Michigan Department of Transportation

Data Use Analysis and Processing II

FINAL PROJECT SUMMARY REPORT

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16. Abstract

The purpose of the Data Use Analysis and Processing (DUAP) project is to support the Michigan Department of Transportation (MDOT) and its partners in evaluating uses and benefits of connected vehicle 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. 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 traffic monitoring, pavement defect and condition assessment, plus origin-destination studies for transportation planning. 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 and deployment of reliable data sources and specific applications for implementation in MDOT day-to-day activities.

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EXECUTIVE SUMMARY

The purpose of the Data Use Analysis and Processing (DUAP) project is to support the Michigan Department of Transportation (MDOT) and its partners in evaluating uses and benefits of their current data sources in addition to connected vehicle (CV) data in transportation agency functional areas. 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 CV infrastructure, vehicle equipment, and initial applications. The DUAP project builds on that foundational work to investigate how the availability of data from CVs throughout the road network may impact the ways MDOT and other transportation agencies perform business.

Recent DUAP research has shown how the increase in availability of CV data, along with the expansion of existing transportation and infrastructure data, continually improves the information available to the agency. The research was initiated and developed on a presumption of data being available from the efforts of other projects such as the Vehicle Infrastructure Integration (VII) Proof of Concept, many of which were not able to meet those data expectations. In working with MDOT to explore a variety of sources of data the team was able to increase the value and usage of MDOT's existing data and leverage mobile platforms developed for MDOT's fleet vehicles including Vehicle-based Information and Data Acquisition System (VIDAS), Integrated Mobile Observations (IMO), and Automatic Vehicle Location (AVL).

The project has successfully worked through a disciplined systems engineering process to develop and demonstrate three CV system capabilities.

The DUAP *system* itself collects, aggregates, processes, and provides interactive views of the CV data. The system design is flexible and can accommodate data of varying types, dimensions, and resolutions.

The DUAP data source *interfaces* demonstrate the ability to pragmatically acquire CV data from whatever sources may be available. Interfaces were developed for several specific data sources to provide a variety of data and interface technologies.

DUAP *applications* demonstrate the potential for enhancing DOT operations with CV data. Applications evaluated with data made available to the project include traffic monitoring, pavement defect and condition assessment, and origin-destination studies for planning.

Combining these processes with processes related to other types of data demonstrates the potential value of the DUAP system to the agency. The continuing goal to expand these existing data sources and to incorporate additional data sources will improve existing applications within the DUAP system and provide the opportunity to develop new applications based on MDOT's needs.

1   INTRODUCTION

This document summarizes the results, accomplishments, and lessons learned from the Michigan Department of Transportation's (MDOT's) Vehicle Infrastructure Integration (VII)[1] Data Use Analysis and Processing 2 (DUAP2) project (DUAP2 is the second iteration of the original DUAP project). It also includes recommendations for further research and development and provides an interface specification for potential data providers.

1.1   Background

1.1.1   Objective

The MDOT *Vehicle-Infrastructure Integration Strategic and Business Plan* laid out a plan that focused on partnering, developing, and deploying infrastructure, CVs, and test beds to support agency functions; increasing safety and mobility; improving asset management; developing outreach programs to better expose others to CV concepts in Michigan; justifying the need for CV research and systems; and determining creative investment funding venues for CV activities.

Within this context, the DUAP2 project objectives were to investigate and evaluate the utility of CV data and its integration with other transportation agency data sources in enhancing safety, increasing mobility, and improving asset management. Tasks within DUAP2 identified uses for the data, developed algorithms to use and process the data, developed prototype applications and data management software, and evaluated the utility of the processed data for MDOT and its partners. Data processing required acquisition from a variety of sources, standardization and integration, storage, synthesis for particular applications, and dissemination. Phase 1 of this work focused on collection and dissemination of information (the project described in this report), and later phases will deal with development of applications that use the data collected by the system.

1.1.2   Scope

The purpose of the DUAP2 project is to support 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 DUAP 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 do business. The project focuses specifically on data uses and benefits in responding to safety concerns, managing traffic, and managing MDOT's transportation assets. The work will ultimately support other CV projects, technology development for MDOT, and economic growth for the state.

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[1] The set of programs, technologies, and services referred to as "Vehicle Infrastructure Integration" at the DUAP program's inception has been programmatically repackaged several times. References in this and any supporting documents to "VII" and "IntelliDrive[SM]" can be understood to be synonymous with "connected vehicle" for technical purposes. "Connected vehicle" will be the preferred term throughout this report, except when referring to specific programs, projects, and documents.

The key tasks within the DUAP2 project are:

- to aggregate data from various data sources

- to identify uses for the CV data

- to develop algorithms to process data from a variety of agency sources

- to develop prototype applications and data management software

- to evaluate how well the data and the algorithms function in a department of transportation

As illustrated in Figure 1, the DUAP system is intended to draw data from existing MDOT data sources, both fixed and mobile, along with other relevant data sources to be integrated with CV data. The integrated system output can be returned to the existing MDOT applications as an enriched data stream or could be used in new applications for MDOT. Other MDOT projects may have influence on or facilitate the data integration. Applications outside MDOT could also receive data feeds from the DUAP system.
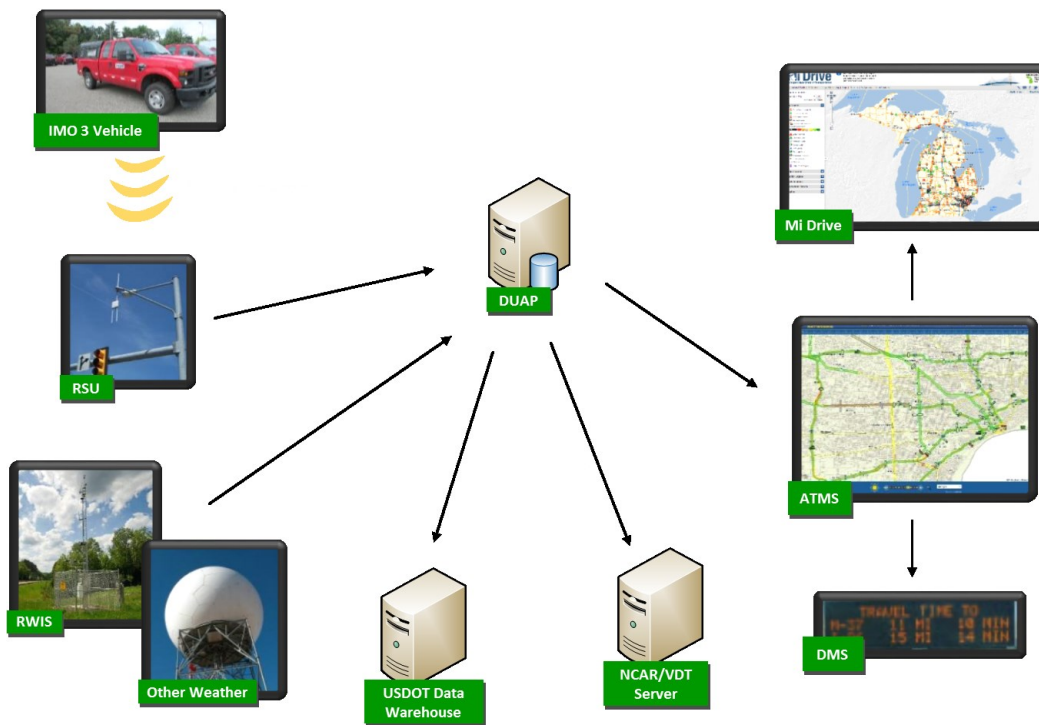
Figure 1 – DUAP2 Data Flows

MDOT concurrently was engaged in projects that complemented the DUAP2 program. These projects included the Wx-TINFO project, the VIDAS platform development, and the IMO 3.0 Project. The Wx-TINFO project was responsible for adding functionality to DUAP by collecting information from various weather data sources, aggregating into weather alerts, and providing alerts to users and the ATMS system. The VIDAS project developed a mobile vehicle platform installed on MDOT agency fleet vehicles that

collected data from the vehicle and sensors on the vehicle. The VIDAS platform has the ability to transmit the data through a variety of communication technologies. The IMO 3.0 Project, using DUAP, integrated data sources from both of these projects to improve transportation management and operations.

1.2 Statement of Hypothesis

Current agency applications typically perform a specific service for a specific functional area or user group. The DUAP2 project introduces the idea that data from various sources can be shared with all of the agency's functional areas. It expands the date 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. Thus, the project hypothesis is that applications within theDUAP2 system can use data from multiple sources to provide information in different forms based on each functional area's needs. This sharing of data will demonstrate the increase of value to the entire agency.

2   METHODOLOGY

2.1   Experimental Design

It has become widely accepted that 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 systems engineering approach used in DUAP2 development follows the USDOT's definition of systems engineering and consists of developing a concept of operations, generating requirements, synthesizing a system architecture, designing the system and components, testing, deployment and ongoing operations. Results of this process are captured in a series of systems engineering documents available separately from MDOT.

The DUAP2 systems engineering process started with determining the scope and objectives of the system through extensive stakeholder meetings. The initial meetings included representatives from across the MDOT organization, partnered Michigan agencies, USDOT, academia, transportation consulting firms, and technology vendors. These gatherings identified opportunities and challenges in transportation operations and emerging CV technologies, with the goal of finding a set of high-value applications for the DUAP system.

The Concept of Operations (ConOps) captures the results of the stakeholder interactions and analyses to determine what the system should do. It describes the existing systems relevant to transportation operations data; establishes the case for change; describes the capabilities and features of the proposed system; and discusses scenarios illustrating future system operation. The document is used to facilitate communications on CV and transportation operations with agency stakeholders and partners and as a basis for generating more detailed user needs.

The System Architecture Description (SAD) identifies the system's components and describes its internal and external interfaces. It expands on the initial system concept as described in the ConOps to provide more detailed descriptions of the system interfaces and internal structures.

The System Requirements Specification (SRS) is generated from user needs described in the ConOps and analysis of the system interfaces as described in the System Architecture Description. The SRS contains descriptions of required 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.

The System Design Description (SDD) documents the intended system implementation to address the requirements as specified in the SRS. The documentation describes each component and its interfaces in detail. The SAD, SRS, and SDD will be published separately by MDOT.

In addition to following the system engineering process, development of the DUAP system followed published standards to ensure compatibility with the transportation industry. Industry standards such as those from Society of Automotive Engineers (SAE)

International, Institute of Electrical and Electronics Engineers (IEEE), American Association of State Highway and Transportation Officials (AASHTO), National Transportation Communications for Intelligent Transportation System Protocol (NTCIP), and National Electrical Manufacturers Association (NEMA) were also employed. These standards help guide the transportation industry and are used throughout development of the DUAP system. This helps in defining interfaces for DUAP to access and configure field devices. Consistently using standards promotes common interfaces between devices and across brands. Issues can arise due to differences in the interpretation of these standards. By adhering to these standards, DUAP is able to create a base set of interfaces which can be reused for different brands and models of a specific device.

Working closely with MDOT and establishing a robust user community provides feedback and additional user needs which will continue to drive development of new applications within the DUAP system.

2.2 DUAP2 System Architecture

The DUAP2 project was based on the presumption of data being available from the efforts of other CV projects. Activities pursued as part of DUAP2 were intended to define and develop applications using that data within MDOT and other transportation agencies.

DUAP2 research and systems development paralleled the development of the data sources by USDOT, the VIIC and others. The means of collecting and presenting data were coordinated with those developments and implemented on an accelerated schedule. MDOT pursued procuring data from various sources including but not limited to:

- Fixed vehicle detection station observations of speed, volume and lane occupancy from the MVDS data feed

- Data from MDOT's VIDAS consisting of mobile environment and asset information

- Road Weather Information System (RWIS) fixed station environmental data

- Information from MDOT's dynamic message signs

- Automated Vehicle Location (AVL) or Winter Maintenance Trucks (WMT)

- Automated Surface Observation System (ASOS)/ Automated Weather Overserving System (AWOS)

The data from these MDOT systems, along with information from the National Weather Service (NWS), provided the DUAP2 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—in order to support existing and new MDOT applications. The output from the DUAP2 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 DUAP2 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. This concept is illustrated in Figure 2. Constructing the DUAP2 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.
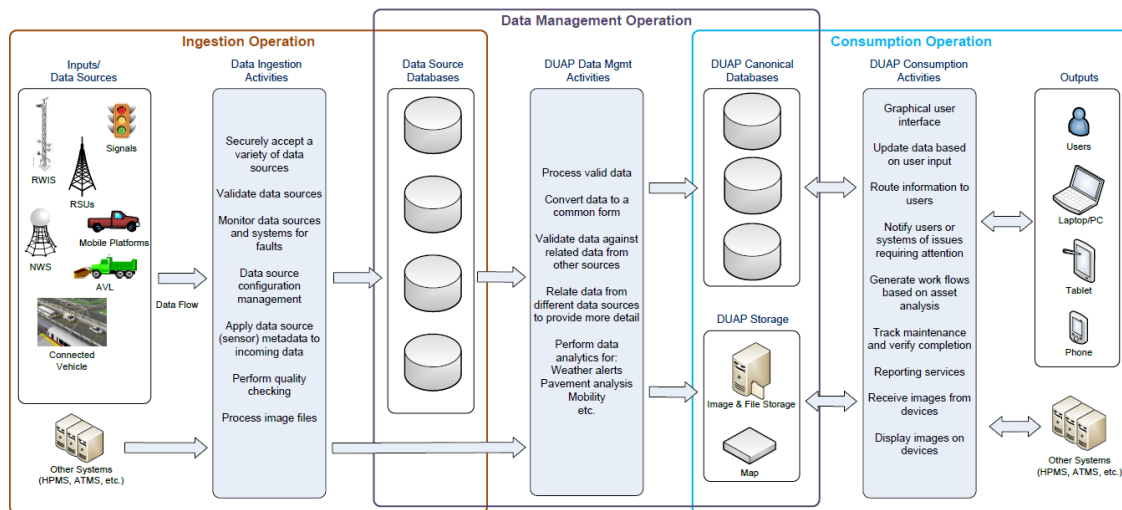
Figure 2 – DUAP2 Process Interactions

2.3 Procedures

This section provides an overview of the system created to support the DUAP2 project. Details include the user interface, security, data sources ingested to support the applications, and storage of the data. These facets of the system explain the procedures the system uses and how they provide the necessary information to support the agency.

2.3.1 User Interface

The user interface is the core application for the consumption process of the system as shown in Figure 2. Other aspects of this process will be described in subsequent sections.

The web application is viewable on browser equipped computers and devices such as tablets and smart phones. Where possible, a responsive Graphical User Interface (GUI) 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 DUAP application data in a geographic and time-related context. Interface inputs and controls allow the user to display system information in a geographic context for a particular time range. Consequently, the input controls allow the selection based on time and observation type. The time zone is based on the settings for the client device 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

- Analysis – graphical views of observations ingested from the data sources

- 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 UTC (Coordinated Universal Time) 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 Basic Safety Message (BSM) 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, temperature, plow status and pavement condition along with other related data elements.

The pavement information includes photos of current conditions, road segments as specified by the Michigan Geographic Framework, and possible pavement defects located from the data collected by the VIDAS devices.

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, as illustrated in Figure 3. The aggregated information is also passed to MDOT's Advanced Traffic Management System (ATMS).
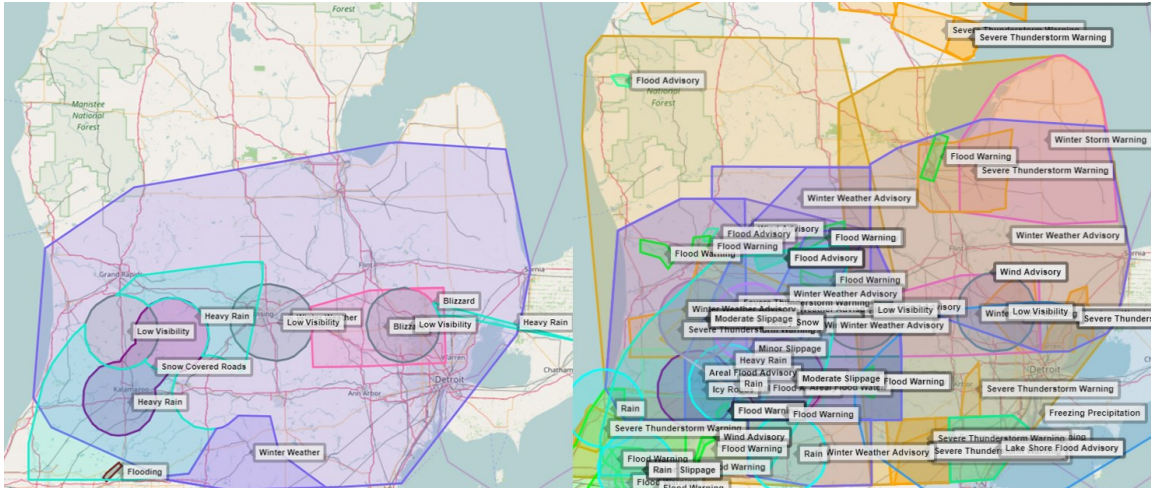
Figure 3 – Weather Alert level Comparison

The traffic-based information includes traffic detection, Closed Circuit Television (CCTV) camera images, message signs, lane restrictions, incidents, traffic signal phases, and CV Roadside Unit (RSU) status. The data are from different systems within MDOT and its vendors.

As mentioned above, the system allows for animation, a historical playback of some of the information available on this screen. Items that include the option to "Include in Animation" are available to view how they change with time based on the selected time frame. This option will display the movements and changes of the observations (vehicles, weather, and traffic signal phases) over the specified time. The playback of this information can be paused, restarted, or the playback speed can be changed. This ability allows the user to see how different information relates and how responses to the situation were coordinated.

The applications allow for selection of any combination of information to allow the user to answer a variety of questions and observe how different aspects of the infrastructure and environment interact.

Most observations displayed on the map include an option to view additional detailed information via popups or detailed panes on the screen. This information can include metadata for a device or the observations collected by the device at the specified time. Legends are also provided to further describe the information being viewed. A legend for the vehicle paths specifies, based on color, whether a plow was down on a winter maintenance vehicle and whether road treatment materials were being applied. There is also a legend for the weather alert polygons. These are color coded to specify the type of alert being displayed. Labels for these alerts can also be shown to assist in the identification of an alert.

Checkboxes are used to turn on and off selections throughout the application. This allows the user to quickly change their selections being displayed to target the information needed.

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. The traffic report displays information based on Microwave Vehicle Detection System (MVDS) observations for the specified highway and time frame. This report aggregates the data specified to show averages across the time selected. The report rows are based on lanes and sensors along the selected route.

Reports can also include a graphing option based on the observations such as displaying 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 use of accelerometry data in pavement condition analysis is further described below. This graphing tool allows the user to see values at any given point along the graph and how the four graphs relate. The accelerometry data is in three axes as depicted in the graphs, as shown in Figure 4. The fourth graph, Net Magnitude in the example, contains the net vector of the three axes. The z-axis which is the vertical axis is offset at negative one showing gravity's effect on the sensor.
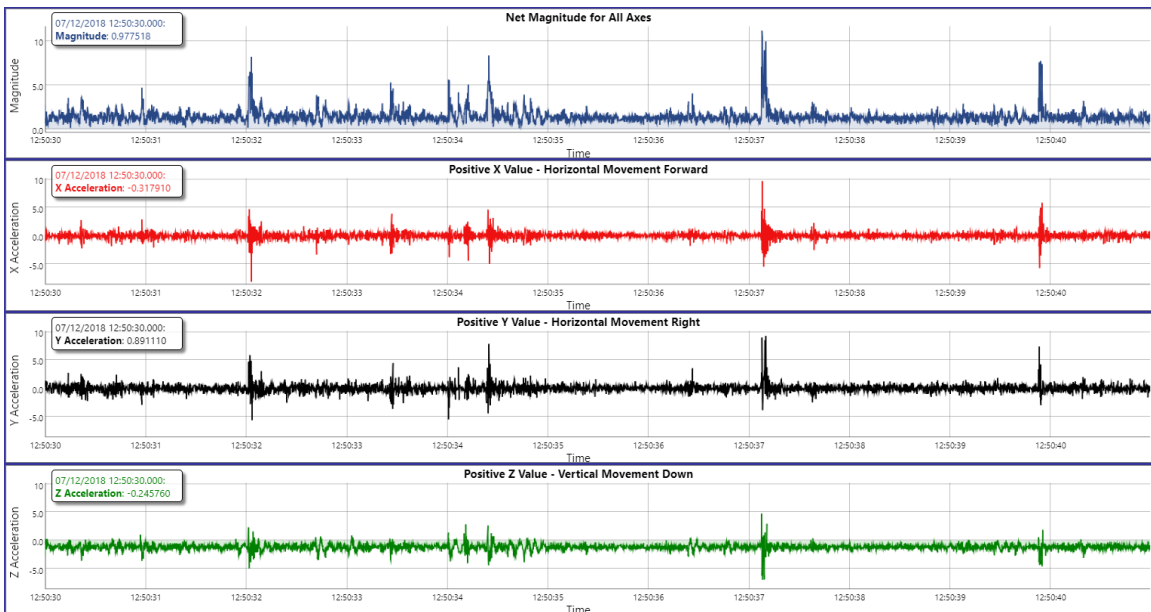
Figure 4 – Accelerometry Graph

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 modify information concerning the vehicle sensors are installed on along with which sensors have been 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 DUAP2 system to ensure the integrity of the system and its data.

The DUAP2 GUI requires user authentication to access its applications and their functionality. Each user can be assigned specific permissions to control which applications and the 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.

Processes within the system are able to monitor various aspects of the system to watch for intrusions and other nefarious situations through internal system monitoring and algorithms.

Physical security is also a concern and has been implemented to increase the security of the system and the site at which it is hosted.

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 DUAP2 system to be able to provide useful information, it must have data. The design of the DUAP2 system necessarily accommodates a 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.

Evidence suggests that the most popular data formats for information exchange are text-based—humanly-readable letters and numbers. Both character-delimited text and Extensible Markup Language (XML) 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.

Even with common data exchange formats consisting of human-readable characters, data content arrangement can vary considerably. One delimited text format might contain a single unique identifier column with its associated data located in several adjacent columns within the same record. Contrast this with another delimited format that identifies all data in three columns where the first two columns represent the unique

identifier and data type and the third column contains the data value. One might refer to these two approaches as short-and-wide versus tall-and-narrow.

XML data sources can easily be classified as anything goes. As long as the structure conforms to the published standard, elements may be labeled anything, located anywhere, and use any defined units necessary to describe data.

Even though text-based data exchange formats are popular, many data sources convey their information in native computer data structures for compactness and processing speed. These data formats are arguably as complex and diverse as their XML counterparts with the added complexity of not being easily read and understood by people. Binary and compressed files are preferred when file size is an important factor due to storage limitations or communication restrictions.

The DUAP system, through its modular data collection approach, is capable of handling the heterogeneous nature of existing and potential data sources:

- Traffic data from microwave vehicle detectors arrive in an XML format that identifies speed, volume, and occupancy at a particular time for each road loop. Other traffic data sources include HERE data (3rd party private-sector data provider).

- Dynamic message sign data from MDOT's fixed and portable signs

- Mobile weather condition data such as temperatures (both air and surface) and humidity from WMTs and VIDAS equipped vehicles

- MDOT test fleet accelerometry data from VIDAS equipped vehicles arrives as a third binary file containing 400 Hz 3-axis acceleration data

- Weather data from the NWS including observations such as temperatures, humidity, atmospheric pressure, precipitation and conditions; radar information such as precipitation and store motions; and warnings and alerts such as storm warnings and watches

- CV test bed data including BSMs from equipped vehicles and traffic signal data

- Camera Images from CCTV installations

- Weather observations from MDOT RWIS installations

- ASOS/AWOS weather observations from NWS installations within Michigan

The purpose of the DUAP2 system data collection modules is two-fold: to gather data of interest from participating sources and to extract that data for homogenous storage and retrieval by application modules to process.

The collector modules can retrieve data using different network protocols. Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP) are the most common. When data are collected, they are stored in a file and archived with a timestamp to maintain the source data in its original format. As data are being copied to the archive file, they are also being processed in their native format and parsed into the DUAP system storage structure.

The data sources ingested by the DUAP system for its application are described in the following sections.

2.3.3.1 Microwave Vehicle Detection System (MVDS)

MDOT provides traffic related data based on MVDS installations. Speed, volume, and lane occupancy are provided from the vehicle detection stations every minute. These observations are ingested by the DUAP system and provided to the user though the map interface for specific locations and reports aggregating the data based on a selected time frame. Locations of the sensors are stored as metadata and related to the observations within the database.

2.3.3.2 VIDAS Platform

MDOT fleet vehicles equipped with the VIDAS platform provide mobile data to the DUAP system. The VIDAS platform provides the ability to install a variety of sensors on a vehicle. The currently installed sensors collect data about the vehicle's mobility, the environment, and the pavement depending on the configuration.

Observations may include:

- Latitude
- Longitude
- Date/time
- Vehicle speed
- Ambient air temperature
- Surface temperature
- Barometric pressure
- Dew point
- Accelerometry (3-axis)
- Inertial rotation (3-axis)
- Distance to the pavement
- Camera images

Due to the different collection frequencies of the data, the platform creates three types of files.

- Mobility – contains time, vehicle location, speed, and environmental observations at 5 Hz

- Accelerometry – one file from each accelerometer which includes time, location, accelerometry, and inertial rotation observations at 400 Hz

- Distance – contains time, location and distance from the sensor to the pavement at 200Hz
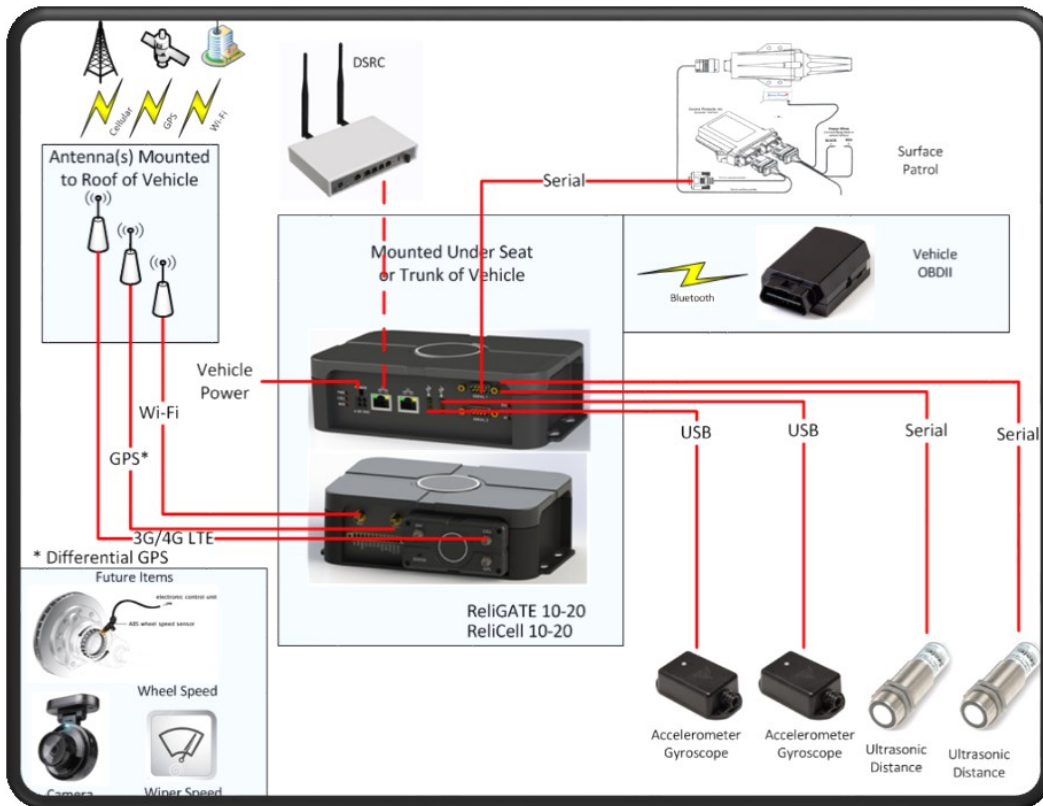
Figure 5 – VIDAS Platform

The data is stored in binary files to decrease the file sizes and minimize transmission costs. The larger files, accelerometer and distance, are sent to the DUAP system via Wi-Fi to minimize cellular expenses. Mobility data is needed closer to real time and 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, vehicle locations, and the condition of pavement. Analytics are performed on the data after ingestion to glean the information important to the agency.

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
- RWIS observations
- Mobile environmental data

The NWS operates four radar installations in Michigan. The radar JPG (Joint Photographic experts Group) 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 Automated Surface Observation System (ASOS) and Automated Weather Observation System (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. DUAP contains a list of all of the stations for Michigan and is able to gather the observations for these stations.

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.

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 Traffic Signals

Traffic signals within Michigan can transmit phase data to the DUAP system. This data arrives at 10 observations per second. The data describes the current phase of the controller along with times until the next phase change. The Map screen described above can display this information to the user.

Analytics can be created to help in analyzing how changes to phase timing would impact the traffic system. This would assist agency operations in developing more efficient timing plans for a traffic corridor.

2.3.3.5 Automatic Vehicle Location (AVL)

A portion of MDOT's fleet of maintenance vehicles have AVL devices installed. The DUAP2 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 DUAP2 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:

- Display location of maintenance vehicles
- Display routes covered by the vehicles
- Track winter maintenance activities such as plowing and distributing materials
- Track effects of plowing and use of material on pavement surfaces
- Camera images of roadway surface condition statement ahead of vehicles

2.3.3.6 Connected Vehicles

RSUs installed within Michigan are able to send messages they receive to the DUAP2 system. BSMs from equipped vehicles are received by the RSUs. Those are forwarded to

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the DUAP2 system for ingestion. The BSMs primarily contain information about the vehicles location and movement. Additional information may be included depending on the On-Board Unit (OBU) vendor and configuration of the OBU.

The DUAP system can 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.

2.3.3.7 Dynamic Message Signs

MDOT provides metadata and message details for the agency's dynamic message signs. This data is ingested by the DUAP system and provided to users for viewing details of the messages currently being displayed on each sign.

2.3.4 Storage

Information can be considered complete when it answers six questions: who, what, how, where, when, and why. The DUAP system has adopted a data model that fulfills the answers to these questions. The fundamental unit of data within the DUAP system is called an observation. An observation can briefly be described as a direct association of a specified measurement retrieved from a source for a location at some time with a magnitude. An observation directly addresses five of the six questions for information completeness:

- Who – each observation keeps track of the source of information. The source is usually called a contributor and can be an organization or data system operated and maintained by an organization.

- What and How – each observation is associated with a type, and the type defines what the observation is and how the observation was obtained.

- Where – this could be defined as any location within the context of the DUAP system. In this case the location is defined by geo-coordinates that include latitude, longitude, and elevation.

- When – this is the time a measurement was taken. It is measured in milliseconds and is relative to UTC. It is possible to use future times to represent predicted states.

Answering the why question is the purpose of the DUAP2 system. Applications use the stored observations to derive new observations and provide the context in which the observations can be compared to infer the reasons for any given transportation state. If a set of vehicles are presented as having a speed of zero for a few minutes on an arterial road segment, an application could infer that the reason is that the traffic signal was presenting the stop condition. If the queue persists for many minutes, an application might infer there is a collision or a stalled vehicle as the reason.

The DUAP2 system data ingestion processes read and process data from each source in its native format. The data are transformed into observations based on the definition in this section by the data management processes. These observations are stored into databases within the DUAP2 system. An archival process also stores the collected data in

its native format in a file that is tagged with the source and collection time for future retrieval and verification needs.

The DUAP2 system applications provide measurement type and geographic and time context. To this end, data are indexed by type, geographic location, and time as they are converted to system observations. These indexes greatly improve processing speeds so that there is very little delay between new data being received and an application being able to inform a user of the resulting transportation system states.

3 FINDINGS

The efforts of gathering requirements from stakeholders, performing detailed analysis, and gathering and evaluating the practical application of gathered data resulted in a software suite that is the DUAP2 system. The DUAP2 system collects data of interest from participating data sources and processes those data into useful information that can be visually presented to decision makers.

3.1 Summary of Data

The following sections describe the projects and applications developed for those projects including the information the applications produced based on the data sources ingested to support them.

3.1.1 Projects

Various projects were supported by the DUAP system. Applications within DUAP related to these projects are further explained in Section 3.1.2.

3.1.1.1 Weather Response Traffic Information System (Wx-TINFO)

MDOT's operations functional area is responsible for notifying the public of events that may affect travel. Using ATMS they are able to update dynamic message signs and their 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 groups responsible for controlling these notifications had to access various tools to gather a view of current weather events. The Wx-TINFO 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 the 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
- Mobile environmental data
- ASOS/AWOS

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 Dynamic Message Signs (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.

3.1.1.2 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 Signal Phase and Timing (SPaT) and MAP messages at equipped intersections

- Broadcast Traveler Information Message (TIM) messages for traveler information including speed limits and curve speed warnings

- Broadcast Crash Avoidance Metrics Partnership (CAMP) Basic Infrastructure Message (BIM) messages containing details about work zones

- Capture of BSM messages by the RSUs

RSUs must be configured with the proper message information to be broadcast. MAP, TIM, and BIM message detail 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, 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. Additional details are described in the section discussing the CV application.

3.1.1.3 Tank Automotive Research, Development and Engineering Center (TARDEC)

MDOT supported the US Army in the testing of platooning vehicles along a highway using CV technology developed by TARDEC. This project field tested a variety of situations including:

- Speed limits broadcast by RSUs

- Curve speed warning information broadcast from an RSU

- Parking information broadcast by an RSU

- Emergency vehicle location broadcast by an OBU

- Disabled vehicle broadcast by an OBU

The DUAP system was instrumental in helping with the configuration of the RSUs and OBUs used in the project. BSMs from the platoon vehicles were received by DUAP to allow the monitoring progress of the test along with the ability to view the data historically to assist in analysis of the project's success.

3.1.1.4 Saginaw

MDOT instrumented a highly-traveled section of Saginaw Highway in Lansing, MI with RSUs at intersections under the Integrated Mobile Observation (IMO) 3.0 Project with funding from the USDOT. Using the VIDAS platform and OBUs the IMO 3.0 Project instrumented 14 vehicles. This installation was 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 being used for configuration of these devices, monitoring the devices, capturing the data, and providing the information to MDOT through applications. Through DUAP applications users can upload MAP data

3.1.1.5 Macomb County

MDOT, Macomb county, and General Motors teamed up to install CV devices at two intersections, a work zone, and in GM vehicles. The initial applications involved red light warnings and work zone reduced speed warnings.

The DUAP system, assisted in the configuration of the RSUs used in this project. It also captured the traffic signal phase data from the traffic controllers and the BSM messages from the GM vehicles within range of the RSUs. Using the DUAP application the team was able to trouble shoot the OBU applications by monitoring the signal phase data and the vehicle locations.

3.1.1.6 I-275 Construction

MDOT's major construction project on I-275 was supported by the DUAP system. The construction project was a replacement of the existing pavement. This involved major detours during the project and changes to impacted areas on a frequent basis. These changes to lane closures were entered into the Traffic Flow Restrictions (TFR) application within DUAP. This information was then routed to external systems to notify the public of changes in work zone configuration as they happened.

In addition to the work zone monitoring processes, the new pavement on I-275 provided a baseline for new pavement within the DUAP Pavement Condition application. This

data was gathered using a vehicle equipped with the VIDAS platform which supplied accelerometry data to the DUAP system for analysis and to be used as a baseline for trending of the pavement.

3.1.1.7 Oakland County

MDOT is working with Oakland County to instrument intersections with CV devices.

DUAP applications are assisting in the configuration of the installed devices, including installing TIM messages to be broadcast by the RSUs. The DUAP system is also receiving traffic signal phase data and BSM messages from equipped vehicles within the infrastructure.

3.1.2   Applications

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. Solutions based on obtaining the location of particular vehicles—for example, AVL systems generally have been for fleet operations or for supplementary probe data.

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 travel times to be utilized by the agency and the traveling public.

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.

3.1.2.2 Pavement Condition Monitoring

The VIDAS platform provides an opportunity to improve pavement condition monitoring by capturing observations from more widely-distributed, lower-cost sensors than are currently available to transportation agencies. Knowledge of pavement conditions is important to a transportation agency's planning processes and State DOTs are required to provide these data to the USDOT's Highway Performance Monitoring System (HPMS). Unfortunately, pavement condition measurements have been time-consuming and expensive to obtain. Advances in vehicle systems and communications are creating new capabilities that are changing the situation. In particular, it may be possible to obtain useful measures of road network pavement conditions from probe vehicle data.

Pavement is one of a transportation agency's most valuable infrastructure assets. As such, the need to preserve that asset will compel the agency to monitor the pavement condition throughout its lifetime. Measurements of newly constructed pavement provide both indicators of construction quality and a baseline for monitoring pavement wear. Periodic measurements while in service are key indicators of the need for maintenance and refurbishment.

Assessment of pavement condition takes several forms. In the broadest sense, drivers make subjective judgments of pavement condition as they use the roadways. Visual inspection may be used routinely by a transportation agency to monitor gross defects like potholes and cracks. Profilographs are often used to measure the vertical deviations in pavement as part of acceptance testing for new construction. Response-type road roughness measuring systems (RTRRMS) record the vertical motion of a vehicle as it travels along the pavement. Road roughness profiling devices measure the distance between the pavement surface and a vehicle's inertial reference point using non-contact laser or ultrasound sensors.[2]

Measures of pavement condition are diverse, reflecting both the equipment used to obtain the measure and the intended application of the measurements. The two most prominent measures are the Present Serviceability Rating (PSR), which represents individual human assessment of ride quality, and the International Roughness Index (IRI), which is an objective measure of pavement surface deviations. Correlations have been developed between these and other measures, and the IRI is generally accepted as the best common measure of pavement condition and is required by the Federal Highway Administration as the standard for ride quality index by the state DOTs.

Current MDOT pavement monitoring practices allow standard assessments of pavement statewide approximately every two years.

Monitoring pavement condition, as for HPMS input, requires consistent data sets over long periods of time—several years. The data have to be indexed precisely to the pavement segments being monitored in order to facilitate correlation to materials, use, and maintenance history. Data also need to be normalized to a consistent set of measures based on techniques and figures of merit, and seasonal biases and anomalies may need to be noted or removed.

In contrast, detecting gross pavement defects (e.g. potholes, blow-ups) requires accurate spatial discrimination. Analysis of the data allows for identification of particular events at particular locations, and identification with a particular pavement segment is secondary to the actual location. Data need to be normalized to a consistent set of measures (size or severity, for example) and be cleansed of seasonal biases.

3.1.2.3 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

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[2] The FHWA's web site for pavement information includes an excellent (if dated) synopsis of pavement measurement at http://www.fhwa.dot.gov/pavement/smoothness/rough.cfm (accessed 2010 Jan 25).

system brings together near-time environmental/weather-related data collected from both fixed and mobile data sources. Initially, the information will be made available to the traveling public via MDOT's ATMS roadside DMS and the Mi Drive website.

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. 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.

During the continual ingestion process, data will undergo numerous quality checking algorithms and other processes to ensure the validity of the information being presented. Other analytical logic will be employed to determine specific weather events indicated by ever-changing conditions. These weather events will be compiled into files that will be picked up automatically by the ATMS and made available to the ATMS operators.

3.1.2.4 Traffic Flow Restrictions

The DUAP system ingested Lane Closure and Restriction (LCAR) data from MDOT systems. This information is displayed for the user's information and use. It is also transmitted to external systems for their use in supporting Michigan's traveling public. Supplying this information to other supporting parties increases the value of the data that MDOT and the public.

DUAP also includes processes to allow approved users to enter and modify information concerning restrictions to traffic flow, including lane closures due to work zones.

3.1.2.5 Connected Vehicles

The DUAP system provides support for CV implementations. 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 devices are developed according to industry standards to attempt to coordinate interfaces used to access the devices and for processes configuring the devices. Differences in the interpretation of the standards and implementation of these interfaces causes inconsistencies within the CV arena. The back-office processes must be able to adapt to these differences to help provide a consistency to the agency deploying the CV infrastructure.

The DUAP system takes this into account in its design. It abstracts these differences away from the user to simplify configuration management of the devices and to present a consistent interface to the user.

3.2   Method of Analysis

The objective of the application analyses, as a subset of DUAP's larger goals, is to investigate and, if possible, demonstrate enhanced transportation agency operations based

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on CV systems and data. 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 DUAP system itself and a common set of capabilities and systems. The needs of a particular application derived largely from the objective served by that application, its associated performance measures, and the physical and operational nature of the application. At a conceptual 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.

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.

As a system, DUAP incorporates many applications to meet the needs specified by the DOT. Developing these applications within the one system provides the ability to share the data, information, and functionality between applications yielding many benefits such as:

- Collecting the data element one time to be used in multiple ways

- Leveraging information from multiple applications to provide a more complete picture of the transportation infrastructure and its use

- Allowing users to make decisions based on multiple types of information

DUAP continues to evolve based on expansion of data sources, feedback from users, and improvements in technology. Existing applications continue to grow, and new applications will be introduced increasing the benefits and value of the data collected to the DOT.

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 variety of applications, within DUAP, and their varying resource needs creates a complex system. While applications can share these resources, each application's requirement for a given resource differs. This drives the need for a variety of resources along with flexibility within these resources. Complex functional resources, such as analytics, neural networks, and creating a living system which is constantly evolving, yields a very involved set of processes making up the DUAP system.

As described below, the DUAP system allows the DOT to have hands-on use of its applications. This experience will continue to support research to further expand the use and growth of the system.

3.2.1 Applications

The following sections detail the primary application within the DUAP system. They provide examples of the abilities of the system in reusing currently available data sources and providing value across all functional areas.

3.2.1.1 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[3] found that probe vehicle

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

populations on the order of 10% 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.

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

- Assisting in traffic signal phase planning

- Improving response time to incidents

3.2.1.2 Pavement Condition Monitoring

Installing sensors on MDOT's fleet of light vehicles to capture data for monitoring pavement condition allows the agency to capture the asset data during normal work routines. This data can be analyzed by the DUAP system to assist in determining pavement conditions. Indications obtained in this manner could then be used to notify maintenance managers of conditions that may require maintenance actions or a more precise assessment.

Deploying the VIDAS platform on these vehicles allows the agency to leverage the flexibility of the platform to instrument the vehicles with a variety of sensors depending on the asset coverage the driver provides and the needs of the agency. This flexibility allows the agency to more effectively meet its needs in operating and maintaining its assets.

Pavement condition concerns for the agency involve weather specific conditions affecting the traveling public and guiding winter maintenance activities. The weather sensors provide a mobile view of weather conditions which fill in gaps between the fixed NWS and agency owned weather stations within DUAP. Together this information creates a more detailed view of what is happening to the pavement during winter weather events.

Other sensors integrated with the VIDAS platform provide information about the quality of the pavement surface. These include accelerometers and distance sensors. These sensors assist in capturing the roughness of the surface.

Data obtained from equipped vehicles would be correlated with other observations to synthesize relative measures of pavement conditions and performance. Since vehicle designs can vary, data from each vehicle observation platform would be calibrated to a known set of pavement conditions. Calibration is likely to depend on the observation type, sensor, sensor installation and configuration, and vehicle configuration. Data from all vehicle observation platforms could then be transformed into a standard set of normalized pseudo-observations.

Data acquisition and characterization for data received from the accelerometer equipped MDOT fleet most closely resemble the response-type road roughness measurements used

prior to more detailed profilometric techniques. Parameters of specific interest to pavement condition monitoring include: acceleration on three axes, vehicle speed, and tire pressure, and individual wheel speed (if available). Other vehicle data may also be evaluated for correlation with road conditions.

Data collection parameters can generally be inferred from prior pavement condition monitoring practices. For example, longitudinal profilometry is typically recorded at one-inch intervals. Profiles are then typically blanked (small variations, less than 0.2 inches, are ignored) and notch filtered (removing both high and low frequency variation). Profiles can then be aggregated or averaged over various path lengths to get figures of merit for roughness. Comparable accelerometry data at 60 miles/hour (88 feet/sec) would be recorded at approximately 1 millisecond intervals, although this could provide substantially more data than would be needed to generate the relevant statistics.

Using three-axis accelerometers mounted on the vehicle's suspension allows the data to closely mirror the tire's reaction to surface roughness. The orientation of the device relative to the acceleration components to be measured can also have a large impact on measurement accuracy[4]. Mounting the sensor in line with the axes of the vehicle will assist in understanding gravity's impact on the data and allow for more accurate analysis. Depending on the slope of the vehicle, gravity's affect can be seen in multiple axes. The impact of this on the data needs to be considered. Changes in speed and direction of the vehicle are also sensed by the accelerometers. This can impact what is seen while analyzing the data and will need to be considered as well.

3.2.1.3 Weather Alert System

Weather affects many aspects of the agency and the traveling public. The NWS 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, and 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. Integrating these processes into DUAP solves this problem.

DUAP is ingesting weather-based data from:

- NWS radar files

- NWS observations from fixed weather stations

- NWS alerts

- NWS forecast information

- MDOT RWIS fixed stations

- Mobile VIDAS platforms

- Mobile AVL fleets

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[4] http://www.pcb.com/techsupport/tech_accel.php

The different weather data information is combined within DUAP 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.

Once the alert is created, the user may view the information within the DUAP GUI. In addition, these alerts can be sent to other 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

3.2.1.4 Traffic Flow Restrictions (TFR)

Lane restriction information is important in guiding the travelling public through the infrastructure. DUAP ingests LCAR data from MDOT's ATMS and other systems specifying impacts from work zones and incidents. Combining this information from the separate MDOT systems provides a more complete view of restrictions to traffic flows within the infrastructure and how they impact the travelling public.

Allowing the agency to maintain this information in a timelier manner increases the value to the agency and public with more accurate information.

Providing this information to MDOT's partners allows the public to use a variety of sources to obtain this information and increases the timeliness of the data. This improved access to the traffic flow restrictions and their impact has multiple benefits to the public and the agency, including:

- A reduction of traffic congestion at the impacted site
- A more positive public view the agency
- Reduced environmental impacts

3.2.1.5 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.

The DUAP system's modular design has allowed MDOT to remain on the forefront of the CV movement. The ability to present the information to the agency to help them understand how the CV data can be leveraged increases the value of the information and assists the agency in performing its duties.

3.3   Presentation of Results

3.3.1   Applications

The DUAP system incorporates a variety of applications throughout the three phases of the system: ingestion, data management, and consumption. This modular design allows for quick adaptation to changes in data sources and agency needs and provides reuse of system resources. The following sections provide details of the different applications developed to meet MDOT's needs.

3.3.1.1 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. For a selected time frame, the user can select types of vehicles and from a list of actual 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. The 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.

3.3.1.2 Pavement Condition Monitoring

The survey and analysis for pavement condition analysis applications used the MDOT fleet equipped with the VIDAS platform described in Section 2.3.3.2 to collect accelerometry data. These 14 vehicles were equipped under MDOT's IMO 3.0 Project.

The VIDAS platform included two three-axis accelerometers. One sensor on each front independent suspension arm to provide a data related to each wheel path.

The IMO 3.0 Project looked at the benefits of collecting and integration CV data and environmental data for transportation management and operations. DUAP was used in the IMO 3.0 Project to aggregate, analyze, and display the data. The experience with those projects fed into the DUAP2 project. Under DUAP2, data were collected through a wireless access point at the originating MDOT facility for uploading to the DUAP system. Figure 6 illustrates the demonstration configuration.
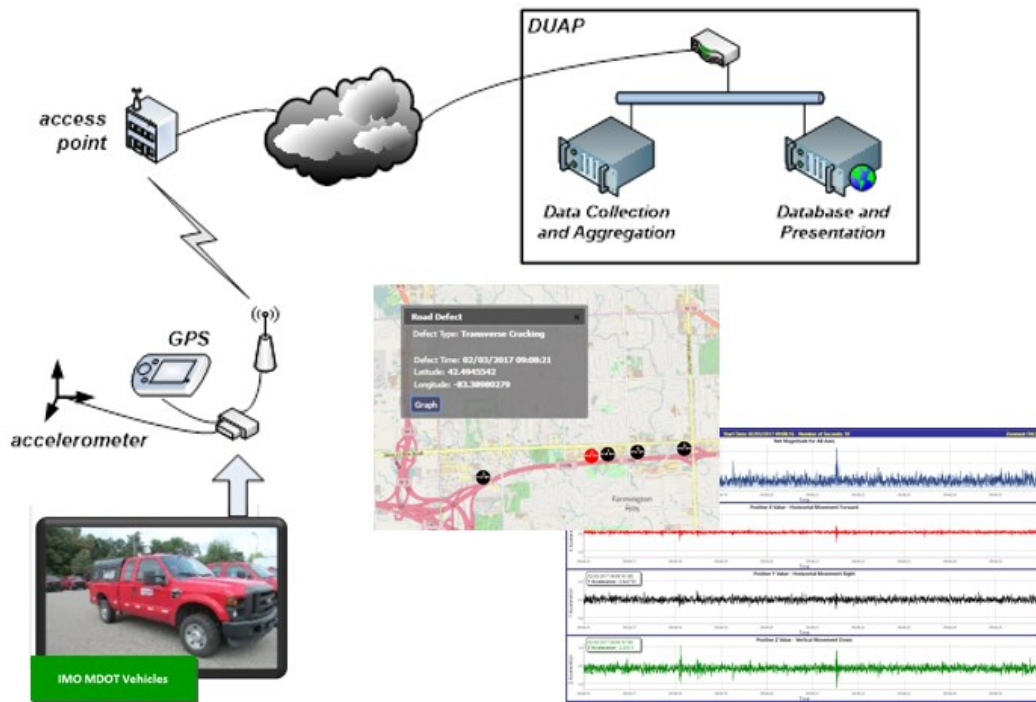
Figure 6 – Pavement Condition Demonstration Configuration

Test routes were selected to provide convenient and effective data collection. Routes started and ended at a MDOT facility with a network access point for data uploads; included a variety of roadway segment types; and showed a variety of pavement conditions and defects. Multiple passes were planned for each route.

Accelerometry, vehicle position, and vehicle speed were synchronized for data logging. The three axes of acceleration data were recorded every 2.5 milliseconds (400 Hz). The GPS data of latitude, longitude, elevation, speed, and heading were reported and logged 5 times every second. Data logging was stopped and data was uploaded after each trip over a test route was completed.

Typical accelerometry results can be displayed for specific pavement defects. The small graph within each figure shows the three axes of acceleration in red, black, and green. The blue graph is the net force vector of the three axes. This defect was run multiple times to determine consistency of the data collection process.

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The similarility of the data shows promise in the capture of the acceleromtery data for the defect. Some of the concerns to be addressed by improvements in the platform or the analysis include:

- Accuracy of the GPS system to ensure defects are located at the proper location

- Consistency between vehicles due to differences in weight, suspension, tires, and other factors affecting the accelerometry sensors

- Accuracy of the installation and vehicle metadata, e.g. sensor location and tire spacing.

Multiple rounds of testing were performed to determine the best mounting location for the accelerometers on the mobile platform. Locations consisted of both body and suspension mounting locations. The body mounts were able to sense most of the defects though the suspension mounted sensors provided a more detailed view of the pavement surface.

Using the road defect application within the DUAP system the user is able to view locations of suspected defects within the agency's infrastructure along with viewing the data analyzed to determine the defect location and type. The icons can represent one or more defects within configurable distance. Selecting a defect will present information about the type and location of the main defect represented.

Pavement conditions varied from new to severely degraded for testing runs. Data was captured on new pavements to use as a baseline in locating defects. Testing was performed on a variety of defects including but not limited to potholes, transverse cracks, and alligator cracking. Progress was made on detecting the larger defects and the study shows promise on analyzing the smaller or less severe defects though further development is required to improve the process.

Measurements were loaded into the DUAP system for comparison, analysis and correlation. DUAP puts all the data feeds into consistent formats and time/space context.

These results are representative of all vehicles, sensing devices, and segments surveyed.

- Accelerometry is, as expected, variable between sensing devices and vehicles. It is, however, relatively consistent between passes by the same device and vehicle over a given segment.

- Sensed accelerations provide an adequate base for approximately locating pavement defects. Locations are relatively consisent across devices and vehicles.

- Statistics derived from sensed accelerations can provide relative indications of vehicle ride response from segment to segment for a given vehicle. It *may* be possible with sufficiently large data sets to correlate a given vehicle and device's characteristic responses to other pavement condition measures like IRI or PASER rating.

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 or weather impacts on the system.

Supplying these alerts through DUAP and 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 is happening at specific locations. Building the system to handle different levels of granularity enhanced the weather reporting and the use of the information.

As new weather data sources are identified, they can be added to DUAP ingestion and incorporated with the weather alert analysis processes to continue to expand and improve the accuracy, detail, and usage of the weather alert system.

3.3.1.4 Traffic Flow Restrictions

MDOT needed a method of relaying information about work zones and their changes to the public in a timely manner. Alerting the public to existing and changing work zones has many benefits including:

- Relieving the road affected of a portion of its usual traffic which can:
  - Decrease traffic incidents
  - Decrease traffic backups
  - Decrease impacts on environment
- Decreasing the public's frustration over the construction events by keeping them up to date with changes and activities
- Decreasing environmental impacts by directing traffic around impacts on traffic flow.

TFR was developed to meet this need by capturing the information concerning work zones and their changes and by transmitting the information to other external systems for dissemination to the public.

TFR Entry is an application for entering and modifying information detailing lane closures related to construction projects. The user enters the specific details of the closure, maps the geographical route, and then saves this information which can then be displayed on the map and sent to other external systems to assist in notifying the public of the construction projects. The information collected from the use of this application includes agency specific reference data, location details, time frame for the closure, reason and descriptions of the closure, and detour information. Part of the location information includes the geographical description of the affected route. This consists of a series of latitude and longitude pairs. Once a closure is created a user may use this same process to make changes to the information by selecting the closure from a list and using these same screens to enter the changes.

Closure information can be displayed on the map. This includes closures received from MDOT's systems such as ATMS and closures entered through TFR.

Using this application along with the traffic information can continue to improve quality of the information available concerning the closure and its impact on the local traffic. This information can help guide operations and maintenance in dealing with the closure and the traveling public.

3.3.1.5 Connected Vehicles

The CV applications cover a variety of areas.

Message types:

- SPaT: Traffic signal phase and timing information can be received directly from the traffic signal controllers and ingested into DUAP and sent to the RSU to be broadcast to listening devices such as OBUs. DUAP can also receive the data from the RSU for ingestion.

- MAP: The DUAP system can assist in configuring the RSU with the MAP data (i.e., intersection map) for MAP broadcasting and for converting signal phase data into a SPaT for broadcasting along with the MAP.

- TIM: DUAP can assist in configuring the RSU with TIM (Traveler Information Message) messages for broadcast to CV devices for traveler information.

- BIM: RSUs can be configured with a CAMP BIM (Basic Information Message) for broadcasting. DUAP can assist in the creation of the BIM information and the RSU configuration for the message

- BSM: RSUs receiving BSM message from mobile devices can forward the messages to the DUAP system for analysis.

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

- 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.

4   DISCUSSION

4.1   *Validity of Hypothesis*

The hypothesis of the ability of a system to share data from a variety of sources for the benefit of the entire agency has been shown during the DUAP2 project. The DUAP system included a variety of applications which leveraged the same data sets. The weather application created under the Wx-TINFO project demonstrated the use of weather related data which was analyzed and used to generate information for both operations and maintenance functional areas. The information was reported at different levels of detail to better meet the specific users' needs.

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 application, in a variety of ways to meet varying needs of the different functional areas.

4.2   *Factors Affecting the Results*

The main factor which currently exists in the ITS industry is the low density of data. The infancy of the connected vehicles has limited the data available. As MDOT continues to expand their CV footprint this will continue to improve. DUAP has shown how the value from the data can increase as the number of installations and device market penetration grows.

The current applications and their results have been based on currently available data sources. DUAP's access to existing and new data sources allows the system to leverage existing infrastructure and information to additional uses over what it may have been originally intended. As DUAP continues to receive additional data sources this value will continue to be realized.

4.3   *Implications*

The results of the DUAP2 project demonstrate that data can be shared and disseminated in a variety of ways in order to meet the needs of different functional areas. Data sources will continue to expand and become more complete across the infrastructure. This data will increase in value as the DUAP system provides new applications reusing the information to benefit different areas of the agency meeting their variety of needs.

These benefits imply a value in continuing to expand the applications' functionality and usage to increase the significance of the system and the value to the entire agency.

5   CONCLUSIONS

5.1   *Conclusions from the Study*

5.1.1   DUAP System Capabilities

DUAP has been successful in fulfilling its original purpose—to evaluate uses and benefits of data from various sources and types within the entire 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

- Sorting and aggregation 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

During this project, DUAP'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 DUAP 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?"

5.1.2 Data Collection and Standards

DUAP experience with data collection has demonstrated its ability to acquire and aggregate data from multiple sources and formats into an integrated repository. The 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.

5.1.3 Applications

Viability of any particular application of 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. As described earlier, DUAP application development proceeded most effectively when data originated with vehicles and systems directly under MDOT's control.

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.

Pavement defect detection has been demonstrated in this project and should be achievable across the DOT with currently available technologies. Equipment deployed on a relatively small fraction of the DOT vehicle fleet around the state would gather data as part of the normal operations of the fleet vehicles. This application would enable the DOT to reduce the time and resources needed to identify pavement defects like potholes and blow-ups.

Correlation of vehicle accelerometry with known pavement conditions is possible—but will need additional research to confirm and reliably demonstrate.

5.2   Recommendations for Further Research

DUAP's purpose, simply stated, was to assess the use of data from CVs (originally, vehicle-infrastructure integration) to improve transportation agency operations. DUAP research was therefore based and developed on a presumption of data being available from other CV projects. Activities undertaken as part of DUAP were directed at applications of that data within MDOT and other transportation agencies.

The DUAP research was forced to take an expanded approach when the original connected vehicle Proof-of-Concept demonstration did not produce the intended volume and variety of CV data. Other sources of vehicle probe data outside MDOT had similar issues of scale and diversity, and were additionally found to be cost-prohibitive. DUAP research therefore turned toward identifying and developing sustainable sources of data within MDOT to support transportation agency applications. Provisions were made for collecting data from MDOT's own fleet vehicles equipped with a variety of mobile platforms across the state. The system used to collect the data has enabled the DUAP program to demonstrate the ability to collect data and provide applications specifically related to the improvement of DOT operations.

Based on this experience, it is recommended that further research using the system demonstrated in DUAP2 continue to be developed in on-going programs. DUAP will

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continue to identify, develop solutions for, and fulfill the data needs of MDOT as they contribute to improving the cost efficiency and enhancing the effectiveness of its operations, with the emphasis on integrating mobile data gathered as part of MDOT's ongoing operations with other data sources from across the agency. Applications to be considered for continuing research should include, but not necessarily be limited to those addressed in the recent research.

5.3   Recommendations for Implementation

The next phases of the DUAP system will continue to add new data sources for it to ingest. As installation of CVs and their infrastructure continues to expand this will increase the information available through the system. 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.

Using the multitude of data sources capture by DUAP, additional applications can be added to the system to meet the needs of all of the functional areas within the agency.

The goal of the DUAP system is to leverage data being collected by a variety of systems to provide the agency with:

- Improved public safety

- Cost efficiencies

- Improved effectiveness of its operations

- More complete information concerning the transportation system

- Decreased environmental impacts

- Integration of data sources – collect it once and use it many times

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.

DUAP has shown, through its applications, examples of how these benefits can be met as the 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
AASHTO	American Association of State Highway and Transportation Officials
ASOS	Automated Surface Observation System
ATMS	Advanced Traffic Management System
AVL	Automatic Vehicle Location
AWOS	Automated Weather Observing System
BIM	Basic Infrastructure Message
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partnership
CFR	Code of Federal Regulations
ConOps	Concept of Operations
CSV	Comma Separated Values
CV	Connected Vehicles
DOT	Department of Transportation
DUAP	Data Use Analysis and Processing
FHWA	Federal Highway Administration
FTP	File Transfer Protocol
g	Unit of gravitational acceleration; 1 g equals 32.2 feet per second-squared
GPS	Global Positioning System
GUI	Graphical User Interface
HPMS	Highway Performance Monitoring System
HTTP	Hypertext Transfer Protocol
Hz	Hertz; 1 Hz equals one cycle per second
IEEE	Institute of Electrical and Electronic Engineers
IMO	Integrated Mobile Observations
IRI	International Roughness Index
ITS	Intelligent Transportation Systems

Term	Definition
JPG	Joint Photographic experts Group
MAP	Map Message with intersection geometry
MDOT	Michigan Department of Transportation
MVDS	Microwave Vehicle Detection System
NEMA	National Electrical Manufacturers Association
NTCIP	National Transportation Communications for Intelligent Transportation System Protocol
NWS	National Weather Service
OBD-II CAN	On-Board Diagnostics II Controller Area Network
OBU	On-Board Unit
O-D	Origin-Destination
PASER	MDOT subjective pavement condition measure
PSR	Present Serviceability Rating
RSU	Road Side Unit
RTRRMS	Response Type Road Roughness Measuring System
RWIS	Road Weather Information Systems
SAD	System Architecture Description
SAE	Society of Automotive Engineers
SDD	System Design Description
SPaT	Signal Phase and Timing
SRS	System Requirement Specification
TARDEC	Tank Automotive Research, Development and Engineering Center
TFR	Traffic Flow Restrictions
TIM	Traveler Information Message
TMC	Traffic Management Center
TSC	Transportation Service Center
USDOT	U.S. Department of Transportation
UTC	Coordinated Universal Time
VIDAS	Vehicle-based Information and Data Acquisition System
VII	Vehicle Infrastructure Integration
VIIC	VII Consortium

Term	Definition
Wi-Fi	A trademark of the Wi-Fi Alliance and a brand name for IEEE 802.11 wireless networking services
WMT	Winter Maintenance Trucks
Wx-TINFO	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   Michigan Department of Transportation. (January 9, 2007). *Vehicle-Infrastructure Integration Strategic and Business Plan.* Lansing, MI: Michigan Department of Transportation.

2   Michigan Department of Transportation. *VII Data Use Analysis and Processing: Concept of Operations*. Lansing, MI: Michigan Department of Transportation, 2007.

3   Michigan Department of Transportation. *VII Data Use Analysis and Processing: Requirements Specification*. Lansing, MI: Michigan Department of Transportation, 2007.

4   Michigan Department of Transportation. *VII Data Use Analysis and Processing: System Architecture Description*. Lansing, MI: Michigan Department of Transportation, 2007.

5   Michigan Department of Transportation. *VII Data Use Analysis and Processing: System Design Description*. Lansing, MI: Michigan Department of Transportation, 2008.

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

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

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

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

10   Michigan Department of Transportation. *The Connected Driver: Integrated Mobile Observations 2.0 (IMO 2.0).* March 2016.

11   Michigan Department of Transportation. *Integrated Mobile Observations 3.0 Connected Vehicles for Road Weather Management.* March 2018.

12   MDOT Use of UAV Phase 2 Final Report