/23 19:15	Urban	Freeway	I- 95	4/21/2023 19:34
4/25/23 07:24:20	10845	4/25/23 7:01	Urban	Freeway	I- 95	4/25/2023 6:43
4/26/23 11:56:29	10883	4/26/23 12:00	CAV	Freeway	DE- 1	4/26/2023 11:48
4/28/23 06:41:53	10969	4/28/23 6:35	Urban	Freeway	DE- 1	4/28/2023 6:27
4/30/23 09:59:21	0	#N/A	CAV	Freeway	DE- 1	4/30/2023 9:41
5/01/23 16:49:41	0	#N/A	Urban	Freeway	I- 95	5/1/2023 16:50
5/02/23 00:05:03	11119	5/1/23 23:55	Urban	Freeway	DE- 1	5/1/2023 23:48

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
5/04/23 22:19:58	0	#N/A	Urban	Freeway	DE- 1	5/4/2023 22:07
5/05/23 06:17:43	11233	5/5/23 6:05	Urban	Freeway	I- 95	5/5/2023 6:04
5/05/23 01:39:42	11231	5/5/23 2:25	Urban	Freeway	I- 95	5/5/2023 0:53
5/07/23 03:50:52	11302	5/7/23 3:10	Urban	Freeway	I- 95	5/7/2023 3:24
5/10/23 15:07:31	11413	5/10/23 14:35	CAV	Freeway	DE- 1	5/10/2023 14:24
5/13/23 11:28:02	11569	5/13/23 12:34	CAV	Arterial	US- 13	5/13/2023 11:14
5/15/23 12:27:31	11642	5/15/23 12:30	CAV	Freeway	DE- 1	5/15/2023 12:20
5/18/23 17:21:05	0	#N/A	Urban	Freeway	DE- 1	5/18/2023 17:15
5/24/23 17:56:12	0	#N/A	Urban	Freeway	DE- 1	5/24/2023 18:07
5/28/23 18:38:36	0	#N/A	CAV	Arterial	US- 13	5/28/2023 18:22
5/31/23 12:54:33	12275	5/31/23 12:15	Urban	Freeway	DE- 1	5/31/2023 12:06
7/02/22 22:53:18	6536	7/2/22 22:11	Urban	Freeway	I- 95	7/2/2022 22:31
7/10/22 13:19:50	6619	7/10/22 12:01	Urban	Freeway	I- 95	7/10/2022 11:53
7/18/22 09:57:32	6730	7/18/22 10:00	Urban	Freeway	I- 95	7/18/2022 9:47
7/18/22 09:57:30	6729	7/18/22 9:48	Urban	Freeway	I- 95	7/18/2022 9:47
8/09/22 18:27:28	0	#N/A	Urban	Freeway	I- 95	8/9/2022 18:16
8/09/22 16:40:45	7042	8/9/22 15:55	Urban	Freeway	I- 95	8/9/2022 15:48
8/23/22 16:48:00	7240	8/23/22 15:55	Urban	Freeway	I- 95	8/23/2022 16:24
8/28/22 19:41:52	7314	8/28/22 19:41	Urban	Freeway	I- 95	8/28/2022 19:27
8/29/22 14:20:00	7317	8/29/22 13:00	Urban	Freeway	I- 95	8/29/2022 13:01
9/06/22 20:28:42	7403	9/6/22 19:55	Urban	Freeway	I- 95	9/6/2022 19:54

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
9/09/22 19:34:41	7435	9/9/22 19:17	Urban	Freeway	I- 95	9/9/2022 19:13
9/11/22 21:59:03	7453	9/11/22 21:15	Urban	Freeway	I- 95	9/11/2022 21:18
9/22/22 07:30:01	7542	9/22/22 8:36	Urban	Freeway	I- 95	9/22/2022 7:09
9/25/22 16:15:43	7579	9/25/22 16:07	Urban	Freeway	I- 95	9/25/2022 16:02
9/27/22 17:28:58	7603	9/27/22 18:28	Urban	Freeway	I- 95	9/27/2022 17:20
10/01/22 03:26:39	0	#N/A	Urban	Freeway	I- 95	10/1/2022 2:46
10/03/22 07:18:20	7667	10/3/22 6:45	Urban	Freeway	I- 95	10/3/2022 6:51
10/12/22 10:27:38	7756	10/12/22 10:20	Urban	Freeway	I- 95	10/12/2022 10:07
10/14/22 19:26:27	7786	10/14/22 18:57	Urban	Freeway	I- 95	10/14/2022 19:18
10/15/22 21:06:50	7792	10/15/22 21:00	Urban	Freeway	I- 95	10/15/2022 20:50
10/22/22 17:24:22	7885	10/22/22 17:20	Urban	Freeway	I- 95	10/22/2022 17:15
11/02/22 14:54:58	8009	11/2/22 14:49	Urban	Freeway	I- 95	11/2/2022 14:50
11/11/22 20:23:02	8147	11/11/22 19:50	Urban	Freeway	I- 95	11/11/2022 20:09
11/11/22 01:07:04	8140	11/11/22 1:01	Urban	Freeway	I- 95	11/11/2022 0:44
11/19/22 15:57:05	8227	11/19/22 15:42	Urban	Freeway	I- 95	11/19/2022 15:36
11/22/22 16:51:45	8253	11/22/22 16:20	Urban	Freeway	I- 95	11/22/2022 16:19
7/01/22 19:49:55	0	#N/A	CAV	Freeway	DE- 1	7/1/2022 19:17
7/02/22 12:27:04	0	#N/A	CAV	Freeway	DE- 1	7/2/2022 12:17
7/05/22 08:46:37	6546	7/5/22 8:47	Urban	Freeway	DE- 1	7/5/2022 8:41
7/15/22 08:32:06	0	#N/A	CAV	Freeway	DE- 1	7/15/2022 8:32
7/19/22 06:17:06	0	#N/A	CAV	Freeway	DE- 1	7/19/2022 5:53
7/27/22 10:52:19	6843	7/27/22 10:25	Urban	Freeway	DE- 1	7/27/2022 10:18

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
8/02/22 06:34:19	6933	8/2/22 7:40	Urban	Freeway	DE- 1	8/2/2022 6:37
8/06/22 07:45:16	0	#N/A	CAV	Freeway	DE- 1	8/6/2022 7:38
8/08/22 16:22:28	0	#N/A	CAV	Freeway	DE- 1	8/8/2022 16:17
8/23/22 07:51:38	7234	8/23/22 7:30	Urban	Freeway	DE- 1	8/23/2022 7:47
8/23/22 00:25:55	7233	8/23/22 0:15	CAV	Freeway	DE- 1	8/23/2022 0:11
8/23/22 05:09:33	0	#N/A	Urban	Freeway	DE- 1	8/23/2022 4:25
8/25/22 12:53:58	7253	8/25/22 12:49	Urban	Freeway	DE- 1	8/25/2022 12:57
8/25/22 03:09:35	0	#N/A	Urban	Freeway	DE- 1	8/25/2022 2:42
8/27/22 17:36:18	7296	8/27/22 17:11	Urban	Freeway	DE- 1	8/27/2022 17:22
9/05/22 17:26:26	7382	9/5/22 16:52	Urban	Freeway	DE- 1	9/5/2022 17:21
9/12/22 09:57:36	7455	9/12/22 9:45	CAV	Freeway	DE- 1	9/12/2022 9:50
9/14/22 10:11:07	0	#N/A	CAV	Freeway	DE- 1	9/14/2022 9:57
9/15/22 11:50:05	7479	9/15/22 11:14	Urban	Freeway	DE- 1	9/15/2022 10:50
9/26/22 08:58:02	7581	9/26/22 9:31	Urban	Freeway	DE- 1	9/26/2022 7:59
9/26/22 12:40:24	0	#N/A	Urban	Freeway	DE- 1	9/26/2022 12:26
10/01/22 22:21:43	0	#N/A	CAV	Freeway	DE- 1	10/1/2022 22:15
10/03/22 13:46:01	7669	10/3/22 13:30	CAV	Freeway	DE- 1	10/3/2022 13:38
10/03/22 07:42:00	7668	10/3/22 6:48	Urban	Freeway	DE- 1	10/3/2022 6:44
10/08/22 06:35:36	7711	10/8/22 6:47	Urban	Freeway	DE- 1	10/8/2022 5:44
10/12/22 03:50:46	0	#N/A	CAV	Freeway	DE- 1	10/12/2022 3:35

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
10/24/22 07:44:21	7900	10/24/22 6:44	Urban	Freeway	DE- 1	10/24/2022 7:01
11/01/22 07:00:35	7986	11/1/22 8:33	Urban	Freeway	DE- 1	11/1/2022 6:41
11/02/22 16:58:49	8013	11/2/22 16:40	CAV	Freeway	DE- 1	11/2/2022 16:49
11/07/22 07:42:52	8103	11/7/22 7:45	CAV	Freeway	DE- 1	11/7/2022 7:26
11/10/22 09:58:00	8132	11/10/22 8:35	CAV	Freeway	DE- 1	11/10/2022 8:27
11/15/22 17:32:49	8176	11/15/22 18:05	CAV	Freeway	DE- 1	11/15/2022 17:02
11/20/22 20:28:17	0	#N/A	CAV	Freeway	DE- 1	11/20/2022 20:21
12/10/22 01:57:42	0	#N/A	CAV	Freeway	DE- 1	12/10/2022 1:10
12/21/22 01:07:15	0	#N/A	CAV	Freeway	DE- 1	12/21/2022 0:40
12/22/22 22:11:59	0	#N/A	CAV	Freeway	DE- 1	12/22/2022 21:47
12/22/22 07:54:40	0	#N/A	CAV	Freeway	DE- 1	12/22/2022 7:42
1/06/23 09:25:30	8750	1/6/23 9:12	Urban	Freeway	DE- 1	1/6/2023 9:06
1/22/23 06:35:59	0	#N/A	CAV	Freeway	DE- 1	1/22/2023 6:26
2/05/23 06:03:24	0	#N/A	CAV	Freeway	DE- 1	2/5/2023 5:46
2/09/23 06:36:32	9036	2/9/23 6:45	CAV	Freeway	DE- 1	2/9/2023 6:27
2/17/23 07:42:37	0	#N/A	CAV	Freeway	DE- 1	2/17/2023 7:35
3/01/23 07:23:37	9179	3/1/23 7:22	CAV	Freeway	DE- 1	3/1/2023 7:06
3/01/23 08:04:59	9181	3/1/23 8:25	Urban	Freeway	DE- 1	3/1/2023 7:54
3/06/23 07:37:05	9214	3/6/23 7:30	Urban	Freeway	DE- 1	3/6/2023 7:22
3/08/23 10:34:19	0	#N/A	CAV	Freeway	DE- 1	3/8/2023 10:23
3/13/23 14:19:51	9355	3/13/23 14:01	Urban	Freeway	DE- 1	3/13/2023 13:48

Tracker Start Time	AI-TOMS Incident ID	AI-TOMS Incident Start Time	Corridor	Route Type	route	CAD Date and Time
3/19/23 19:51:59	0	#N/A	CAV	Freeway	DE- 1	3/19/2023 19:36
3/23/23 17:27:59	9712	3/23/23 16:45	CAV	Freeway	DE- 1	3/23/2023 16:24
3/25/23 11:48:58	9777	3/25/23 11:51	CAV	Freeway	DE- 1	3/25/2023 11:49
4/10/23 16:47:45	10362	4/10/23 16:35	CAV	Freeway	DE- 1	4/10/2023 16:12
4/16/23 12:15:56	10551	4/16/23 12:20	Urban	Freeway	DE- 1	4/16/2023 11:42
4/26/23 11:56:29	10883	4/26/23 12:00	CAV	Freeway	DE- 1	4/26/2023 11:48
4/28/23 06:41:53	10969	4/28/23 6:35	Urban	Freeway	DE- 1	4/28/2023 6:27
4/30/23 09:59:21	0	#N/A	CAV	Freeway	DE- 1	4/30/2023 9:41
5/04/23 22:19:58	0	#N/A	Urban	Freeway	DE- 1	5/4/2023 22:07
5/10/23 15:07:31	11413	5/10/23 14:35	CAV	Freeway	DE- 1	5/10/2023 14:24
5/15/23 12:27:31	11642	5/15/23 12:30	CAV	Freeway	DE- 1	5/15/2023 12:20
5/18/23 17:21:05	0	#N/A	Urban	Freeway	DE- 1	5/18/2023 17:15
5/24/23 17:56:12	0	#N/A	Urban	Freeway	DE- 1	5/24/2023 18:07
5/31/23 12:54:33	12275	5/31/23 12:15	Urban	Freeway	DE- 1	5/31/2023 12:06

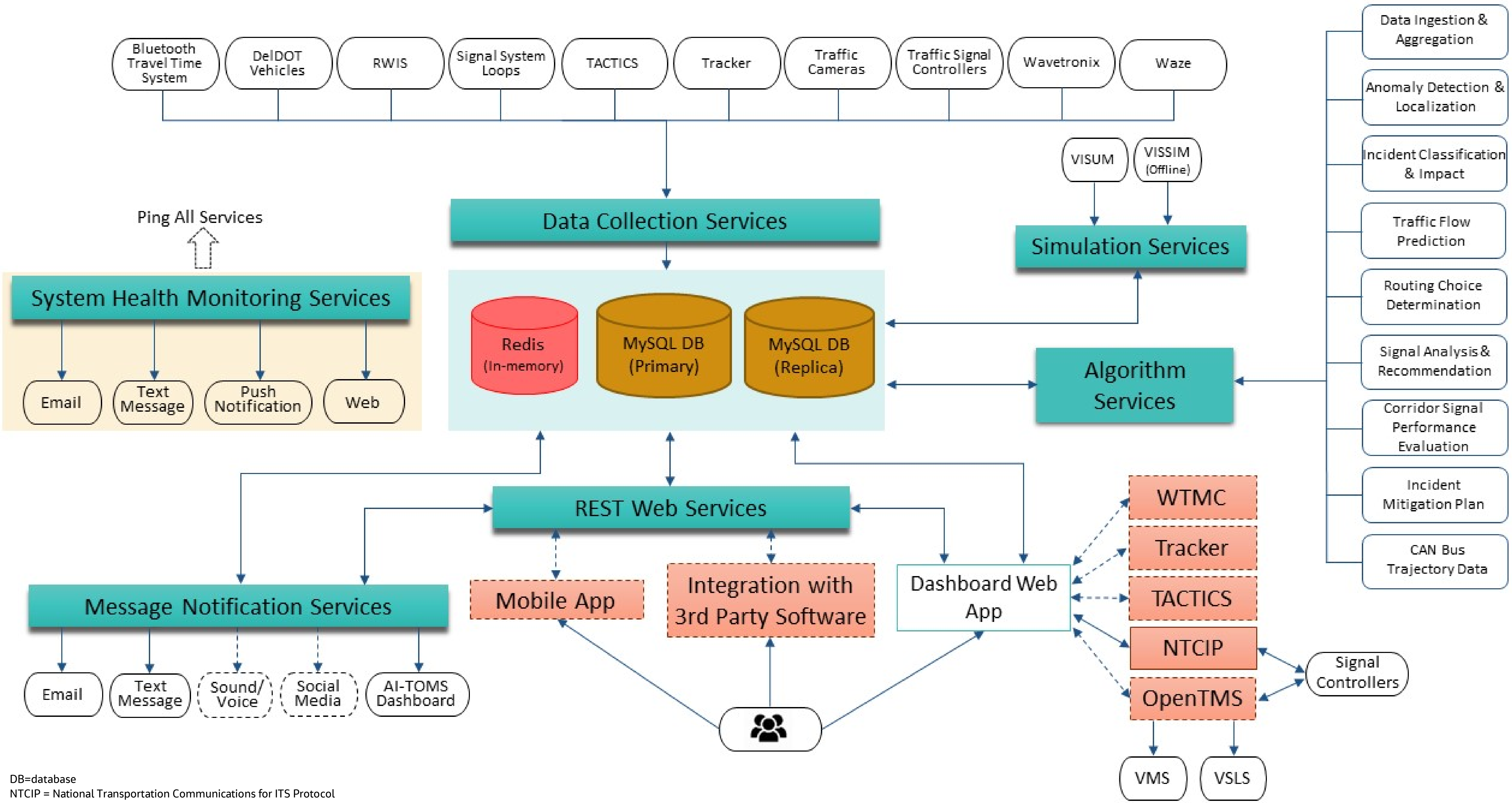
7 Appendix B. Additional Materials

Table B1. Key Functional Services and Supporting Algorithms and Software Services

Key Functional Service	Supporting Algorithms									Supporting Software Services					
	Data Ingestion & Aggregation	**Anomaly Detection & Localization**	**Incident Class & Impact**	**Traffic Flow Prediction**	**Signal Analysis & Recommendation**	**Routing Choice Determination**	**Incident Mitigation Plan**	**Corridor Signal Performance Evaluation**	**CAN Bus Trajectory Data**	**REST Web**	**Message Notification**	**Mobile Services and TIS**	**Signal Timing Implementation**	**System Health Monitoring**	**Simulation**
Automatic Incident Detection	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	No	No	No
Traffic Flow Prediction	Yes	Yes	-	Yes	No	No	No	No	No	No	No	No	No	Yes	No
ATSPM and Signal Timing Optimization	Yes	No	No	No	Yes	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes
Predictive Signal Control	Yes	No	No	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	No
Incident/Event Mitigation DSS	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes
Live SPaT and CAV Applications	No	No	No	No	No	No	No	No	Yes	Yes	No	Yes	No	No	No
System Health Monitoring	Yes	No	No	No	No	No	No	No	No	Yes	Yes	No	No	Yes	No
Machine Vision Traffic Monitoring	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No

CAN = controller area network

Figure B1. AI-TOMS Architecture



DB=database
NTCIP = National Transportation Communications for ITS Protocol
REST = Representational State Transfer
RWIS = Roadway Weather Information System
VMS = Variable Message Sign
VSLS = Variable Speed Limit Signs

Table B2. Evaluation Performance Measures

Name	Deployment Stage Performance Measures	Post-Deployment Stage Performance Measures
Incident Detection Time	Freeway: Incident detection time[1] ≤ **10 minutes** Arterial: Incident detection time ≤ **15 minutes**	Freeway: Incident detection time ≤ **5 minutes** Arterial: Incident detection time ≤ **10 minutes**
Incident[2] Detection Accuracy	Major Incident[3]: **≥ 90%** detection accuracy, Medium Incident[3]: **≥ 85%** detection accuracy Minor Incident[3]: **≥ 75%** detection accuracy	Major Incident: **≥ 95%** detection accuracy Medium Incident: **≥ 90%** detection accuracy Minor Incident: **≥ 80%** detection accuracy
Transportation System Condition Updates	Provide automatic road anomalies/congestion updates every **7 minutes**	Provide automatic road anomalies/congestion updates every **5 minutes**
Notification Update Speed[4]	**≤ 3 minutes** following incident detection	**≤ 1 minute** following incident detection
Notification Update Accuracy[5]	**≥ 95%** accuracy following incident detection	**≥ 98%** accuracy following incident detection
AI-ITMS Approval Rating	***Evaluated Post Deployment only.***	Public: **≥ 70%** approval rating TMC Employee: **≥ 90%** approval rating Stakeholders: **≥ 95%** approval rating
Public Participation	***Evaluated Post Deployment only.***	DelDOT Website: **5% increase** in page views, sessions, and new users DelDOT Application: **10% increase** in downloads
Average Delay Time	No decrease in roadway segment average delay time	**≥ 5% decrease** in roadway segment average delay time
Concurrent Monitoring Capabilities	AI-ITMS simultaneously monitors of **50%** of the DelDOT ITS and internal networks	AI-ITMS simultaneously monitors of **90%** of the DelDOT ITS and internal networks
Benefit-Cost Ratio	Positive ratio of AI-ITMS benefits to cost for specific deployment	Positive ratio of AI-ITMS benefits to cost for entire project
Incident Mitigation Suggestions	Suggestions for incident mitigation are offered in **≤ 5 minutes** following incident detection	Suggestions for incident mitigation are offered in **≤ 3 minutes** following incident detection

1: Timestamp associated with detection of a traffic incident by AI-TOMS.
2: The *Highway Capacity Manual 6th Edition* defines an incident as any occurrence on a roadway, such as crashes, stalled cars, and debris in the roadway, that impedes normal traffic flow.
3: Project team defined major, medium, and minor incidents using *Manual on Uniform Traffic Control Devices* (MUTCD). Major incidents are defined as having a duration longer than 2 hours, medium incidents are defined as having a duration between 30 minutes and 2 hours, and minor incidents are defined as having a duration of less than 30 minutes.
4: The length of time AI-TOMS takes to update traffic/detour notifications across all platforms.
5: The word for word message accuracy AI-TOMS achieves when updating traffic/detour notifications across all platforms.

Name	Deployment Stage Performance Measures	Post-Deployment Stage Performance Measures
Transit Schedule Adherence	**4-5%** improvement in on-time performance (OTP)	**8-10%** improvement in OTP
Preparation for Emerging CAV Technology	Accurately determine the penetration rate of OBU-equipped vehicles broadcasting vehicle to infrastructure (V2I) basic safety messages (BSM) from **30%** of the DelDOT RSU-equipped intersections	Accurately determine the penetration rate of OBU-equipped vehicles broadcasting V2I BSM from **60%** of the DelDOT RSU-equipped intersections
Lessons Learned	List of lessons learned per AI-ITMS deployment phase	Compiled list of AI-ITMS project lessons learned

8 Appendix C. Document Review Comment & Response Matrix

COMMENT RESPONSE FORM
Project Name: ATCMTD
Document Name: ATCMTD Final Report
Reviewer Names: Susi Marlina (FHWA), Edward Fok (FHWA), Margaret Petrella (Volpe)

Page #	Comment	Date	Initials	Response	Initials
iii	Please review whether all acronyms mentioned in the report captured in the table of acronym such as: - CI = Connected Infrastructure - FAST Act =Fixing America's Surface Transportation Act -RWIS To name a few	11/21/2023	SM	Reviewed; changes made throughout the table and document	AQ
1	No comment, but highlighted "final report to the Secretary of Transportation"	11/15/2023	EF	Remove "to the Secretary of Transportation"	AQ
2	"...and executing response solutions to existing and predicted traffic congestion." Are these including recurring and non-recurring events?	11/20/2023	SM	Yes, update to "recurring and nonrecurring" rather than "existing and predicted"	AQ
2	"…alert technicians…" and operators? (if any)	11/20/2023	SM	DelDOT does not use the term operators for this context - update to "DelDOT personnel"	AQ
3	1.3 Project goals - suggest to review the goals/objectives in the technical application on Chapter 2.9 Table 4, please edit if needed.	11/20/2023	SM	Edited Table 1 to be more consistent with language in the technical application	AQ
6	"The system diagram shows the core system architecture where data from various types of traffic detectors and sensors are collected and ingested for near real-time traffic condition monitoring." Consider to add narrative about: TACTICS	11/21/2023	SM	Added language above Figure 3, "...DelDOT has heavily emphasized integrating its traffic signal system, *currently managed by the control system TACTICS* , into the AI-ITMS."	AQ

Page #	Comment	Date	Initials	Response	Initials
9	Overall, DelDOT's final report is very well written and provides an excellent, detailed summary of its project. The map, along with the tables and figures (e.g., Table 3, Figures 2 and 3) are very useful in understanding the project scope and project components. Having said that, the upfront section could be streamlined, so that Evaluation results are presented sooner. The reviewer does not want to cut any of the information, but the more detailed information and tables, such as Table 4 could be put into an Appendix. For the map or background section, one addition to consider is the total corridor miles per study area. DelDOT sufficiently describes the changes in project scope.	1/15/2024	MP	Created a new appendix, "Additional Information" and moved Table 4 there.	AQ
12	Some of the figures were difficult to read (e.g., Figure 6b). Can they be made bigger? DelDOT also will need to ensure that these figures are 508 compliant.	1/15/2024	MP	Figures 6a and 6b were made bigger. An enlarged version of Figure 3 (AI-TOMS Architecture) was also added to the new Appendix B.	AQ
13	"Figure 6 (a) shows an example of vehicle count data compared with loop detector count data" Unsure about this, the loop detector can provide similar to or the same data of the traffic (annual average daily traffic/AADT)?	11/21/2023	SM	Updated language, "Figure 6a shows an example of vehicle volume data *from the machine vision cameras (shown in orange) compared with vehicle volume data from signal system loops at the same intersection (shown in blue). The machine vision volume is more granular, collected every minute compared to the signal system loops' five-minute bins, but shows results very similar to the in-pavement technology* ."	AQ

Page #	Comment	Date	Initials	Response	Initials
13	"(b) shows the detailed vehicle classification counts using 6 tiers of vehicle classification." Is this meant 6 vehicles class like passenger car, truck, bus, etc. instead of 13 vehicle class (FHWA)? Suggest to add the 6 tiers of vehicle class encompasses of...	11/21/2023	SM	Added a footnote, "The six tiers of classification currently collected by machine vision cameras are coupe, sedan, SUV, van, large vehicle, and truck. These classifications are based on common vehicle types and are used internally within DelDOT for monitoring. They are not used for federal Highway Performance Monitoring System submittals."	AQ
14	Found the TACTICS narrative here even though it shows earlier in the AI TOMS Architecture.	11/21/2023	SM	No update needed.	AQ
16	"...all data ingested, manipulated, and output…" wondering whether it can be rephrased to something similar to a process of adjusting data…	11/21/2023	SM	Updated to "processed" rather than "manipulated"	AQ
17	"Moving forward, the project team is looking at possible automated incident detection by combining DelDOT's ITMS data and third-party data sources for future improvement." Suggest to add example of third-party data sources.	11/21/2023	SM	Don't want to mention any vendors by name, DelDOT is not tied to anyone specific right now. Updated language, "Moving forward, the project team *will consider combining DelDOT's ITMS data with third-party data sources to enhance automated incident detection. In order to be effective, third-party data will need to be available to DelDOT in real-time from a trusted and verifiable source as evaluated by the project team* ."	AQ
18	"The freeway incident detection algorithms are simpler since they focus on high-speed, linear traffic patterns." This means: the higher the volumes the lower the speed? Consider to add narrative.	11/21/2023	SM	Updated language, "The freeway incident detection algorithms are simpler since they focus on high-speed, *limited-access facilities separated by direction, resulting in fewer conflict points.* "	AQ
18	"Scores range from 0-100, with a severity score of 70 or higher indicating a possible need for TMC attention." & possible action?	11/21/2023	SM	Updated.	AQ

Page #	Comment	Date	Initials	Response	Initials
18	"...and from the same time of day and day of week in the previous 20 weeks as well as meta data…" the meta data can be from previous year, since 20 weeks prior may not be in the same season, please verify.	11/21/2023	SM	Updated language, "The project team trained new long short-term memory (LSTM) freeway detector models on I-95 and DE 1 in the urban and CAV areas. The LSTM deep learning neural network model utilizing the following input parameters for the training of traffic prediction: •Sample data: Volume, Speed, Occupancy •Metadata (categorical): Month (value 1-12), Day (value 1-7), Hour (value 0-23), Minute (12 possible values in five-minute increments from 5-60), Weather (48 varied weather conditions as defined by Yahoo weather), Holiday (binary 0 or 1 depending on whether it is a holiday or not) The overall input matrix consists of multiple sets of datapoints from the predicting sensor as well as from all the nearby sensors consisting of 20 datapoints from immediately preceding the current sample, 20 datapoints from past 20 days corresponding to the same time of day, 20 datapoints from past 20 weeks corresponding to same time of day and same day of week. The "month" category within the metadata helps account for seasonal variations of traffic within the model. Even if the input data for prediction corresponds to a different season, the model will implicitly capture the impact of seasonal variations. The team also trained arterial system detectors using a graph for time series algorithm (GTS model) along two major signalized corridors—the US 13 corridor in CAV area and the DE 1 corridor within the beach area."	AQ
19	Table 7. Interesting, the historical average or the future value is the same across the board and the Naiive (current value) is different across the board.	11/21/2023	SM	Added language, "The historical average is calculated based on the time of day and day of week, without considering the current datapoints. Therefore, the Mean Absolute Percent Error corresponding to historical average does not depend on the prediction horizon. This means that the prediction of volume for 5 pm on a Thursday will always be a constant regardless of whether it is predicted at 4:30 pm or at 10 am of that day or even 6 months prior to that day."	AQ

Page #	Comment	Date	Initials	Response	Initials
20	"Temporal Oversaturation Severity Index (T-OSI) and Spatial Oversaturation Severity Index (S-OSI). Using this guidance, project team developed a software module in AI-TOMS to calculate the T-OSI and the S-OSI index for arterial signals." Consider to add narrative the difference between T-OSI and S-OSI	11/21/2023	SM	Added language, "...for arterial signals, *two key indicators used to assess overflow queuing in traffic scenarios. the Temporal Oversaturation Severity Index measures the severity of traffic oversaturation over time (e.g., oversaturation due to insufficient green time) whereas the Spatial Oversaturation Severity Index assesses the severity of oversaturation in terms of space (e.g., oversaturation due to a downstream blockage).* "	AQ
20	"The optimization engine calculates CMS using HR or system detector data from the field to determine the ideal cycle length at a given intersection." Any limit on the cycle length apply, such as no less than 60 seconds and more than 180 seconds. So, when the ideal cycle length determines at one intersection, will these be offset and adjusted cycle lengths at other intersections to have smooth progression along the corridor?	11/21/2023	SM	Updated language, "AI-TOMS matches the determined cycle length and progression priority with a known signal timing pattern, *typically with a cycle length ranging from 60 seconds to 240 seconds,* and updates the signal timing in the field within the signal group...The project team is continuing to test the signal optimization algorithm in the field and expand the types of signal timing recommendations the System can make, including offset adjustments and split timing adjustments. *With these advancements and integration of signal offsets and split timings, the System will be able to create and recommend new signal timing patterns not previously stored in TACTICS, implementing them at individual intersections as opposed to whole signal groups. The System will continue to learn what works best in the field and the project team will evaluate any new minimum or maximum cycle lengths that may need to be built into the System.* "	AQ
21	Figure 10. Typo: priority	11/21/2023	SM	Updated.	AQ

Page #	Comment	Date	Initials	Response	Initials
21	"...provide an “optimal” plan with VISUM simulations and SUMO model verifications." How about the model calibration/validation?	11/21/2023	SM	Added language, "More information on the calibration and verification of these models can be found in section 4.6.1 Calibration Criteria. A long-term model maintenance program including periodic validation and recalibration has yet to be determined and will be further investigated as part of subsequent program efforts."	AQ
21	"When...traffic rerouting onto a parallel arterial is necessary…" How's traffic rerouting? By informing drivers via....? input and throughput?	11/21/2023	SM	Updated language, "When traffic is rerouted onto a signalized roadway, this algorithm recognizes the increased demand and recommends signal timing adjustments to TMC staff. *Current instances of traffic being rerouted is a manual one, typically with DelDOT setting up detour routes for long-term closures or drivers self-rerouting based on local knowledge. In the future, the System will be able to automatically determine alternative routes using simulation and modeling (fed by roadway types, travel time information, travel demand vs. capacity, etc.) and then inform drivers through TIS.* "	AQ
25	Simulation Services. Similar comment, how's the calibration and validation process to make sure the model replicates the actual condition, prior to using it?	11/21/2023	SM	Added language throughout section, including references to specific model framework and memorandum documents providing additional detail.	AQ
27	"Field equipment and infrastructure have been installed but still need to be integrated and configured before the system is operational." Agreed, different posted speed limit would result in different second for either driver stop or continue safely through the intersection.	11/21/2023	SM	No update needed.	AQ

Page #	Comment	Date	Initials	Response	Initials
32	The original project goals, objectives, evaluation questions, and performance measures are clearly articulated and adequately described. Tables 8 and 9 are particularly informative….Table 9 should clarify which performance measures are not measured as part of DelDOT's current evaluation. DelDOT may want to remove the column, Post-Deployment Stage Performance Measures, since none of these have been measured (this part of the table could be moved to the Appendix). For the Deployment Stage Performance measures, a footnote or note should be added to the performance measures that are either not measured or have changed. For example, transit schedule adherence is not measured. And BCA presents a qualitative assessment. The write up does include the data collection time periods, but it would be helpful to see this information in a table. Perhaps this information could be added to Table 9, particularly if the column of Post Deployment measures is removed.	1/15/2024	MP	The "post deployment" column from Table 9 was moved to the new Appendix B. A new column was instead added to Table 9 in the report body noting the evaluation period for each measure, or stating that the measure was not evaluated with reference to specific sections for further reading.	AQ
38	Equation 2. I think this should be called "aggregate incident detection accuracy" to clearly say it is the aggregate accuracy during the operational period.	11/16/2023	EF	Updated.	AQ
42	both equation 3 & 4 should be labeled as "Average Incident xxx Notification Speed Formula"	11/16/2023	EF	Updated.	AQ
43	Table 19. from page 35 there were 105 incidents during the evaluation period. I think there should be enough data to generate a sigma value for these average performance values.	11/16/2023	EF	No update needed. With negative values, the standard deviation does not provide value to the analysis.	AQ

Page #	Comment	Date	Initials	Response	Initials
46	Table 20. any info about non-standard traffic signal, it can in percentage or total number. I think the reason it's not included is described in Chapter 4 - challenges	11/21/2023	SM	Updated language from "standard" to "intersection traffic signal" instead. The intention was to describe all red/yellow/green traffic signals throughout the state.	AQ
47	"Therefore, the evaluation team concluded that our initial goal of performing a quantitative benefit-cost analysis for the project's deployment phase was set too high." Further description may need to add.	11/21/2023	SM	Updated language, "Given these challenges, the evaluation team does not have an adequate sample period to pull data from for a full quantitative benefit-cost analysis, nor does the evaluation team have enough information to meaningfully project quantitative benefit-cost analysis for the deployment phase of the project. Therefore, *the evaluation team concluded that they did not have the scale of data necessary to complete the quantitative benefit-cost analysis that was initially scoped.* "	AQ
61	I don't understand what we have blockchain reference here. this project did not deploy any blockchain base techniques. Should we really be listing papers that mentioned the project? Or should we focused on papers that the project extensively utilized or were written directly out of the work done by this project?	11/16/2023	EF	Although the project didn't directly explore blockchain techniques, its data/insights significantly contributed to informing the proposed approaches highlighted in these papers (e.g., traffic prediction/management). Updated language, "*The work done on this project had a broad influence, accelerating and enabling research within this space. The data and insights gathered by the project team were critical in developing methodologies for the* 12 peer-reviewed articles, listed below, published in prestigious journals and highly competitive conference proceedings."	AQ
62	Outreach. this is good. can we also have the location where the presentation or publication can be located for each of these 10 references?	11/16/2023	EF	Added sentence, "Copies of these presentations may be available from DelDOT upon request."	AQ

Page #	Comment	Date	Initials	Response	Initials
64	Summary. I am wondering to add a brief summary of the technology readiness level for AI-TOM Services per Table 5 on page 11.	11/21/2023	SM	Added TRL table and additional sentences for context.	AQ
66	Appendix A. How big of a confusing map will it be to show the locations of these incident within the project area?	11/16/2023	EF	No update. The map would not provide much context to the reader. Appendix A is more focused on the comparison of Tracker vs. CAD data for each incident, not the specific locations. All crashes are within the project study areas.	AQ
email	It seems some of information were stitched from over 12 peer-reviewed articles. The draft needs to be updated per comments to be seamless with dense information provided.	11/22/2023	SM	Updated comments per responses above. The 12 peer-reviewed articles were influenced by this project (and vice versa, to a degree), but this report was put together independently of these articles.	AQ