Michigan Department of Transportation

Integrated Mobile Observations 3.0

Connected Vehicles for Road Weather Management

PROJECT SUMMARY REPORT

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16. Abstract

The purpose of the Integrated Mobile Observation 3.0 (IMO) project is to support the Michigan Department of Transportation (MDOT) and its partners in evaluating uses and benefits of connected vehicle and environmental data in transportation agency management and operations. The project complements efforts throughout the transportation community in designing and deploying connected vehicle infrastructure, vehicle equipment, and initial applications and investigates how data from connected vehicles may benefit the ways MDOT and other transportation agencies perform business. The MDOT Data Use Analysis and Processing (DUAP) research has been constrained by the relative unavailability of connected vehicle data, but has successfully demonstrated: the capability to collect, aggregate, process and provide data from connected vehicles; the pragmatic acquisition of diverse data from a variety of sources; and the development of applications that may enhance weather responses, traffic monitoring, and condition assessment. The project concludes that there is substantial potential for the use of connected vehicle data in transportation management and operations. It is recommended that the next phase of research focus on development of reliable data sources and specific applications for implementation in MDOT.

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EXECUTIVE SUMMARY

The purpose of the Integrated Mobile Observation 3.0 (IMO 3.0), Connected Vehicles for Road Weather Management, project was to support the Michigan Department of Transportation (MDOT) and its partners in evaluating benefits of enhancing their current data sources with connected vehicle data for transportation agency functional area uses. The IMO 3.0 project focused on collecting weather-related observations from connected vehicles and mobile data acquisition platforms such as Vehicle-based Information and Data Acquisition System (VIDAS). The project investigated the use and viability of the data collected in conjunction with other agency's systems such as the National Center for Atmospheric Research (NCAR) Pikalert™ Vehicle Data Translator, Federal Highway Administration (FHWA) Weather Data Environment (WxDE), and MDOT's Wx-TINFO. As such, the project complements parallel efforts of MDOT, the U.S. Department of Transportation (USDOT), the Vehicle Infrastructure Integration Consortium (VIIC), and others to design and deploy the connected vehicle infrastructure, vehicle equipment, and initial applications. This project builds on that foundational work to investigate how the availability of data from connected vehicles throughout the road network may impact the ways MDOT, the USDOT, and other transportation agencies perform business.

The IMO 3.0 project has shown how the increase in availability of connected vehicle data, along with the expansion of existing transportation and infrastructure data, continually improves the information available to the agency. It expanded the MDOT Data Use Analysis and Processing (DUAP) project to further examine how the weather-related data within the DUAP system can be integrated with the collection of additional mobile weather observations to be used in supplementing the agency's information when formulating and guiding road weather management responses.

The mobile nature of this data increases the coverage of weather observations from fixed stations by allowing the agency to collect data where gaps in the data exists and in locations most affected by the weather. The available data is based on the sensors installed on the vehicles. For this

project, the mobile weather observations include ambient temperature, surface temperature, humidity, barometric pressure, and dew point along with other vehicle data such as position, speed, and acceleration.

MDOT's VIDAS system is a mobile vehicle platform installed on many agency fleet vehicles that collects data from the vehicle and sensors on the vehicle. Incorporating the VIDAS system provides the ability to collect weather observations from a variety of sensors and provides additional flexibility that was not available using the smartphones for the IMO 2.0 project. For this project, vehicles were equipped with the VIDAS platform, Surface Patrol sensors, and accelerometers to provide information concerning the pavement surface along with atmospheric conditions.

The VIDAS platform includes the ability to transmit this environmental data directly to the back office via cellular. This ability provides DUAP with current information which is used to determine the impact of weather on the traveling public. This information can then be relayed to the agency and the public to assist in guiding weather maintenance plans, travel suggestions, emergency responses, etc.

In addition, the vehicles were equipped with On-Board Units (OBU), which were integrated with VIDAS to provide the Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) capabilities. This data provides details such as current traffic flow and changes to the flow caused by events such as incidents, weather impacts, or traffic signals, to name a few. This data can also be received by the back office as additional information used by the DUAP system.

The DUAP system was responsible for forwarding the weather data received from the connected vehicles and the VIDAS platform to both NCAR and WxDE (Weather Data Environment) external systems in support of these related weather initiatives with the FHWA.

The project has successfully worked through a disciplined system engineering process to develop and demonstrate applications leveraging existing connected vehicle system capabilities. These applications used the mobile weather observations from the OBU and the VIDAS platform installed on the MDOT vehicles to assist in determining the types of weather affecting the state and reporting this information to the operations functional area.

The architecture design for the connected vehicle (CV) deployment had to consider the existing infrastructure and its limitations. The solution implemented was able to deal with a lack of communications backbone to the intersections which were equipped. The data from the RSUs had to be transmitted to one of the central intersection's signal controllers which then transmitted the data from all of the RSUs to the back office. While this deployment was relatively small in size, this solution would not be able to manage a deployment with a large number of equipped vehicles and intersections. The line of sight restriction on the radios limits the locations this solution can be deployed. Large scale deployments add complexity in working around this restriction, depending on the geographical topology, existing infrastructure, and building density. The processing ability and allowable data flow through the central radio also restricts the number of intersections and vehicle data which can be processed and forwarded to the back office per central radio.

1 INTRODUCTION

This document summarizes the results, accomplishments, and lessons learned from the MDOT's IMO 3.0 project. It also includes recommendations for further research and development and provides an interface specification for potential data providers.

As a progressive expansion of the integrated mobile observations collected by smartphones in the IMO 2.0 projects, IMO 3.0 introduced CV technologies in both vehicles and infrastructure along with a robust mobile platform to provide flexibility in the type of data being collected.

1.1 Background

1.1.1 Objective

The IMO project aimed to capture mobile weather observations from sensors connected to the VIDAS platform to supplement observations from existing fixed sensors and data sources to enhance winter maintenance reactions to events affecting the traveling public and to provide more detailed information to the public to assist in dealing with the weather threats and hazards. It is thought that these enhancements can improve safety, improve the effectiveness of the DOT's winter maintenance activities, and increase mobility.

Leveraging the DUAP system, for the IMO 3.0 project, takes advantage of an existing system which uses weather data to formulate event warnings to the agency and the public based on a variety of data sources. Increasing the amount of mobile data ingested by the system increases the coverage and detail of weather events occurring throughout the state. The DUAP system can also disseminate the data to other external systems in support of additional FHWA weather research activities.

1.1.2 Scope

The purpose of the IMO 3.0 project was to support USDOT, MDOT, and its partners in evaluating uses and benefits of CV data in transportation agency management and operations. As such, the project complements parallel efforts of MDOT, the USDOT, the VIIC, and others to design and deploy the CV infrastructure, vehicle equipment, and initial applications. The project builds on that foundational work to investigate how the availability of data from CVs throughout the road network may impact the ways transportation agencies manage the transportation infrastructure. The project focused specifically on the uses and benefits of weather-related data in responding to safety concerns, managing traffic, and managing MDOT's transportation assets. The work also supported other CV projects, technology development for MDOT, and economic growth for the state.

As illustrated in Figure 1, the IMO 3.0 project provides additional mobile source data to the DUAP system which is integrated with existing MDOT data sources, both fixed and mobile, along with other relevant data. The integrated system output can be returned to the existing MDOT and FHWA systems and applications as an enriched data stream providing value to these other applications and research initiatives.

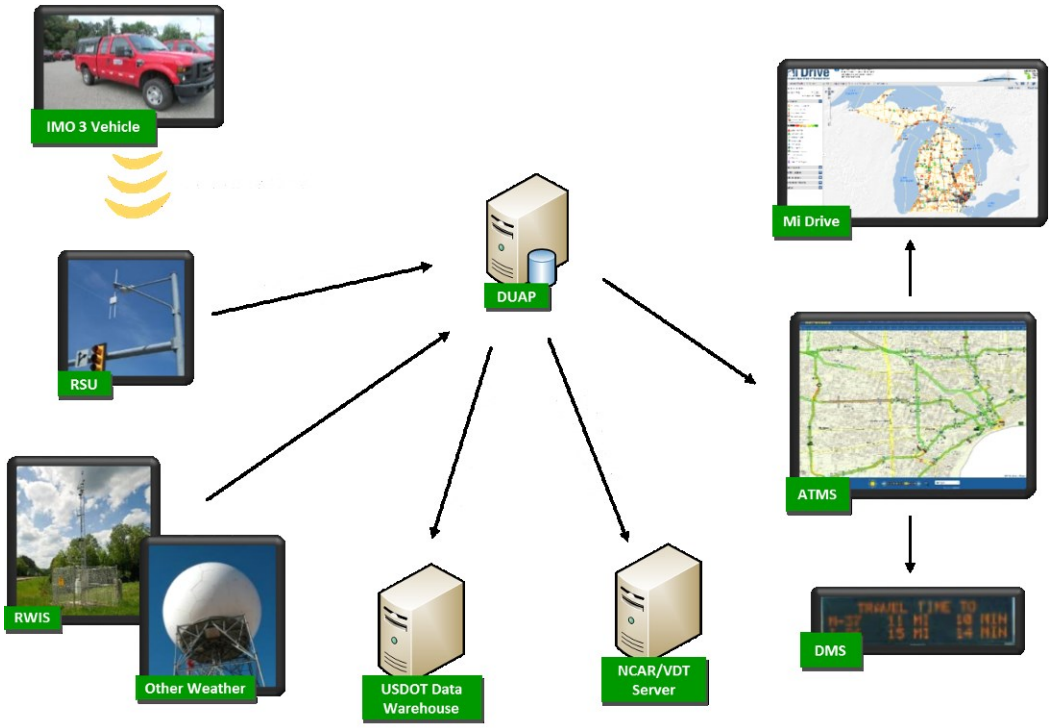

Figure 1 – IMO 3.0 and DUAP Data Flows

A portion of the Saginaw Highway corridor in Lansing, MI, shown in Figure 2, was equipped with nine Road-Side Units (RSUs) as part of the CV deployment. The corridor is approximately five miles in length and comprised of a typical 5-lane cross-section consisting of four lanes with a common turning lane in the center. The Saginaw Highway corridor is a major arterial that contains urban, suburban, and rural facility characteristics. This section of the Saginaw Highway carries approximately 22,000 Annual Average Daily Traffic (AADT) and I-96 carries approximately 50,000 AADT.

Figure 2 – Saginaw Highway Corridor in Lansing, MI

The 9 intersections equipped for this project include:

1. M43E and Marketplace Blvd (MM0194)
2. M43E and I-96-2 (MM0199)
3. M43E and Canal Road (MM0201)
4. M43W and Creyts Road (MM0211)
5. M43W and Mall Drive (MM0216)
6. M43W and Elmwood Road (MM0221)
7. M43W and Robins Road (MM0225)
8. M43E and Waverly Road (MM0231)
9. M43E and Rosemary Street (MM0007)

1.2 Statement of Hypothesis

The IMO 3.0 project hypothesizes that data from CVs in conjunction with other related data sources can be leveraged to provide the agency with details concerning weather-related threats and hazards to improve their response to these events. Expanding the amount of information beyond the fixed weather sensors to include CVs and other mobile platforms improves the data coverage across the state. It expands the data sources of the original DUAP project to include a variety of transportation related data in addition to the CV data studied in the DUAP project. Applications within the system can use this data to provide information in different forms based on each functional area's needs. In addition, this data can be shared with other external systems to provide them with more information. This sharing of data will demonstrate the increase of value to the entire agency.

2 METHODOLOGY

2.1 Experimental Design

The experimental design for the IMO 3.0 project followed the system engineering design process. System development projects should follow a disciplined systems engineering process from planning through operations. Indeed, the use of a standard systems engineering process is a requirement of Title 23 of Code of Federal Regulations (CFR) Section 940.11, which defines eligibility for Federal Intelligent Transportation System (ITS) funding.

The process used for the IMO 3.0 project started with determining the scope and objectives of the system through stakeholder meetings.

The IMO 3.0 project's use of the existing DUAP system and its expansion of data ingested by DUAP did not require a modification of the overall concept of the DUAP system. Therefore, a concept of operations was not required for this project. Additional user needs and requirements were, however, addressed in an abridged System Requirements Specification (SRS). The SRS contains details of the changes to the existing DUAP system describing system functions for each of the system's major components; design constraints presented by policy and standards; quality characteristics; and any external factors that may impact the system design based on changes for the IMO 3.0 project.

The abbreviated System Architecture Description (SAD) identifies the changes to the system's components and describes its internal and external interfaces based on the changes identified in the IMO 3.0 project.

The abbreviated System Design Description (SDD) documents the intended system changes to address the requirements as specified in the SRS based on the IMO 3.0 project. The documentation describes each component and its interfaces in detail. Both the SAD and SSD documents will be published at a future date by MDOT.

2.2 Project System Architecture

The IMO 3.0 project was based on the presumption of data being available from the efforts of CV projects along with other mobile platforms, such as Automatic Vehicle Location (AVL) and VIDAS. The IMO 3.0 project includes equipping additional vehicles with the VIDAS platform and on-board units (OBU) to provide V2V and V2I communication capability.

Intersections in Lansing Michigan along the Saginaw Highway (State of Michigan Trunkline; M-43) corridor, as shown in Figure 2, were equipped with RSUs to provide the infrastructure for the CV deployment. The corridor installations included Cohda RSUs at nine intersections chosen by MDOT. The RSUs were connected to the existing MOD 50 Siemens controllers.

The Siemens Model 50 controllers have Siemens ACS Lite software installed for their operation. These controllers supply the signal phase and timing information to the RSU. The RSU is then able to encode and broadcast the Society of Automotive Engineers (SAE) J2735 Signal Phase and Timing (SPaT) message along with the associated SAE J2735 Map message configured on the device.

Existing and new VIDAS installations were used for integrating OBUs into nine MDOT vehicles to provide Basic Safety Messages (BSM) to be captured by the RSUs along the corridor. The BSMs contain information concerning the vehicle's current status including location, speed, and heading. These BSMs were to be forwarded to the DUAP system to be integrated with the other information received; however, this functionality is still pending deployment.

In addition to the BSM data, the VIDAS platform included weather sensors to capture weather-related data not provided by the BSMs to supplement the data available to the weather processes and algorithms within the DUAP system. The weather and vehicle data are used for formulating information concerning the current weather and road-weather conditions.

The DUAP system includes functionality for sending its data to other systems. For the IMO 3.0 project, this functionality was used for forwarding the weather information from the VIDAS installations to NCAR and the WxDE systems to support their programs.

Data from the MDOT AVL equipped winter maintenance trucks (WMT) or snow plow trucks were also ingested by the DUAP system. This provided additional observations leveraging existing equipped vehicles' information.

The data from these mobile systems, along with information from the National Weather Service (NWS), provided the DUAP system with data concerning the condition of and impacts on MDOT assets, including pavement, the traveling public, and CV testbeds.

As was shown in Figure 1, the DUAP system collects data from many different sources, stores that data, and applies algorithms to the available data—new and previous—to support existing and new MDOT applications. The output from the DUAP system can be used to assist the agency in managing their assets, to feed information to other systems, or as an application in a geographic context supported directly by the user interface described in this section.

The DUAP system is built upon a foundation of modular computing blocks. This modular approach provides flexibility to the system in that all possible data sources, analysis algorithms, and applications are indeterminate. The modules involve ingestion from a variety of data sources, data management to quality check and analyze data, and consumption to supply information to the user and other systems. Command and control functionality is utilized to communicate, manage configuration, and receive data from field devices. These concepts are illustrated in Figure 3. Constructing the DUAP system with a singular purpose from what was known at the time would have potentially limited its future application and increased the costs associated with updating it.

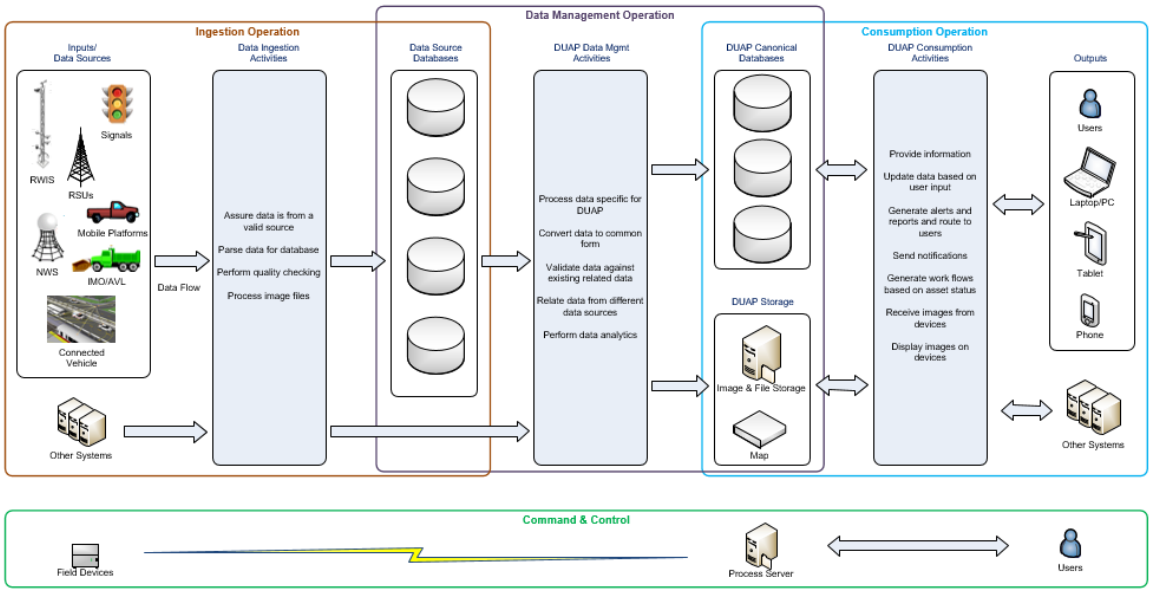

Figure 3 – DUAP Process Interactions

2.3 Procedures

This section provides an overview of the changes to the DUAP system to support the IMO 3.0 project. Details include the user interface, data sources ingested to support the applications, security, and the storage model for the data. The descriptions of these facets of the system further explain the procedures the system uses and how the system provides the necessary information to support the agency.

2.3.1 User Interface

The user interface is the core application for the consumption phase of the system as shown in Figure 3. Other aspects of this phase will be described in subsequent sections.

The web application is viewable on browser equipped computers and devices such as tablets and smartphones. Where possible, a responsive GUI (graphical user interface) design is employed to provide the user with a quality experience regardless of the type of device being used.

The interface provides the tools needed to visualize the CV and weather data in a geographic and time-related context. The user selects which information to display for a particular time range. In addition, the time zone is based on the device on which the user is viewing the application.

The applications interact with the user in the following ways.

- Map – a geographic display of information
- Reports – report-based views of observations ingested by the system, such as traffic speeds
- Analysis – graphical views of observations ingested from the VIDAS system, such as the acceleration (in G) as measured by the accelerometry sensors
- Data entry – allows users to enter or modify information in the system for a variety of purposes including configuring field devices, entering traffic flow restrictions, and modifying user information.
- Feedback – a link to allow the user to email the support team with comments, issues, or suggestion concerning the DUAP system

The primary screen displayed to the user is a map view. This provides a geographic context of the various observations captured by the system. Map controls allow panning and zooming in and out, and to display a plain map background. This screen provides a variety of applications which can interact with each other.

The screen provides the ability for users to select various items to be displayed on the map based on time, locations, and information types. Associating time with data can be complex, but users generally work to their current local time. The code handles this by converting the local time for the user to Coordinated Universal Time (UTC) when requesting time-based data. Different types of information can be displayed to provide a clearer picture of what is happening on the infrastructure.

The vehicle related applications contain selections for viewing data related to roads, vehicles and their movements. The vehicle specific information includes data from AVL, VIDAS, and OBU equipped vehicles. The user can select to view the paths of a specific vehicle or all of the vehicles of the selected types during the specified time frame. There is also the option to animate the trip and view the details of the collected data as the vehicle(s) moved along the road. Depending on

the equipment installed, this detailed information can include location, speed, front facing camera image, ambient temperature, surface temperature, humidity, dew point, plow status, treatment materials and pavement condition along with other related data elements.

The Weather application contains selections for weather related information including observations from state and NWS-owned fixed weather stations. NWS radar is also available based on the radar installations and various radar types including precipitation and storm motions. In addition, the user can view the weather alerts created by the system based on these and other observations. Two views of the alerts are included to provide separate detailed and aggregated views. The aggregated information is also passed to MDOT's Advanced Traffic Management System (ATMS).

The traffic-based information includes traffic detection, CCTV images, message signs, lane restrictions, incidents, traffic signal phases, and CV RSU status. This information can supplement the weather-related observations for verification of types and extent of weather impacting the roads.

Most observations displayed on the map include an option to view additional detailed information via popups or detail panes on the screen. This information can include

- Metadata from field devices such as weather sensors, traffic sensors, dynamic message signs, cameras, etc.
- Observations collected by the field devices at a time specified by the user
- Data from winter maintenance vehicles equipped with AVL, specifying whether a plow was down and whether road treatment materials were being applied
- Weather alerts which are color coded to specify the type of alert being displayed.

The user interface allows the user to turn on and off selections throughout the application. This allows for easily changing selections to be displayed to target the information required for a selected task.

The Vehicle tab also displays the latitude and longitude coordinates of any location clicked on the map. This information is provided so the user can get a better sense of relative scale and distances to known landmarks.

The Reporting application allows the user to select criteria for generating reports based on the ingested data.

Reports can include a graphing option based on the observations such as displaying microwave vehicle detection systems (MVDS) data for a selected location in a graphical form. Together the two forms of presenting observations ingested by the system provide a variety of tools to assist the agency in interpreting data from their systems and infrastructure. This process has been designed to easily incorporate additional reports based on data ingested by the DUAP system.

The Analysis applications provide graphical views of data, such as accelerometry data ingested from VIDAS devices. The view includes graphs for each of the accelerometer's axes. This graphing tool allows the user to see values at any given point along the graph and how the graphs relate. The accelerometry data is in three axes as depicted in the graphs. A fourth graph contains the net vector of the three axes.

The Configuration application allows authorized users to make configuration changes to field devices such as the VIDAS platform. This provides the ability to modify aspects of the platform and the metadata around its installation. The user can configure the mobile platform to specify which sensors are installed and their location on the vehicle. This information allows the DUAP system to ingest and process the data that the platform collects. Additional information detailing this process will be further described below.

2.3.2 Security

Multiple levels of security have been employed within the DUAP system to ensure the integrity of the system and its data.

The DUAP GUI requires user authentication to access its applications and their functionality. Each user can be assigned specific permissions to control which applications and functionality within these applications that they have access to use. This granularity provides the ability to assign access to only the processes required by the user to perform their work.

The ingestion processes use a variety of methods to ensure the integrity of its data including various quality checking algorithms, verifying the source of the data, and controlling how data is received.

Through these methods and others not mentioned, a multitude of processes keeps a vigilant watch over the system for a variety of security risks. The goal is to follow and expand on best security practices to help ensure security for the system, its data sources, and all entities interfacing with the system.

2.3.3 Data Sources

For the DUAP system to be able to perform useful work, it must have data from a variety of sources. The design of the DUAP system necessarily accommodates this variety of data sources through its modular architecture. No single data representation mechanism exists that will accurately convey information in every possible instance. The best approach is to create collection software that can deal with source data in its native format and copy what it defined as relevant to the DUAP system.

Leveraging the DUAP system and its current data sources for the IMO 3.0 project provides a foundation for investigating the use of CV data for road weather applications. The project expands the coverage of the system's data sources through additional vehicle and infrastructure deployments.

Data received by the system, specifically non-CV data, involves a variety of data formats. Evidence suggests that the most popular data formats for information exchange are text-based—humanly-readable letters and numbers. Both character-delimited text, JavaScript Object Notation (JSON), and XML (extensible Markup Language) are text-based data exchange mechanisms. The former typically defines columns by a header record, with data separated by a special character with comma, semicolon, tab, and space being popular choices. The latter uses tags formatted to the XML standard specification to identify data elements.

In addition to textual data, the DUAP system can ingest binary data which CV technologies use almost exclusively for the data messages, including BSMs and SPaTs. This data follows the SAE J2735 standard and uses the ASN.1 (Abstract Syntax Notation) format as specified by the SAE J2735 standard. This functionality was used throughout the IMO 3.0 project to support the CV data from the equipped vehicles and intersections along the corridor and transmitted by the OBU and VIDAS equipped vehicles.

The data sources related to the IMO 3.0 project's goals are ingested by the DUAP system for its applications are further described in the following sections.

2.3.3.1 VIDAS Platform

MDOT fleet vehicles equipped with the VIDAS platform provide mobile data to the DUAP system. The VIDAS platform, Figure 4, provides the ability to install a variety of sensors on a

vehicle. The currently installed sensors collect data about the vehicle's mobility and the environment including the pavement surface.

The platform installed in support of the IMO 3.0 projects consisted of:

- Eurotech Reliagate 10-20
- Cellular and Wi-Fi connectivity
- Cohda MK5 OBU
- YEI 3-Space Sensor
- Vaisala Surface Patrol
- Antenna (GPS, Cellular, Wi-Fi)

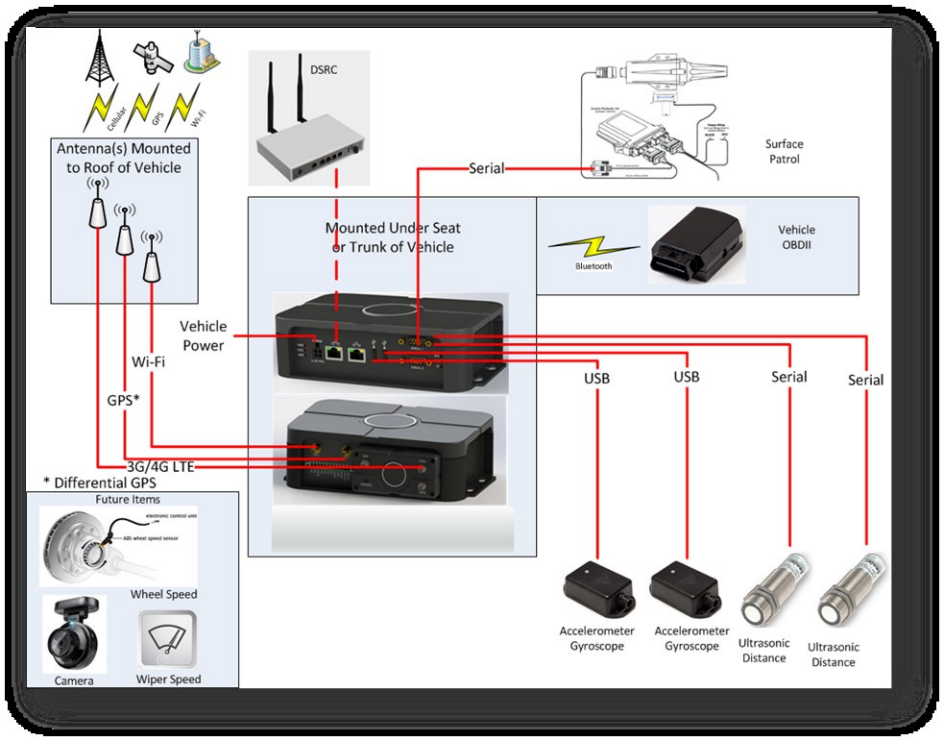

Figure 4 – VIDAS Mobile Platform

The platform was installed on nine MDOT operated Ford F-150 trucks (seven new vehicles and two vehicles from a previous effort). These trucks are located in the Lansing, Michigan area. Some of these are located at the Grand Ledge garage to be near the IMO 3.0 deployed infrastructure on the M-43, Saginaw Highway. This provided a base set of vehicles to monitor for the project. The other vehicles chosen for the project were based on the number of miles the drivers cover each week.

The mobile platform is able to collect a variety of observations, such as:

- Latitude
- Longitude
- Date/time
- Vehicle speed
- Heading
- Ambient air temperature

- Surface temperature
- Humidity
- Dew point
- Accelerometry

The mobility data is needed near real-time since the weather information is time sensitive and is transmitted via cellular at a configurable frequency. The DUAP system receives, ingests, quality checks, and analyzes the data.

This data is used by the system in determining current weather conditions and vehicle status. Analytics are performed on the data after ingestion to glean the information important to the agency.

2.3.3.2 Connected Vehicles

For the IMO 3.0 project the number of vehicles equipped with OBUs and VIDAS was expanded by five additional vehicles (for a total of 14 vehicles). The project focused on the M-43, Saginaw Highway corridor in Lansing, Michigan. The installation of ten RSUs along the stated corridor provides feedback to the DUAP system from the CV deployments. This area was chosen based on its features, including:

- Four lane road
- Major arterial
- Urban characteristics
- Suburban characteristics

The Saginaw Highway corridor had limited access to communications with the MDOT network and no access to the back office. To solve this issue, the intersections were equipped with Proxim 954 5GHz radios (point-to-point communication repeaters) to transmit their information to a central intersection's radio. This limited the amount of back office connections and cost needed to support the infrastructure (e.g., this configuration eliminated cellular modem communication backhaul at each intersection). Of the nine intersections, only the central intersection was equipped with a Digi Transport WR21 router. The router provided the ability to communicate between the back office, RSUs, and Traffic Signal Controllers to allow the back office to manage the device configuration and allow for the transmission of the messages from the devices to the back office.

Figure 6 shows the equipment installed at the at the central intersection, Mall Drive (Figure 2 intersection 5) which in addition to the RSU communications, acts as a hub for the intersections and all communications to the back office. This equipment includes the additional radio to communicate with the other intersections and the networks components, firewall and modem, which are required to communicate with the back office. The equipment for the other intersections, (Figure 2 intersection 1, 2, 3, 4, 6, 7, 8, 9), is shown in Figure 6. This includes the RSU, a radio to communicate to the central intersection, and a switch for communications between the devices.

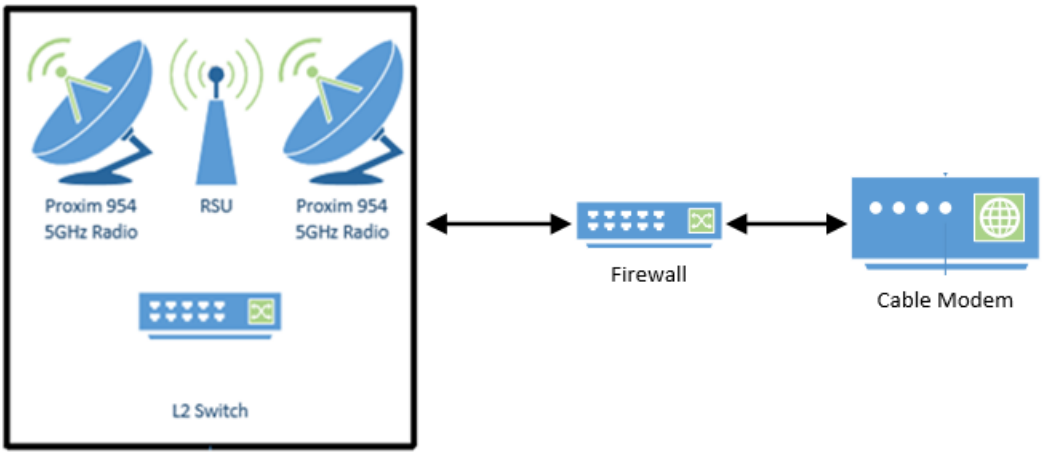

Figure 5 – Central Intersection Equipment

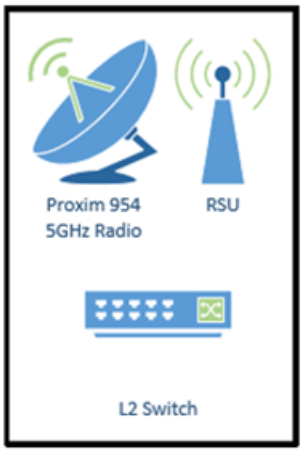

Figure 6 – Standard Intersection Equipment

Each intersection was equipped with a Cohda MK5 RSU. The RSUs were connected to the Proxim radio through a network switch to provide connectivity. The RSUs were also connected to the traffic signal controller for the intersection to provide the signal phase information to the RSU. The RSU uses this information along with the installed SAE J2735 MAP message details to create the SAE J2735 SPaT message. Both the SPaT and the MAP messages are then broadcast.

The RSUs are also able to send messages they receive from the vehicles to the DUAP system in the back office. BSMs from the OBU equipped vehicles are received by the RSUs. These messages are forwarded to the DUAP system for ingestion. The BSMs primarily contain information about the vehicles location and movement. Additional information may be included depending on the OBU vendor and configuration of the OBU.

This data is integrated with the other weather and traffic related data to formulate information about the current weather situation. The Weather Response Traffic Information System (WxTINFO) functionality of the DUAP system has been leveraged for this IMO 3.0 project to perform these tasks. The expansion of the available data for the system installed for this project

provides a more complete image of the weather situation in the Lansing, Michigan area. Together, this provides the agency with enhanced information concerning the weather events affecting the infrastructure and the traveling public.

The DUAP system can also display the vehicles movements based on user selected criteria. This information can be used by the agency in a variety of ways including traffic movements and conditions, queue lengths, and traffic signal phase timing.

2.3.3.3 Weather Observations

The DUAP system receives a variety of weather related observations including:

- NWS radar
- NWS sensor data
- NWS warnings and alerts
- NWS forecast data
- Road Weather Information Systems (RWIS) observations
- Automated Surface Observation System (ASOS) and Automated Weather Observing System (AWOS)
- Mobile environmental data

The National Weather Service operates four radar installations in Michigan. The radar JPG images from each station are gathered into the DUAP system from NWS internet-based sources. The images are analyzed to determine the location of precipitation. As this functionality expands in the future, additional information about storm movements can be integrated into the system.

Other NWS observations include current condition data from ASOS and AWOS installations throughout Michigan. These conditions include temperature, barometric pressure, dew point, wind speed and direction, and precipitation information. These CSV files are obtained from the NWS websites based on the station.

NWS also supplies information about warnings, alerts, and forecasts that they have issued. The system gathers this information for Michigan from the NWS site for ingestion and use in the weather applications.

In addition to the NWS installations, MDOT maintains RWIS installations across the state. These include sensors for detecting a variety of weather related data including but not limited to:

- Ambient temperature
- Pavement surface temperature
- Roadside subsurface soil temperature
- Humidity
- Barometric pressure
- Wind speed and direction
- Camera image
- Precipitation

DUAP contains a list of all the NWS and RWIS installations for Michigan from which it gathers the observation data.

Upon ingesting this data, the observations are vetted against each other to determine their quality and brought together to provide a more complete picture of the current weather situation. Analytics are performed to create weather-based alerts to provide users, MDOT's ATMS, and other agency systems with details about weather impacts on the agency and its assets.

2.3.3.4 AVL

All MDOT's WMTs (approximately 320 maintenance trucks) have AVL devices installed. The DUAP system can ingest this data which consists of information about the state of the vehicle, plow usage, and winter maintenance material distribution. MDOT supplies this information to DUAP as a subset of the data points throughout the day. Only 1 data point per vehicle per minute is transmitted in this data feed. A nightly complete data file provides more data points to complete the information.

This data can be used by the agency in multiple applications including:

- Displaying location of maintenance vehicles
- Displaying routes covered by the vehicles
- Tracking winter maintenance activities such as plowing and distributing materials
- Tracking effects of plowing and use of material on pavement surfaces
- Determining efficiencies from Performance Metrics and vehicle usage
- Disseminating vehicle information to a public facing website
- Front facing camera images of the road condition from the vehicle

2.3.3.5 Traffic Signal Phase and Timing

Some traffic signal controllers within Michigan are equipped for sending their phase and timing data to the DUAP system. This includes the current phase group being displayed and the time remaining until the next phase change.

The DUAP system uses SAE J2735 MAP message data to determine the phase for each lane specified in the MAP and is able to display this information for monitoring the status of the intersection.

2.3.4 Data Feed to External Systems

Using the DUAP system for the IMO 3.0 project allows for sharing the data from the CV and VIDAS deployment with a variety of DUAP applications and external systems. This includes sharing the weather-related data from the VIDAS and OBU equipped vehicles through subscriptions to the data. Subscriptions were setup in the DUAP system to send the IMO 3.0 data to both the WxDE and NCAR for use with the Vehicle Data Translator (VDT). This process supplements the data for these other research initiatives while also being able to leverage the data in the DUAP applications supporting MDOT including the WxTINFO application which supplies information to MDOT's ATMS.

3 FINDINGS

The IMO 3.0 project has shown the viability of collecting information from CV deployments, along with other mobile platforms, to be used for identifying weather-related situations affecting the traveling public. Leveraging the DUAP system provided new and existing functionality which was used for analyzing the weather events and for sharing the collected data with other weather and operational systems used for assisting the agency in managing their response to the events.

The following sections further explain the use of the systems and the findings of the project.

3.1 Summary of Projects and Applications

The following sections describe the related projects and applications developed for or used in support of the IMO 3.0 project. The descriptions include the information produced by the applications related to and used by the systems identified in the IMO 3.0 project.

3.1.1 Projects

The projects used in the IMO 3.0 project are described below to provide additional context to the functionality available and used to support the project.

3.1.1.1 Connected Vehicles

MDOT has operated and been involved with multiple CV test beds and installations. These installations have included a variety of brands of RSUs and OBUs. Field tests have included the ability to:

- Broadcast SPaT and MAP messages at equipped intersections
- Broadcast Traveler Information Message (TIM) messages for traveler information including speed limits and curve speed warnings
- Broadcast CAMP Basic Information Message (BIM) messages containing details about work zones
- Capture BSM messages by the RSUs

RSUs must be configured with the proper message information to be broadcast. MAP, TIM, and BIM message details can be loaded on the RSUs remotely to avoid the requirement to visit the device for configuration changes.

Since each device has its own nuances concerning configuration methods based on the vendor, the system must be able to be adapted to various methods of updating configuration information.

MDOT leveraged the DUAP system for configuring the RSUs and for capturing and presenting the data from the devices and for assisting in the configuration of the installations. The CV devices are dependent on configuration and monitoring from a back office to ensure they are operating correctly and providing the pertinent information to the traveling public. The RSU must be configured with the correct messages to be broadcast. This can include the SAE J2735 message set along with the CAMP BIM message.

The IMO 3.0 project expanded the number of equipped vehicles within the MDOT fleet by adding Dedicated Short-Range Communications (DSRC) capabilities connected to the VIDAS installations. This provided MDOT with the ability to target specific areas using DSRC and other area using cellular where DSRC is not available.

This provided a basis for the functionality required by the IMO 3.0 project for gathering the data from the new CV and VIDAS deployment.

3.1.1.2 Saginaw Highway Corridor

Specifically, for the IMO 3.0 project, MDOT instrumented a highly-travelled section of Saginaw Highway in Lansing, Michigan, with RSUs at intersections along the route along with fleet vehicles installed with the VIDAS platform and OBUs. This installation is designed to handle a variety of applications along with the ability to expand in the future. Some of the current applications include:

- Safety
- Mobility
- Weather impacts and alerts
- Expanding CV installations
- Asset management

The DUAP system is used for configuration of these devices, monitoring the devices, capturing the data, and providing the information to MDOT through DUAP's applications.

3.1.1.3 WxTINFO

MDOT's operations functional area is responsible for notifying the public of events that may affect travel. Using ATMS, MDOT can update dynamic message signs and the Mi Drive website with this information. Weather is a primary event of interest. Understanding the weather events occurring within the agency's jurisdiction is instrumental to this task. Previously the traffic operations within the operations functional area, who is responsible for controlling these notifications, had to access various tools to gather a complete view of current weather events. The WxTINFO project was responsible for adding functionality to the DUAP system to collect information from various weather data sources, aggregate it into weather alerts based on this information, and provide it to users and the ATMS. This automates the process of loading data concerning weather events directly into ATMS to be pushed to dynamic message sign (DMS) signs and Mi Drive.

Additional weather-based data sources were added to the ingestion processes to accept:

- NWS radar
- NWS sensor data
- NWS warnings and alerts
- NWS forecast data
- RWIS observations
- ASOS and AWOS
- Mobile environmental data

This data is quality checked individually and in conjunction with other related data to improve the accuracy of the information and to assist in monitoring the operational quality of the sensors providing the data.

Once data is deemed valid and accurate, data analysis is performed to determine the types and locations of weather events. A multitude of decision-based processes are able to build this information based on available data. As the amount and frequency of the data increases, the accuracy of the alert information increases.

The resulting information is available for viewing through DUAP's weather application and fed directly to the ATMS for use by operations. The provided information guides the operator in what message should be displayed on DMS and which signs should receive the message.

As a weather event moves through the state, the signs can be updated automatically, thereby reducing the operator's work load during the hectic times of large weather events.

Leveraging this weather alerting functionality provided additional uses of the data created by the IMO 3.0 deployments and supported the project's goals of identifying road weather events which can affect the traveling public.

3.1.2 Applications

The following sections describe applications which relate to the IMO 3.0 project. The descriptions explain how they apply to the project and provide a basis for additional applications in the future.

3.1.2.1 Traffic Condition Monitoring

Traditional and current traffic monitoring solutions are almost exclusively based on using spatially-fixed vehicle detection stations to detect, count, and characterize the vehicles passing each station. Independent of the particular technologies used to implement that detection and characterization—induction loops, radar, video, and so forth—the detection is limited to those

particular locations at which the detector is stationed. Probe vehicle solutions based on obtaining the location of particular vehicles, such as VIDAS, AVL, and CV systems, can be used for monitoring traffic in addition to their other roles.

Currently probe vehicle solutions sample a subset of the driving population; however, a broad deployment of CV systems along with other mobile platforms would dramatically change this situation. If all vehicles can report their locations, fixed detection and counting becomes a means of confirming performance measures that are aggregated from the individual vehicle data. Traffic monitoring would no longer be limited to the number of stations that could be deployed by the transportation agency. For example, the agency could use CV data for generating accurate and reliable arterial travel times and traffic demand at intersections in advance of detectors to be utilized by the agency in optimizing a corridor.

Combining traditional traffic detection data with CV data provides a more accurate and complete view of traffic conditions within the infrastructure. As the amount of data continues to expand the value of the information will continue to increase.

The data from the vehicles equipped through the IMO 3.0 project were integrated into this application to provide additional data expanding the available information for the agency.

3.1.2.2 Weather Alert System

The purpose of a weather alert system is to provide the agency with near-time information concerning the weather impacts on travel and maintenance activities. The system brings together near-time environmental/weather-related data collected from both fixed and mobile data sources.

While the weather-based processes are designed to operate as fully functional applications, they are also a part of the overall DUAP system. The data sources that are being utilized for the weather alert processes consist of some of the same sources used for applications within DUAP. Weather event information generated by the system based on this data is forwarded to the ATMS and made available to the operators to assist in notifying the public. This concept fits with MDOT's desire to define the data once, collect it continually, and use it many times for the benefit of the entire agency.

For the IMO 3.0 project, this application was instrumental in determining the weather's impacts on the roads based on the data collected by the newly instrumented vehicles. Providing the additional vehicles expanded the available coverage of the mobile data supporting the application. MDOT is able to use these vehicles to provide targeted data collection where weather events occur.

Specific to the IMO 3.0 project, the system is able to share the incoming mobile weather observations by forwarding the data to NCAR and the WxDE in support of other road weather research initiatives.

3.2 Method of Analysis

The objective of the application analysis for the IMO 3.0 project is to investigate and, if possible, demonstrate enhanced transportation agency operations based on CV systems and weather-related observations from CV and other mobile platforms. Within the frame of that objective, each application area has particular objectives for safety, mobility, environmental affect, cost, and timeliness. These objectives are likely to be driven by established agency performance measures for that application area. Objectives may also relate to the existing agency systems—providing a particular kind or format of data to fulfill regulatory, policy, or procedural goals.

The concept for each application area starts and ends with the needs of the client for a particular application but is built around the existing DUAP system and a common set of capabilities and data sources. The needs of a particular application derive largely from the objective served by that application, its associated performance measures, and the physical and operational nature of the application. At a conceptually high level, some applications are focused on the transportation system and data pertaining to each asset operating within the transportation system.

The application research consists of three phases, each of which serves as a gate for further development and testing. The initial system *development* testing asks, "Can the system collect usable quality data?" A successful development test then confirms accurate data collection and synthesis into usable metrics. *Acceptance* testing asks, "Are the data reflective of actual conditions?" Successful acceptance testing demonstrates correlation of application metrics as compared to existing methods employed to solve similar issues. *Application* testing asks, "Can the data collection be used to enhance DOT operations?" Successful application testing finally demonstrates the ability of the application to meet the user needs of the agency.

Each application within the system has different resource needs which are evolving over time to continue to improve the quality of the information they provide and the viability of their value to the agency. This emphasizes the importance of the data's quality, availability, and sustainability. An application's value is based on its ability to have reliable and correct data.

The analysis of each application is completed with conclusions on the relative success in meeting the objectives for that application and suggestions for next steps in research and implementation.

3.2.1 Applications

The following sections detail the primary applications related to the IMO 3.0 project initiatives and analysis. They provide examples of the abilities of the system in related to leveraging CV data for identifying and responding to road weather events.

3.2.1.1 Connected Vehicles

Still in the infancy of CVs, standards and implementations continue to evolve. These changes can have a costly impact on systems designed without the flexibility to evolve with the changes. Creating a system which is configurable and that is able to ingest a variety of data formats from multiple data sources allows the agency to adapt to the changes in the industry.

Vehicles for this project were chosen based on the number of miles they cover weekly, along with the area of the state and types of roads the drivers cover. This provided a large amount of data in a variety of situations.

The equipped corridor was a focus for a number of the trucks housed at the MDOT Grand Ledge maintenance garage. This facility is in proximity to the equipped Saginaw Highway corridor. This allows for collection of data through the VIDAS platform along with collection of the CV data. Each of these data sources supplements the other in the quality checking of the data and helping to provide ground truth in understanding the information.

3.2.1.2 Traffic Condition Monitoring

A vehicle's relationship to the traffic flow is provided by data describing vehicle motion. These data could include, at a given time, the vehicle:

- Location (latitude and longitude from GPS)
- Speed

- Heading
- Brake status and ABS actuation
- Steering status, yaw rate, and stability control actuation
- Longitudinal and lateral acceleration

Traffic measures would then be derived from the aggregation of data from individual vehicles. Traffic speed, for example, could be represented by the mean and standard deviation of speeds of the vehicles along a given roadway segment within a certain time interval. Incident detections might be synthesized from correlation of vehicle speeds with braking, acceleration, and steering status. Travel time estimates could be derived from analysis of vehicle positions and speeds.

Low data latencies (on the order of seconds rather than minutes) will be required for vehicle probe data to be useful in traffic monitoring and management. Current ATMS sensors and networks operate in near real time, and any significant increase in data latency would compromise both operations and public trust.

The number of vehicles needed to generate useful traffic data may be a constraint on traffic monitoring applications, especially in the near term when CVs would represent a small fraction of overall vehicle populations. A 2007 study[1] found that probe vehicle populations on the order of 10 percent of vehicles are needed for accurate and reliable traffic travel time estimates, with slightly more vehicles needed to estimate mean traffic speed. Increasing the number of vehicles would provide both higher confidence and more accurate statistics. Traffic control applications depending on vehicle counts (e.g., signal control) would require even higher population percentages, approaching CV saturation, to be effective.

Expanding the number of vehicles equipped with CV systems or other mobile platforms increases the quality and coverage of data supporting this application. Equipping vehicles in support of the IMO project supplemented the data available for monitoring traffic conditions.

Sharing this information with all functional areas within the agency provides a variety of benefits including but not limited to:

- Monitoring traffic conditions
- Planning maintenance and construction activities
- Origin and destination planning
- Assisting in traffic signal phase planning
- Improving response time to incidents

3.2.1.3 Weather Alert System

Weather affects many aspects of the agency and the traveling public. The National Weather Service supplies general weather alerts and warnings which can be used to assist the agency in notifying the public, planning road maintenance activities such as road repairs or treating snow covered roads. Additional information, such as NWS radar, weather-based websites, probe vehicle weather sensor data, and camera images, can be used to help determine the impacts of weather events. Combining this information into one application simplifies the task of tracking the weather events. MDOT is using DUAP to integrate these various data.

DUAP is ingesting weather-based data from:

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[1] Noblis Inc. *Vehicle-Infrastructure Integration (VII) Probe Data Characteristics: Analysis of Three Field Data Sets*. Falls Church, Virginia. June 2007.

- NWS radar files
- NWS observations from fixed weather stations
- NWS alerts
- NWS forecast information
- MDOT RWIS fixed stations
- ASOS and AWOS
- Mobile VIDAS platforms
- Mobile AVL fleets (WMTs)
- CV equipped vehicles (VIDAS & IMO)

The different weather data information is combined to provide the ability to quality check the data to ensure accuracy, analyze the data to determine the type and location of weather events, and provide a variety of granularity of the information based on user needs.

Each data source has a specific resolution and frequency of data which is supplied to the DUAP system. The data analysis processes must handle these differences, along with the continuous stream of information, to continually adjust the type and location of weather alerts being generated.

Using the DUAP GUI, the user may view the information concerning the weather alerts generated by the system. In addition, these alerts can be sent to other external systems, as needed. DUAP currently provides the information to MDOT's ATMS to assist operations in notifying the public of the weather events. Other uses of the information include but are not limited to:

- Determining if road construction or maintenance can be performed
- Determining the areas that require winter maintenance
- Determining type of winter maintenance needed
- Notifying emergency agencies where weather is impacting the public
- Trending impacts of winter weather and maintenance on roads
- Tracking winter maintenance material usage
- Tracking winter maintenance coverage
- Adjusting traffic signal timing based on weather

Weather observations are also being shared with other external systems including NCAR and WxDE in support of the IMO project. Leveraging DUAP's ability to route data to these external systems provided for the data sharing to support these research initiatives.

3.3 Presentation of Results

The IMO 3.0 project made the move from using smartphone technology for capturing mobile weather-related data to using CV technology along with an integrated mobile platform capable of capturing data from a variety of sensors. These technologies improved the accuracy, timeliness, and reliability of the information and expanded the uses of the data. The data was used to supplement existing data sources in weather and mobility related applications along with providing the data to systems external to the DUAP system to expand the use of these systems.

The following sections detail the use of the system's applications for the IMO 3.0 project.

3.3.1 Applications

The following sections provide details of the different applications developed to meet MDOT's needs. The IMO 3.0 project was able to leverage and to provide enhancements to these applications to leverage the CV deployments for capturing and using road weather information. The following applications were involved with this analysis.

3.3.1.1 Connected Vehicles

The CV applications cover a variety of areas including but not limited to traffic conditions, weather, construction, maintenance, and safety. Equipped vehicles and RSUs provide the data for these applications. The message types can include:

- BSM: RSUs receiving BSM message from mobile devices can forward the messages to the DUAP system for analysis.
- SPaT: Traffic signal phase information can be received directly from the traffic signal controllers and ingested into the DUAP system and sent to the RSU to be broadcast to listening devices such as OBUs. The DUAP system can also receive the data from the RSU for ingestion.
- MAP: The DUAP system can assist in configuring the RSU with the MAP data for MAP broadcasting and for converting signal phase data into a SPaT for broadcasting along with the MAP.
- TIM: The DUAP system can assist in configuring the RSU with TIM messages for broadcast to CV devices for traveler information.
- BIM: RSUs can be configured with a CAMP BIM for broadcasting. The DUAP system can assist in the creation of the BIM information and the RSU configuration for the message

The DUAP system uses the information from these messages to assist the agency in a variety of uses including:

- Monitoring traffic situations
- Monitoring queues at intersections
- Supplementing weather information
- Planning and adjusting traffic signal phase timing
- Notifying the equipped travelers of information via TIM or BIM

The DUAP system has adapted as the CV devices and standards have evolved. The standards for the messages have consisted of three primary format versions, 2009, 2015, and 2016. This initial implementation of CV within DUAP involved the 2009 message format. This has been expanding to incorporate 2015, as needed, with the target to totally support 2016 format enabled devices.

DUAP is able to display BSM data for vehicles within range of the RSUs along with the traffic signal phase information.

These applications were used for the IMO 3.0 project for the ingestion of the BSMs from the vehicles and managing the configuration of the RSUs deployed in the project.

3.3.1.2 Traffic Condition Monitoring

The DUAP system ingests data from a variety of data sources dealing with traffic flow including fixed detection devices, such as MVDS, and mobile data, such as CV and VIDAS. The mobile data sources provide data showing speeds at various points across the infrastructure to supplement the fixed station data. As the equipped fleet continues to grow, the coverage of this data will increase.

The application shows the traffic averages obtained by the fixed sensors for a specified route and time frame. The GUI provides a list of equipped routes from which to select. This data can be further expanded to show more detailed time-based graphs for a selected location along the route. The actual sensor location and their data can be displayed on the map interface.

Mobile data can be displayed graphically on the map interface. An example of the map interface showing the mobile data for a vehicle in the Saginaw Corridor is shown in Figure 7. The displayed data coming from the VIDAS shows the time, location, speed, heading, and surface temperature information.

For a selected timeframe, the user can select types of vehicles and actual vehicles from a list of vehicles which were active within that time frame. Equipped intersection status and vehicle movements can be displayed moving within range of the intersection's RSUs. Black lines show the captured vehicle paths for the specified time frame. Animating the vehicles allows the user to see the movements and speeds of the vehicles.

Installing CV and VIDAS platforms and infrastructure for the IMO 3.0 project expands the available data for this application. When focused on the equipped corridor, the application enhances the ability to monitor traffic flows along with the impact from weather on these flows, when the equipped vehicles are present along the corridor.

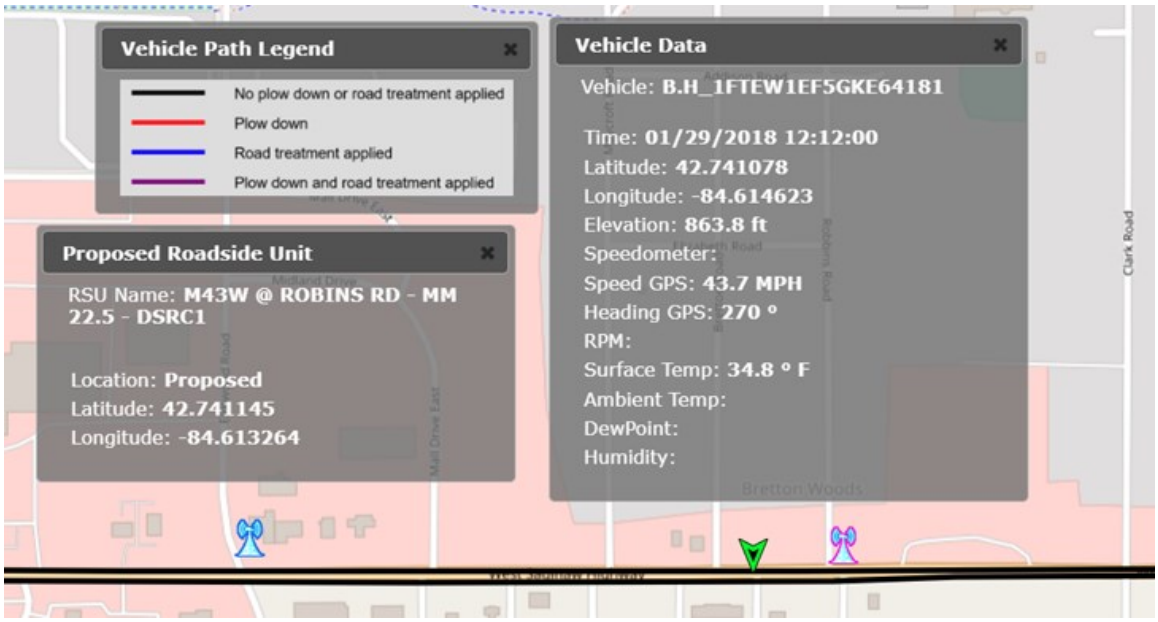

Figure 7 - Map Interface Display of Mobile Data

3.3.1.3 Weather Alert System

The weather alert application has the ability to aggregate weather-based data and create weather alerts to notify the agency and the public of weather impacts on the system.

Supplying these alerts, including various levels of detail, and the ability to export the information to other systems is a very useful tool. The DUAP system's strength of combining multiple data sources to build reliable and detailed information is suited well for these processes. The level of detail supplied to the ATMS changed during the project to better suit the work flow in notifying the public of weather events. It was seen during this change that maintenance groups would still need the finer detail to better understand what was happening at specific locations. Building the system to handle different levels of granularity enhanced the weather reporting and the use of the information.

Expanding the amount of mobile data through the IMO 3.0 project improves the accuracy and coverage for this application. The mobile aspect allows the agency to target specific areas during

weather events. Not only does this improve the information being reported to the agency, it provides traffic operations with additional ground truth concerning the event.

4 DISCUSSION

4.1 Validity of Hypothesis

The IMO 3.0 project's hypothesis of a system being able to leverage CV and other mobile platform data to determine the occurrence and effects of weather on the traveling public has been shown to be valid. Integrating the data from the CV deployment's additional VIDAS platforms, with the existing data being ingested by the DUAP system, has shown improvements in the coverage of the weather-related details which can be provided to the user or other systems. Employing the Wx-TINFO applications to expand the uses of the data further demonstrated the viability of using vehicles to supplement the available data from fixed stations in determining the types and location of weather events.

Sharing the mobile data with the other systems, NCAR and WxDE, further demonstrated the importance of mobile data in analyzing and responding to weather events. Instead of each system being responsible for deploying and collected its own CV infrastructure, this deployment leverages the CV infrastructure for use by several systems. This one deployment is able to inform many systems of environmental situations. Each system, DUAP, NCAR, and WxDE was able to leverage the same data to provide their individual and combined functionality to the agency for a more complete description of the current weather and how it was affecting the traveling public.

Establishing the interface between the systems provides functionality for continuing to expand the mobile and CV deployments as these technologies continue to become adopted by the agency and the public. Data from new deployments can be shared between the systems, increasing the value of the data collected.

Applications can continue to be developed using the data sets currently ingested into the system. Information based on this data can be disseminated, within these applications, in a variety of ways to meet varying needs of the different functional areas.

4.2 Factors Affecting the Results

Infrastructure owners and operators are continually challenged to have the appropriate data in the right locations at the right time. The infancy of the CVs has limited data availability. As MDOT continues to expand their CV footprint this will continue to improve. The IMO 3.0 project has shown how the data's value can increase as the number of installations and CV market penetration grows. Expanding the deployments for IMO would continue to improve the amount and value of data generated.

One of the issues affecting the CV corridor was the lack of communications infrastructure at the intersections. Due to this limitation, the RSUs were connected to radios at the intersections. These radios were used to pass data between the RSUs and the back office. There were issues installing the radios and ensuring each radio had stable communication to the primary radio used to interface with the back office. The back office also needed to understand which RSU was sending the data as all data was transmitted from the same radio. Using this architecture design met the basic needs of the project but was not an ideal solution to the CV deployment.

There was a delay in completing the deployment due to the lack of an available communication backbone at the intersections in the corridor. This prevented the collection of the CV data during most of the winter timeframe during the project. The VIDAS platform, however, was able to continue to collect the information concerning the weather and the pavement condition. This data

was ingested by the DUAP system and forward to NCAR and WxDE for their use. Having this data available helped in meeting the goals of the project in utilizing mobile weather-related data.

The current applications and their results have been based on currently available data sources. In some cases, coverage from existing data sources may be lacking in specific geographical areas. Depending on the needs of the agency, these data sources can be expanded or supplemented by mobile platforms. As the DUAP system continues to receive additional and expanded data sources the value of the data and the systems will continue to be realized.

4.3 Implications

The results of the IMO 3.0 project demonstrate that CV deployments can further enhance the road weather data collected from other data sources to provide greater and more targeted coverage of geographical areas. The data can be shared and disseminated in a variety of ways to meet the needs of different functional areas. Expanding these deployments and other data sources would provide more accurate and complete information across the infrastructure. This data will increase in value as systems such as DUAP, NCAR, and WxDE continue to provide new applications reusing the information to benefit different areas of the agency meeting their variety of needs.

As these deployments and data sources expand, the amount of data will also continue to increase. This has a direct concern and increased cost to the systems ingesting the data. Processes are required to ensure sustainability of the systems and to control the costs of operating the systems.

The architectural solution implemented to deal with the lack of a communications backbone to all of the intersection was able to deal with the data from this deployment. However, it was seen that a larger deployment with many equipped vehicles and intersections could result in the solution not being sustainable or able to transmit the amount of data that would be generated. This showed the importance of a quality communication backbone to the intersection included in CV deployments.

These benefits imply value to the agency in continuing to expand the CV deployments, data source coverage, system applications, and application usage.

5 CONCLUSIONS

5.1 Conclusions from the Study

The IMO 3.0 project has shown that is it viable for CV data to be used in identifying weather-related threats and hazards. Combining this information with other fixed and mobile data can provide additional coverage and details of the ground truth during weather events. Changing from the use of smartphones to the CV and mobile platform technologies expands the capabilities and uses of the deployment. This provides data for not only mobility applications but expands into weather and safety applications.

CV technologies include V2V and V2I safety and mobility applications as shown in prior deployments. IMO 3.0 pushes these capabilities into supporting agency responses to road weather events by supporting multiple weather response systems such as DUAP, NCAR, and WxDE. The DUAP system has shown how the data can be used to enhance the Wx-TINFO capabilities in expanding the availability of weather data for notifying the agency of the type and location of weather events. In passing this information to the traffic operations staff, improved weather response plans can be developed.

As CV deployments continue to expand, the availability of the data will continue to improve the resolution and accuracy of the road weather information. As this improves, agencies and the traveling public will be better equipped to deal with the many hazards of weather.

5.1.1 Benefits

- Traveling Public: Provides traveling public with more timely/valuable information allowing them to make safer decisions both pre-trip and en-route during inclement weather conditions.
- DOT TOC/TMC Operators: DOT operators are critical in providing motorists with valuable information during winter weather events. Mobile information can provide better roadway coverage and localized messaging for TOC/TMCs thereby better informing motorist decisions as to the safest trip alternative.
- Maintenance Staff: Provides the ability to utilize an alert system to advise maintenance staff of necessary winter maintenance locations, including unsafe pavement/roadway conditions, and enhances response times.
- Savings: Optimizes the use of maintenance resources through data driven performance metrics (tracking material usage, time on roadway/overtime, automates completing vehicle logs & reports, reduced fuel consumption/emissions, etc.).

5.1.2 System Capabilities

DUAP has been successful in meeting the needs of the IMO 3.0 project, to evaluate uses and benefits of mobile and CV weather observations from various platforms across the agency. The program demonstrated, for example:

- Acquisition of data from multiple data sources, including mobile platforms, CV devices, weather, and traffic detection
- Deployment of aftermarket on-board sensors and data acquisition units for measurements of specific operational interest to DOTs
- Analysis of multiple data types from each of the sources
- Synthesis of performance measures for specific DOT applications (for example, segment average speeds, or relative pavement conditions) from the probe data
- Presentation of raw and processed data in consistent, flexible map-based operator interfaces
- Sharing of data with external systems

IMO 3.0's success has shown the quality and availability of data from a variety of data sources, including CVs, continues to expand and improve. This will continue to expand the usefulness of the system and improve the information it creates. The availability of large volumes of data from diverse systems led to a research plan exploring what might be done with the data. The current reality is that data will continue to become available only as it is needed and can be obtained for particular applications. The focus of research needs to shift from "what can we do with everything that's available?" to "what do we need, and how do we get it?"

5.1.3 Data Collection and Standards

The IMO 3.0 project demonstrated the ability to acquire and aggregate data from multiple sources and formats into an integrated repository. The DUAP system philosophy and architecture of isolating the data collecting components from the data repository enables the system to add new collectors as needed to accommodate interfaces with varying data specifications, timing, and network protocols. If a data source already provides an interface, a new collector component for DUAP will be the most effective means of getting the data from that particular source.

Given the capability to collect data from a wide variety of interfaces, the data repository also needs to be able to accommodate data from different sensors and sources at differing times and

spatial resolutions. Each data source may provide values for a given parameter with its own resolution, which may or may not match the resolutions needed by particular applications of that data. For example, "speed" could be provided by multiple sensors on a vehicle (for each wheel, for the average wheel, based on GPS coordinates) and by roadway sensors (which generally provide only time averaged speeds over multiple passing vehicles). Each of these cases needs to be specifically identified within the repository with metadata (for example, source) that may be needed in the application of that data.

Maintaining the quality of data within the system based on the standards related to each data source helps to preserve the value of the information used as a basis for the many applications of the DUAP system.

Integration of a variety of data sources helps provide a more complete and accurate image of the status of transportation to the agency and other systems. Sharing this information with the other research initiatives provides additional value of expanding the use of the CV and mobile platforms along with collecting the data for the variety of uses.

This capability was essential in meeting the needs of the IMO 3.0 project in expanding the availability of CV and mobile platform data and integrating it with existing information to improve the quality and use of the information.

5.1.4 Applications

Viability of any particular application using CV data depends directly on data characteristics including:

- Availability of the data types relevant to that application
- Availability of sufficient data volumes
- Data spatial and temporal resolutions consistent with the needs of that application
- Metadata linking the data to the sensors and loggers that provided it to enable appropriate data quality checks

Given these data conditions and the prototypical nature of CV systems, applications of value to DOTs are likely to depend in the near term on data from DOT-controlled vehicles. Test bed and demonstration deployments to date have been consistently unable to provide sufficient data to enable DOT application development. The IMO project continued the deployment of additional vehicles equipped with OBUs and VIDAS along with additional RSUs to support these equipped vehicles.

CV technologies may eventually be valuable for traffic monitoring applications, but only after they are sufficiently distributed within vehicle fleets. This conclusion reflects experience not just within a formal "connected vehicle" context, but results seen in other AVL deployments and commercial traffic data service providers. Combining a DOT's fleet data with other transportation and CV related data is beginning to provide valuable information for driving further research along with actual application development.

Weather detection has been demonstrated in this project and should be achievable across the DOT with currently available technologies. The availability of weather observations across the different mobile platforms provides a variety of options to supplement the available weather-related data. Deployment of these platforms continues to expand the information coverage across the state to assist the agency with its operations. The value of this information continues to grow as research initiatives examine uses of the data.

6 LESSONS LEARNED

The following section provides the lessons learned through the course of the IMO 3.0 project.

6.1 Overall Project Lessons

There were several general lessons learned on the overall project that are applicable across the different applications of the project:

- Collecting mobile data and sharing it with other systems demonstrated the importance of mobile data in responding to weather events.
- A more complete description of the current weather and the impact to the traveling public has the potential to improve public safety and improve the agency's operational effectiveness.
- Agencies should build hardened platforms to increase the stability of the data collection and system operation.
- Agencies should build hardened backhaul communications to increase the reliability of data transmission.
- Agencies should incorporate data use protocols to facilitate data interoperability.
- Agencies should build institutional knowledge to support existing deployments and gain greater involvement in expanding future applications.
- Agencies should enhance sustainability with operations and management funding and data usage.
- Solutions may require proprietary software to run on off-the-shelf hardware. This produces software to accomplish the specific tasks needed where open-source software does not exist.
- Agencies should build partnerships internally within the agency and externally with public and private sectors of industry. These partnerships bring additional support, resources, and expertise to achieving the goals of the agency.
- Agencies should build a back office with the proper support to handle data storage and communication for the system. The back office also provides the ability to monitor and maintain the devices remotely. This can be done by the agency or built and managed by others.
- Agencies should educate internal stakeholders, external stakeholders, and sponsors to maintain management support.

6.2 Preinstall Process

There were several lessons learned in the pre-installation process that help ensure the success of the installation and overall project:

- Scheduling of trucks for the install and cooperation with the drivers is critical.
- Logistics of the vehicle availability for the required time needs to be well planned.
- Administrative support is needed for coordination of the vehicle installations.

- Vehicle selection should be based on the availability, miles traveled, geographic coverage.

6.3 Install Process

There were several lessons learned in the installation process that help ensure the success of the project:

- Have hoists available to simplify installations.
- Have tools to support the installations (including lighting, hole saws, drill and bits, etc.).
- Installing antennas on the truck cab is better than installing on truck bed toppers.
- Package installation kits containing all of the correct components for each truck is critical.
- A spare kit would help for replacement of devices experiencing problems during install.
- Bad sensors cause problems with the assigned devices. Make sure there is an easy method for documenting the changes in which devices are installed on the vehicle.
- Environmental impacts on the cables and devices (moisture, corrosion, grim, etc.) can cause failures.
- Installers should ensure mounting materials and processes alleviate impacts from environment and wear.
- Design cables for easy installation (potentially using wireless sensors if available) wherever possible.
- Installers should use a standard measurement process for collecting metadata for the locations that the device is installed on the vehicle.
- Make sure a driver is available for testing the installation.
- Automate the testing of the install within the software to provide a consistent and streamlined method for verifying installation of the components.
- Installers should provide access to the communication channels (i.e., cellular, Wi-Fi, DSRC).
- Agencies should develop a backup plan for issues with the Wi-Fi at the facility for testing the installation.
- Agencies should support the needs of the installers (i.e., provide facilities, restrooms, food, environmental, and access after normal working hours to facility).
- Having two people to make the measurement of everything is much easier. Once installed, it is necessary to measure the locations of the sensors and tires in relation to the GPS antenna. It helps having two people doing those tasks to be more accurate.
- Agencies should have internal coding to charge their time to for installation and operations and maintenance needs. This allows the agency to track effort.
- Stakeholders should clearly communicate (via meetings, written correspondence, etc.) roles and responsibilities of all stakeholders in this process, including the vehicle drivers.

6.4 Post Installation

There were several lessons learned post-installation that will support future deployments:

- It is critical to have ongoing maintenance and support.
- Agencies should monitor installed components and alert team to devices with problems.
- Agencies should have spare kits available for replacements parts.
- Agencies should have a maintenance program that includes annual maintenance inspection, review, and calibration.
- Agencies should have a process for tracking shock degradation, compare to baseline for the vehicle.
- Agencies should have a plan in place for vehicle turn over as equipment will need to be removed from old vehicle and placed on the new vehicle.

6.5 Field Devices

There were additional lessons learned related to the field devices:

- Field Infrastructure installation and communication are critical issues.
- Agencies and field personnel should ensure compatible interface and applications between the RSU and traffic signal controller.
- Due to the lack of installed communication backhaul, the radios used with the RSUs required line of sight to communicate.
- Agencies should determine backhaul needs for the infrastructure for communicating with the back office.
- Resource needs and cost of field deployment should be determined based on the existing infrastructure.
- Equipment and communication costs (including justifying fleet expansion) may be challenging and may compete with other funding requests.

6.6 Mobile Devices

There were also lessons learned related to the mobile devices:

- Use more Public fleet vehicles to increase the number of deployed vehicles and make sure there is funding to support those vehicles
- The proprietary nature of OBD/CANBus data can be limiting (e.g., it is difficult to receive data beyond basic CANBus information).
- Coordination and installation of equipment on agency vehicles creates challenges.
- Agencies should be sensitive to installation issues and be diligent in documenting sensors on vehicles (e.g., meta-data needs).
- Multiple communication protocols (cellular, WiFi, DSRC) were used to transfer data from the mobile devices to the back office. This optimizes the efficiency of the system by

using the appropriate communication channel based on the type and volume of data as well as the intended use cases for the data and the back office.

7 RECOMMENDATIONS

The following recommendations are offered to support MDOT's continued deployment of the weather, traffic monitoring, and CV applications.

- The IMO 3.0 project can be used as a success story for others to deploy these applications and for deployment of additional applications.
- Mobile data can be used by agencies to support weather management, traffic monitoring, and transportation management applications.
- Providing data to NCAR can enhance the overall weather information available to the public.
- For these applications to be successful, it is critical that the agency or agencies establish a back office, database, data management system, and communication to support the applications and integrate those into current business models
- Agencies should secure system operations and maintenance funding for program sustainability.

7.1 Recommendations for Further Research

IMO 3.0's purpose, simply stated, was to assess the use of data from CVs and available mobile weather observations to improve transportation agency operations. The research was therefore based and developed on a presumption of data being available from CVs along with the expansion of mobile platforms such as VIDAS and AVL. Activities undertaken as part of IMO 3.0 project were directed at applications of that data within MDOT, other transportation agencies, and other weather-related systems.

The IMO 3.0 project expanded the volume of data available to the DUAP system by continuing to deploy sustainable sources of data within MDOT to support transportation agency applications along with other FWHA research initiatives through the installation of CV technologies and the VIDAS platform. Provisions were made for collecting data from MDOT's own fleet vehicles equipped with these mobile platforms and RSUs installed along the Saginaw Highway in Lansing, Michigan. The system used to collect the data has enabled the DUAP system to demonstrate the ability to collect data, provide applications specifically related to the improvement of DOT operations, and to provide the data to other weather systems, namely NCAR and WxDE.

Based on this experience, it is recommended that further research using the system demonstrated in DUAP continue to be developed in on-going programs and the expansion of the CV deployments. Solutions will continue to be identified and developed to fulfill the data needs of the agency to improve the cost efficiency and enhance the effectiveness of its operations, with the emphasis on expanding the available mobile data gathered as part of MDOT's ongoing operations with other data sources from across the agency.

7.2 Recommendations for Implementation

Next phases of the IMO 3.0 project can continue to expand CV and other mobile platforms and to add new data sources to increase the coverage, accuracy, and quality of the data to improve the

information within the system. As installation of CV technologies continues to expand, information available through the system will continue to provide additional benefits and increase the value of this data. The applications presented in this document are the beginning of what they can truly be. Continuing to evolve and expand the applications within the DUAP system, along with more complete data coverage, will continue to increase the value of the system to the agency and other external systems using DUAP's information.

It is important to consider the available infrastructure at locations planed for CV deployments. The CV devices generate a large amount of data which is valuable to the agency in monitoring the infrastructure and the environment. The availability of sufficient communication backbone is essential for a successful deployment. The Saginaw Highway corridor demonstrated the importance of adequate infrastructure to support the additional devices and data associated with CVs.

The goal of IMO is to provide accurate and pertinent information for dealing with weather threats and hazards. Leveraging a system like DUAP helps to meet this goal along with providing the agency additional benefits, such as:

- Cost efficiencies
- Improved effectiveness of its operations
- More complete information concerning the transportation system
- Improved public safety
- Decreased environmental impacts

Continued growth of the DUAP system depends on:

- Development of additional applications to meet the needs of the different functional areas of the agency
- Installation of additional fixed devices such as RSUs, weather detection, traffic sensors
- Installation of additional mobile devices such as the VIDAS platform, AVL, and OBUs

IMO 3.0 has shown, through the expansion of the CV deployment, DUAP's applications, and the sharing of data with other systems, how these benefits can be met through continued expansion of CVs and the coverage and accuracy of data sources continue to increase.

APPENDIX A -ACRONYMS AND ABBREVIATIONS

The following table provides definitions of terms, acronyms, and abbreviations used in this document.

Term	Definition
ASN.1	Abstract Syntax Notation. One
ASOS	Automated Surface Observation System
ATMS	Advanced traffic management system
AVL	Automatic vehicle location
AWOS	Automated Weather Observing System
BIM	Basic Information Message
BSM	Basic Safety Message
CFR	Code of Federal Regulations
Coops	Concept of operations
CSV	Comma Separated Values
CV	Connected Vehicle
DMS	Dynamic Message Sign
DOT	Department of Transportation
DUAP	Data Use Analysis and Processing
FHWA	Federal Highway Administration
GPS	Global Positioning System
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronic Engineers
ITS	Intelligent Transportation Systems
JSON	JavaScript Object Notation
MAP	Map Message
MDOT	Michigan Department of Transportation
MVDS	Microwave Vehicle Detection System
NCAR	National Center for Atmospheric Research
OBU	On-Board Unit
RSU	Road Side Unit
RWIS	Road Weather Information Systems
SAD	System Architecture Description
SAE	Society of Automotive Engineers

Term	Definition
SDD	System Design Description
SPaT	Signal Phase and Timing
SRS	System Requirement Specification
TIM	Traveler Information Message
USDOT	U.S. Department of Transportation
UTC	Coordinated Universal Time
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VDT	Vehicle Data Translator
VIDAS	Vehicle-based Information and Data Acquisition System
VII	Vehicle Infrastructure Integration
VIIC	Vehicle Infrastructure Integration Consortium
WMT	Weather Maintenance Truck
WxDE	Weather Data Environment
WxTINFO	Weather Response Traffic Information System.
XML	Extensible Markup Language

APPENDIX B - REFERENCES

The following documents contain additional information pertaining to this project and the requirements for the system:

1 Noblis Inc. *Vehicle-Infrastructure Integration (VII) Probe Data Characteristics: Analysis of Three Field Data Sets*. Falls Church, Virginia. June 2007.

2 VII National Working Group. *PD-22.c-1 – Traffic Management: Corridor Management Planning Assistance (Day 1)*. Version 3. 2006 April 06.

3 Cambridge Systematics, Inc. *Travel Survey Manual*. Washington, DC: U.S. Department of Transportation and U.S. Environmental Protection Agency. June 1996

4 Michigan Department of Transportation. *Slippery Road Detection and Evaluation, Project Final Report.* May 31, 2012

5 Michigan Department of Transportation. *Weather Responsive Traveler Information Evaluation, Project Final Report.* January, 2016

6 Michigan Department of Transportation. *The Connected Driver: Integrated Mobile Observations 2.0, Project Final Report.* March 2016