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Providing Traffic Control Device Information in a Connected and Automated Vehicle Environment

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Final Report VTRC 19-R19

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Abstract:

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This project investigated the development of a digital TCD (DTCD) data service, focusing on signs and pavement markings. To do so, the research team investigated emerging wireless communications capabilities, identified infrastructure information needs of automated vehicles, reviewed Virginia Department of Transportation (VDOT) current TCD practices, and surveyed existing data service systems.

The results of the study led to the following conclusions:

- Automated and connected vehicles will be most directly served with a comprehensive DTCD data service as opposed to deriving information from physical devices.

- A portion of the data needed to populate a DTCD data service exists in VDOT database systems.

- There is a need for a national standard for DTCD data services.

- VDOT should conduct a prototype study to gain experience developing and operating a DTCD data service.

FINAL REPORT

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DISCLAIMER

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INTRODUCTION

A long established, fundamental responsibility of transportation agencies is to provide clear regulatory, warning, informational, and guidance information to travelers. Owners and operators of roadway infrastructure meet this responsibility through the use of traffic control devices (TCDs). The Virginia Department of Transportation (VDOT), devotes considerable resources to the design, installation, inspection, maintenance, and replacement of physical TCDs. According to VDOT's Traffic Engineering Division, the Commonwealth's TCD inventory includes over one million signs and 69,000 miles of pavement markings. In the current state of transportation, where people operate vehicles with little digital connection to the infrastructure, this use of physical TCDs to visually provide information is necessary. However, in the near future, as connected and automated vehicles (CAVs) mature and are introduced to the market, there will exist a direct digital communications connection between the infrastructure and vehicles that has the potential to create a "digital" TCD data service (DTCD data service) to supplement, and ultimately possibly replace, the physical TCD infrastructure. A DTCD data service will be a set of static data, as well as a data feed of dynamic data that VDOT will make available for use directly by automated vehicles, as well as third party application developers to create supplemental driver awareness applications for CAVs.

As stated, TCDs, whether traditional physical devices or a digital service, are essential to allow VDOT to meet its responsibility of operating a safe transportation system. Given this, the fundamental goal of introducing a DTCD data service is to improve the ability of VDOT to provide clear regulatory, warning, informational, and guidance information to drivers—whether they are automated or people. While there is the potential for a DTCD data service to reduce costs over a long period of time if it allows for the elimination of the existing TCD physical infrastructure, this is not the primary goal for introduction of the service.

The creation of a DTCD data service will be no small undertaking. While the information content of the physical TCD infrastructure will certainly guide the service, there are many questions to be answered. Furthermore, the sheer volume and complexity of the data will require a significant period of time to develop the data service. Given these challenges, VDOT commissioned this study to provide a foundation for future development.

PURPOSE AND SCOPE

The purpose of this study was to investigate how the provision of TCD information may be changed in a CAV environment and to identify specific actions VDOT can take to effectively prepare for such a future. Specific objectives of the study were as follows:

1. To summarize, at a high level, the current state of VDOT TCD practices to identify fundamental requirements of TCD information delivery that may be met by a DTCD data service.

2. To review the capabilities of connected vehicles to deliver digital infrastructure information directly to drivers.

3. To review vehicle automation research to identify the infrastructure data needs of automated vehicles.

4. To review new and emerging technologies and opportunities to support a DTCD data service in a CAV environment.

5. To develop a vision for a future DTCD data service.

6. To identify potential issues and challenges that must be addressed for the effective introduction and operation of a DTCD data service.

The scope of this study was limited to two classes of TCDs: physical static signage and pavement markings. Other classes of TCDs, such as traffic signals, changeable message signs, and work zone devices, were not considered in this study due to their complexity and unique roles. In addition, the scope of the study was limited to the provision of TCD information through digital communications. Enhancements to the physical TCD infrastructure to better support vehicle detection and sensing of physical TCDs was outside the scope of this study.

METHODS

The following tasks were conducted to achieve the study objectives:

1. *Literature Review*: The goal of this task was to gain an understanding of the state-of-the-practice in TCDs in relation to CAVs. The research team focused the literature review on the following areas:

    - research efforts investigating the introduction of TCD information directly into vehicles

    - connected vehicles' standards-related efforts focused on infrastructure information and data

    - CAV research and development with a focus on techniques used to acquire infrastructure-related information.

2. *Virginia TCD State of Practice:* The objective of this task was to summarize VDOT's practice with respect to TCDs. For this, the research team reviewed fundamental policy and standards documents and VDOT asset management documentation. In addition, this task included investigation into current data storage practices related to TCDs.

3. *Foundation for a Future Digital TCD Data Service:* The goal of this task was to develop two critical foundational elements for a future DTCD data service. The first element was to explore a phased approach to incorporate TCD information in a DTCD data service. The second element was a data service model to be used for the proposed DTCD data service.

4. *Vision of Future Traffic Control Device System:* In this task, the research team crafted the vision for creation of, and transition to, the DTCD data service including the data service architecture, data contents, and the expected evolution of the role of the DTCD data service. This vision includes both immediate actions and long-term plans.

RESULTS

Literature Review

The key results of the literature review are documented in this section.

Traffic Control Device Information and In-Vehicle Displays

A number of researchers have addressed the issue of delivering TCD information directly to in-vehicle displays. This section summarizes the literature in this area.

Delivery of TCD Information to Vehicles

In recent years, researchers have investigated methods to extract TCD information from traditional physical signage to transmit to vehicles to increase driver awareness. In 2012, (Paul, Bharadwaj, Bhat, Shroff, Seenanna, and Sitharam, 2012) developed a prototype for in-vehicle road signs based on a Radio-Frequency Identification (RFID) system to alert drivers of TCD information. RFID tags were placed on existing road signs, and an in-vehicle RFID reader was used to sense them to provide that information to the driver. The authors also employed beacon rate estimation on the road so that its beacon could be picked up anywhere within a radius of 10 meters. The manufacturers of the RFID readers had collision-avoidance algorithms enabled to ensure validity of sign information, and the researchers tested 100 tags within its read range in a dense environment. This testing was done to ensure that, when several tags are placed in the vicinity of the reader, the reader can pick up any RFID tag information and properly display the messages on an LCD to the driver in the vehicle. A vocal alert system was connected to offer audible notifications to the driver. Two vocal alert systems were considered, but a simple voice playback module was preferred to the voice synthesizer because it provided better voice quality. The tag placement test on the roadway was carried out and the study results showed that readings from tags on the roadway were inconsistent; tags placed on the curbs along the road provided better and reliable readings.

In 2014, a study titled "Road Sign Detection on a Smartphone for Traffic Safety" was conducted to develop a low-cost driver assistance system that is capable of using image processing techniques to detect speed limits and present them on a driver's mobile device (Pritt, 2014). This system was run on a smartphone and displayed speed limits and alerts to the driver while driving on highways. The authors performed speed limit detection in two ways: (1) storing of previously determined speed limits in a database for future access, and (2) with real time image processing. The system was implemented using a client-server architecture, and this client ran as an Android application on smartphones which can be placed on the windshield of the vehicle. The posted speed limit as well as the actual vehicle speed are both displayed on the smart phone screen, and the alarm is sounded when the actual speed exceeds the posted speed limit. It is important to note that current smartphone applications, such as Waze, provide exactly this functionality without the use of image processing. Thus, the inclusion of this effort helps to illustrate the incredibly rapid rate of development in this space (as evidenced by the advances in less than 4 years) and points to the need to be proactive in consideration of a digital TCD data service.

In a 2015 study, the researchers investigated two approaches: Hypothesis Generation (HG) and Hypothesis Verification (HV), to derive TCD information from physical TCDs (Abdi, Abdallah, and Meddeb, 2015). Testing revealed that the system performed well in the recall, precision and false positive alarm rates in adverse lighting conditions. Traffic sign detection results also showed that, the algorithm of the system achieved a 97.4% and 98.1% average precision rate and average recall rate respectively.

Recently, the Michigan Department of Transportation (MDOT) has partnered with 3M to utilize connected vehicle technologies along more than 3 miles of I-75 in Oakland County (3M, 2017). In this study, 3M provided MDOT with retro-reflective signs with smart sign technology, named ‘Smart Code Signs’ and Dedicated Short Range Communications (DSRC)devices to aid in vehicle-to-infrastructure (V2I) communications and in improving machine vision detections. 3M also collaborated with the Texas Transportation Institute (TTI) in 2017 to test the Smart Code Signs. The ‘Smart Code Signs’ linked with meta-data including GPS location of the signs, and upcoming roadway conditions, such as sharp curves, provide TCD data to both human and machine drivers. The meta-data associated with each sign is stored on a central database.

While most of the studies focused on deriving TCD information from signs, there has also been research focused on deriving the TCD information content of pavement markings. (Vacek, Schimmel, and Dillmann, 2007)) addressed the issues associated with extraction of information regarding lanes from the types of road markings on the highways. Specific road markings analyzed in the study were longitudinal lane line markings and arrow markings. The findings of the study found that lane marking could be detected and followed consistently, and that arrow markings were identified and correctly classified in greater than 90% of cases.

Impact of TCD Information on Driver Performance

Beyond investigating how to deliver and display TCD information to vehicles, researchers have also addressed the impact of this information on driver performance. (Noble, Dingus, and Doerzaph, 2016) investigated the influence of an in-vehicle adaptive stop display on both behavior and safety of drivers. The authors developed an in-vehicle adaptive stop display sign and tested it on the Virginia Smart Road facility in Blacksburg, Virginia. They conducted this study to determine whether stopping behavior of drivers with adaptive display signs differs significantly from stopping behavior of drivers at a conventional stop sign. A data acquisition system was connected to the interface of the vehicle through controller area network protocols to accurately record all driver performance data. The experimental in-vehicle adaptive display device consisted of a five-inch liquid-crystal display monitor that was positioned offset from the steering wheel. The state of the stop sign was based on traffic conditions and was communicated to the vehicles using a DSRC network. A standard stop sign was displayed on a black background and was displayed to drivers when a stop is required. The authors also developed a “Proceed with Caution” sign aimed at providing permission to drivers to proceed through an intersection without stopping, if conditions allowed. The research team also connected an auditory alert system to the visual display system. The results of the study indicated a higher rate of driver compliance with the system, than with conventional stop signs. This led the authors to conclude that there is significant potential for in-vehicle delivery of TCD information to reduce crash risk.

Another recent study (Ma and Zhou, 2016) was conducted to prototype and analyze a virtual dynamic message sign (VDMS) system to help improve traveler information by providing information through smart phones or on-board units of a connected vehicle. In this study, the location of a traveler on the highway was monitored using an in-vehicle GPS or smart phone GPS and information were sent out to a central server at the traffic management center (TMC). As soon as a traveler was detected in a “message zone”—or an area with an applicable dynamic message—the message was presented to the driver in the vehicle in the form of audible and visual messages. A driving simulator was used to conduct a behavioral analysis. The results indicated that the VDMS did result in improved comprehension of messages, particularly when message content was more complex.

Connected Vehicles Standards

In a CAV environment, vehicles equipped with communications devices transmit information to surrounding vehicles through vehicle-to-vehicle (V2V) communication and to the infrastructure through V2I communication. At the same time, a vehicle can receive the information from surrounding vehicles as well as from the infrastructure. For these two-way communications, the CAV community has developed and published several standards in an attempt to support the development and implementation of a CAV environment and its applications. The most advanced of these is the Society of Automotive Engineers (SAE) J2735, DSRC Message Set Dictionary.

The current J2735 standard includes several message sets directly related to the infrastructure, encompassing a portion of TCDs. These messages are MAP (MSG_MapData), SPaT (MSG_SignalPhaseAndTiming), and TIM (MSG_TravelerInformationMessage) messages. Brief descriptions of these message sets follow:

- The MAP message provides geographic information about the road, with an emphasis on intersections.

- The SPaT message includes the status of one or more traffic signals at intersections. Detailed data elements in a SPaT message are movement name, list of lane numbers, signal state, time to change, etc.

- The TIM message is used to deliver various travel information to drivers. This travel information includes traffic conditions, traffic accidents, pre-planned event information, speed warnings, limited traffic signage, and other general information.

Recognizing that the messages in the current standard SAE J735 do not fully cover infrastructure elements, the Connected Vehicle Pooled Fund Study initiated a project entitled “Basic Infrastructure Message (BIM) Development and Standards Support.” While the standard for vehicle-related information, i.e. Basic Safety Message (BSM), is fairly well defined; from the infrastructure side, which infrastructure information will be or needs to be broadcasted has not received equal attention. With this, the purpose of this study was to develop a corollary message from the infrastructure, a Basic Infrastructure Message (BIM). Having a standard BIM would help the automobile manufacturers and the third party application providers to understand that there will be some infrastructure for them to rely on, and will give them some basis for the kind of message they can expect from the infrastructure. In addition, this will also help the public transportation agencies to know what kind of information to broadcast from their Road Side Equipment (RSE). This project is being conducted by the Southwest Research Institute (SwRI) and will be completed in 2019.

In this effort, SwRI has developed 11 use cases related to infrastructure information, including Static Signage, Dynamic Traveler Information, Map Information, Situational

Awareness, Limited Access, Data Collection Requests, Incidents, Restriction Enforcement, Driver Safety/Assistance/Support, Emergency Vehicle Operations, and Intersection. For each use case, detailed information has been prepared including geographic scope, timing scope, graphical illustration, pre-conditions, main event flow, post-conditions, and information requirements (data elements). Based on this, the BIM message definition along with 57 data frames was developed and submitted to the SAE committee for possible inclusion in the next version of the standard.

CAV Research and Development

In order to understand TCD data needs of CAVs, the research team focused on information on research and development from leading CAV firms.

Google Self-Driving Vehicle

Urmson, a technology lead for the Google automated vehicle project described the heart of Google self-driving car as a laser range-finder mounted on the roof of the vehicle. The device is a Velodyne 64-beam laser, and it generates a detailed 3D map of the environment of the vehicle. This is later combined with laser measurements with high-resolution maps to generate several types of data models. Other sensors exist on the vehicle to aid in navigation, including four radars mounted on the front and rear bumpers. These sensors provide the vehicle a broader field of view to deal with fast moving traffic on the highways. Other sensors include a camera positioned near the rear-view mirror to help in detecting traffic lights, a Global Position System (GPS), inertial measurement unit, and wheel encoder. These are used to determine the location of the vehicle and also help in keeping track of the movement of the vehicles (Guizzo, 2011).

One of other technologies of the Google driverless vehicle that is worth mentioning is mapping in advance. In particular, before setting a self-driving vehicle on any roadway, map information such as the road condition, location of features (e.g., poles, road markers and marking, road signs, location of curbs, curves), and other useful information are collected and stored in the vehicle's memory. This helps the vehicle identify regular portions of the road. As the self-driving vehicle is driving on the road of which the mapping data is pre-loaded, the Velodyne laser range finder starts to generate a 3D map of the same environment. It then compares this new map with the stored map to correctly determine and identify non-regular parts such as pedestrians and other road users so that it can avoid them.

Tesla Driverless Car Technology

Tesla has stated that its vehicles are equipped with the hardware needed for full self-driving capability (Tesla, 2016). The vehicle will generally have eight surround cameras to provide 360 degree visibility around the vehicle up to a 250 meter range. The vehicle will also possess twelve updated ultrasonic sensors with added sensitivity and a forward-facing radar to allow it to see through the heavy rain, fog, dust and other vehicles ahead.

The system includes wide, main, and narrow forward cameras.

- *Wide Forward Camera:* provides a 120 degree fisheye lens to help capture traffic signals, and identify obstacles potentially in the path of travel.

- *Main Forward Camera:* will cover a broad spectrum of use scenarios and its maximum distance will be 150 meters.

- *Narrow Forward Camera:* provides a focused, long-range view of distant objects. The type of camera is particularly useful in high speed operation and its maximum distance is 250 meters.

Mercedes-Benz Intelligent Drive

Mercedes-Benz has produced an automated vehicle system known as Intelligent Drive which includes the following key sensors and functions (Mercedes Benz, 2017).

- *360° Camera:* A total of 4 cameras monitor the entire area surrounding the vehicle and assist in parking and maneuvering especially in limited visibility when driving on highways. Based on the images from these 4 cameras, the system computes a number of views to show the vehicle surroundings to help make maneuvers while on the highway.

- *Active Lane Keeping Assist:* Radar sensors monitor other vehicles around the vehicle and a camera checks whether the vehicle is driving over broken or continuous road markings. The system then provides a heads up to the driver and protects the vehicle from being involved in a collision.

- *Active Steering Assist:* This helps in keeping the vehicle in its lane when on the straight section of the highway. This component of the vehicle uses the vehicles ahead and the lane markings for its orientation on the roadway.

Virginia TCD State of Practice

In order to investigate the future of TCDs and to provide sound recommendations to guide the transition from physical TCD infrastructure to a DTCD data service, a fundamental understanding of the current state of practice being carried out by VDOT is necessary. As such, the goal of this task was to develop a high level summary of current VDOT practices with respect to TCDs.

It should be noted that the intent of this section is to document only the information of highest relevance to this study, rather than creating an exhaustive summary of VDOT TCD practice. The research team reviewed documents ranging from the Manual on Uniform Traffic Control Device (US DOT, 2009), Virginia MUTCD Supplement (VDOT, 2011), and the VDOT Road and Bridge Specifications (VDOT, 2016), Before delving into the VDOT state of practice, it is important to state that Section 1A.07 of the MUTCD and Virginia MUTCD Supplement describe the general responsibility for traffic control devices. It states that public agencies, officials with jurisdiction, or owners of private roads that are open to the general public shall be responsible for the design, placement, operations, maintenance and uniformity of TCDs. Based on this responsibility, one could reasonably conclude that the responsibility for providing the information content of TCDs that govern safe and efficient use of the roadway infrastructure will remain with VDOT in a DTCD data service "era."

VDOT TCD activity can be categorized in the following two processes:

1. *TCD Planning (Design) Process:* Chapter 3 Section 4 of the Virginia Traffic Engineering Design Manual (VDOT, 2014) documents the design process to be followed to produce signing and marking plans. This provides an insight into planning activities of VDOT for TCDs. While a large part of this process focuses on physical aspects of TCDs, such as size, letter series, mounting details, etc., much of the process does focus on the (a) information content and (b) geospatial location where the information is to be provided to a driver. This also includes an inventory of existing signs to determine what new TCD content will be required with a new or improved facility.

2. *TCD Installation Process:* VDOT's installation of signs and markings also passes through several stages before they are finally erected on the roadside or roadways. The principal guidelines for the installation/ placement of these signs and markings are described in the MUTCD (USDOT, 2009) and Virginia Supplement (VDOT, 2011). These documents provides standards, guidance, support, and option for traffic control devices, including their placement, design, size, color, content of messages.

The VDOT Road and Bridge Specifications (VDOT, 2016) provide details on installation procedures for signs and markings. This document describes the general construction items, materials, methods and procedures common to the furnishing and installing of signs (section 701) and markings/markers (section 704). In this study, special attention was given to the documentation requirements (section 701.03 - f) related to the installation of signs and markings given that these documentation requirements provide an insight into the data elements that need to be included in any comprehensive database system of future TCDs, i.e., the DTCD data service.

TCD Asset Management and Maintenance

Managing 58,000 miles of roadway, VDOT maintains over one million signs. The number of signs increases each year because of construction of new roads, operational, and safety requirements, federal and state level requirement for new signs, as well as requests from the general public. VDOT replaces nearly 90,000 signs each year, at an estimated cost of $2.9 million. Data from the VDOT's Northern Virginia District showed that 78% of the signs ordered from the Central Virginia Sign Shop (CVSS) were replacements for damaged signs and the rest for newly installed signs.

VDOT's Traffic Engineering Division (TED) together with Information Technology Division (ITD), the Operations Division (OD), the Structure and Bridge Division (SBD), the Asset Management Division (AMD) and the five Operations Regions have been conducting several activities to lay the foundation for a comprehensive statewide inventory of TCD assets. A brief summary of these activities is included here.

VDOT Traffic Control Device Asset Management Activities

VDOT in 2007-2011 made an attempt to develop a comprehensive asset management system of TCDs from video images collected on roadways in Virginia. VDOT's Maintenance Division (MD) contracted Fugro-Roadware to develop and provide digital pavement condition data, which could also be used to identify TCDs. The team collected video images of roadways for all of the mainline interstate and primary road network and 22% of secondary roads. Some of the prominent data elements that can be found in the VDOT's Roadware database include: sign panel, location/maintenance jurisdiction, legend, color, MUTCD sign code, and structure/post type.

Three years later, the data collection exercise was extended to ramps, loops, and the return direction for primaries. Additional secondary mileage was included, increasing the coverage of the secondary system to 65%. Fugro-Roadware delivered the data to VDOT in MDB files with links to the video images from which assets information was extracted. In 2013, the data set for 2008-2010 were provided to the GIS Integrator and were available from the Maintenance map under Maintenance Data->Asset Data. While each data set was made up of separate layers, it is worth noting that the original 2008 data set was loaded into Oracle tables within the Asset Management System (AMS) database, and a Business Objects universe for the creation of AMS_ROADWARE.

Although the plan was to use the Roadware data to create an inventory of TCDs, no plan was put in place to update elements. Currently TED staff uses the Roadware data as a secondary source of independent inventory development and quality assurance (QA) purposes. Other departments performed further processing and QA of the data to make them good for planning purposes, but they could not use the data for needs assessment due to quality issues.

The Integrated Directional Signing Program (IDSP) maintains an inventory with more current and accurate data than the Roadware database. The IDSP program covers about 10,491 sign structures with over 19,000 panels/messages, 3,772 logo sign structures, 5,112 Supplemental Guide Signs (SGS) structures, 1,175 General Motorist Services (GMSS) sign structures, and 432 Tourists Oriented Directional (TOD) sign structures. While 99% of the signs are ground-mounted, a few signs share VDOT sign structures.

VDOT has implemented a new Highway Maintenance Management System (HMMS) to manage the Department's assets. HMMS does not currently include sign data, however HMMS may be expanded in the future to include a real-time sign inventory to support operation and maintenance decisions. This HMMS will be useful in keeping records, creation and maintenance of sign inventory, record inspections, historical data as well as activities relating to maintenance.

Another thing of note is that all these activities were initially started by a comprehensive list of information needs and data elements identified through the Traffic and Safety Asset and ITS Asset data Communities of Interest (COI). The COI activity covered signs, changeable message signs (CMSs), signals, and guardrails. More details for signs are provided here:

- Information is needed to do the following:
  - Identify the needs for maintenance, rehabilitation and replacement strategies as well as budgets.
  - Help update standards and specifications.
  - Help adhere to established standards.
  - Set benchmarks and improve asset performance.
  - Assist in the maintenance and operational activities.
  - Assist in the scoping and design of construction projects.
- Reporting and query requirements are as follows:
  - Detail Views: They deal with pulling up of detailed information for an individual asset.
  - Ad-Hoc Queries: These deal with searches for sign assets that meet specific criteria.
  - Thematic Maps: These produce maps that show locations and characteristics of signs.
  - Summary Reports: These produce asset quantity reports by system.

VDOT's Sign Maintenance and Retro-reflectivity Compliance Plan

In 2017, VDOT's Traffic Engineering Division developed a sign maintenance and retro-reflectivity compliance plan (VDOT, 2017). While this plan focuses on maintenance of sign visibility, information in the plan focused on sign replacement priority is relevant to the DTCD data service. The prioritization is as follows:

- *First Priority:* This category refers to emergency replacement of critical regulatory and warning signs. Examples of such signs are STOP and DO NOT ENTER signs. These signs are replaced within 24 hours of receiving the reports of their damage. Other districts such as the Northern Virginia District replace the STOP sign within an hour.

- *Second Priority:* This refers to other regulatory and warning signs that are less critical to safety. These signs are repaired or replaced after 7 days of receiving the report of their damage.

- *Third Priority:* This refers to guide signs that are in unacceptable condition, knocked down, damaged or destroyed. Repair or replacement of these signs can take up to 45 days of receiving the report of their damage.

- *Fourth Priority:* This refers to signs that have marginally acceptable reflectivity. These signs are repaired or replaced when budget or resources allow.

VDOT Pavement Markings Practices

There are 69,000 miles of pavement markings, 712,000 markers, and 110,000 messages on VDOT-maintained roads. VDOT is responsible for the application and maintenance of all pavement markings. Thus, it is clear that VDOT invests significant attention into providing information to drivers on proper positioning of vehicles using the physical infrastructure. Limited information has been included in this report because it provides insight into the estimated distance and quantity of pavement marking, messages and markers VDOT maintains. It further provides information on measurement, application and reapplication of these TCDs on the pavement surfaces which are vital to determine the virtual georeferenced locations in the future DTCD.

Summary of Virginia Traffic Control Devices State of Practice

Beyond the review of VDOT procedures for planning, installing, maintaining and replacing TCDs, this task identified that VDOT has existing database systems of TCD-related information, particularly for traffic signs, that could serve as a starting point for a future DTCD data service. Key findings from this review are summarized here:

- VDOT's existing procedure for the design of sign and pavement markings should be retained to support the development of the future DTCD data service. With the exception of sign supports and physical signage specifications, these procedures will still apply to a digital system.

- Some information, such as spatial locations of signs and markings may be extracted from existing VDOT's plan sets for the future DTCD data service. However, the plan sets will not be available for much of the system.

- Data from the numerous VDOT database systems may provide a start for a DTCD data service, but will require extensive upgrades for accuracy and completeness.

- VDOT's rule for the prioritization of sign replacement could be used to rank the most critical signs and markings that can be transitioned to the future DTCD data service.

Foundation for the Future Digital Traffic Control Device System

In this task, the research team developed two critical foundational elements of a future DTCD data service. The first is a prioritized set of TCDs to be included in the DTCD data service, and the second is a data service architecture currently in use in the transportation industry that will be used as a model for the proposed DTCD data service.

TCDs to Include in DTCD Data Service

In order to identify specific TCD information content that is recommended to transition from the current physical approach to a virtual system using wireless communications, the research team reviewed the MUTCD, the Virginia Supplement to the MUTCD and other relevant documents. A brief overview of the types of traffic signs and pavement markings is presented first, followed by tables presenting prioritized data element lists.

Traffic Signs

Traffic signs are very important elements of the roadway because they communicate the rules and regulations, warnings, guidance and other information that road users need to traverse the network safely and efficiently. The basic requirements for traffic signs are high visibility by day and night and high legibility. Messages could be in the form of a word, symbol, and/or arrow legend. An effective traffic sign fulfills a need, commands attention, conveys a clear and simple meaning, commands respect from road users and provides sufficient time for proper response. Traffic signs are classified into three categories based on their functions. These categories along with a brief description are presented here:

- *Regulatory Signs:* Regulatory signs provide notice to road users of some traffic laws or regulations. They also show their applicability of the legal requirements. They are installed at or near the locations that the regulations should be applied. The signs should clearly show the requirements enforced by the regulations and should be mounted such that they will be conspicuous and legible to improve its compliance. They should be retroreflective or illuminated so that their shape and form are maintained during the day and night.

- *Warning Signs and Object Markers:* These are signs that provide advance notice of potentially hazardous situations or conditions of the road ahead that may not be clearly revealed to motorists. They are mostly helpful to motorists who are new to particular roads. Their use should be based on engineering study or judgement. The general rule is that these signs should be replaced or repaired when they are damaged or missing within three days of notice.

- *Guide Signs—Conventional Roads:* Guide signs show route designations, directions, distance, service, points of interest and other geographical, recreational or cultural information. An accepted practice is, when detected that any of these signs are damaged, removed or missing, they are replaced in seven working days.

Pavement Markings

Pavement markings provide information and guidance to road users to help improve safety. They are also used in some cases to supplement other traffic control devices or may be used alone to provide regulations, guidance or warnings that cannot be obtained with other devices without distracting road users from the roadway (US DOT, 2009). Pavement markings should be easily recognized and understood, well-maintained, and used only in consistent applications, including design, color, and placement location.(US DOT, 2009) and (VDOT, 2011) describes the colors of markings and where each of these colors may be used.

Roadway markings can be classified as either longitudinal line, transverse markings, or words and symbols. While markings such as center lines, lane lines, edge lines, crosswalks, or stop bars provide positive guidance by defining limits of safe travel, markings such as no passing zones, gore areas, or painted medians and islands provide negative guidance and also advise drivers where not to travel. Sections 3A.05 and 3A.06 of the MUTCD/ VA supplement to the MUTCD provide a list of several principles or concepts for longitudinal lines. They further recommend the general widths and patterns for longitudinal pavement lines as shown in Table 1. This table is included in this report to provide a foundation for vertex accuracy and density standards that will be needed to demarcate lane delineation in a DTCD data service.

Table 1. Recommended Widths and Patterns for Longitudinal Pavement Lines

No	MUTCD	VA Supplement to the MUTCD
1	Normal line: 4 to 6 in wide	Normal line: 4 in wide, with exception (see 7-9 in this table)
2	Wide line: at least twice the width of a normal line	Wide line: twice the width of a normal line
3	Broken lines should consist of 10-ft line segments and 30-ft gaps, or dimensions in a similar ratio of line segments to gaps as appropriate for traffic speeds and need for delineation.	Broken lines shall consist of 10-ft line segments and 30-ft gaps.
4	A dotted line for line extensions within an intersection or taper area should consist of 2-ft line segments and 2- to 6-ft gaps. A dotted line used as a lane line should consist of 3-ft line segments and 9-ft gaps.	A dotted line for line extensions or taper areas at an intersection shall consist of 2-ft line segments and 4-ft gaps. A dotted line used for lane drop markings at intersections shall consist of 3-ft line segments and 9-ft gaps.

Critical Traffic Control Devices for the DTCD Data Service

The research team's underlying philosophy guiding the development of the DTCD data service recommendations was that provision of TCD information is a fundamental responsibility of transportation agencies. Signs and marking are used to do this based on today's technology and human-operated vehicles. However, signs and markings are only the physical approach used to meet the responsibility of providing TCD information. Since automated vehicles operate in a different way, the importance of specific TCD information will likely be different. For example, a curve warning sign might not as important to an automated vehicle as to a human driver since automated vehicles will have advanced geometric knowledge that a human cannot visually detect. Therefore, it is recommended that a DTCD data service be developed on a corridor basis – with high volume corridors designated for CAV usage receiving the highest priority. Within corridors, it is recommended that TCDs prioritized for inclusion in the data service be based on the order of priority for replacement of signs being used by VDOT. Brief explanations of these priorities are provided here:

- *First Priority:* This list consists of the most critical TCDs that are recommended for the initial DTCD data service development. The signs and markings are largely selected from regulatory and warnings. These signs have been selected because they require immediate replacement (within 24 hours) when they are removed or damaged. Given that these represent the most safety-critical information content, there is a need to address these TCDs first to provide sufficient time to create a complete and accurate DTCD data service.

- *Second Priority:* This list also comprises all other regulatory and warning signs, markings and messages not listed in the first priority list. These will be included in the DTCD database system in the second phase of its development because they are less critical and replacement can be done in 7 days.

- *Exclude:* This refers to all other signs including guide signs that have marginal or no reflectivity. These TCDs are not critical and as such their replacement can take up to 45 days. These TCDs are not recommended for inclusion in the DTCD data service.

Finally, example prioritized lists are presented in Tables 2 through 5. These tables are not meant to be final. Rather the priorities in these tables can be easily revised by the experts within VDOT based on the prioritization logic they would like to utilize.

- *Tables 2 and 3 describe the category of traffic signs at Intersections and Roadway links, respectively*. The tables further categorize the traffic sign elements based on the order of priority for replacement when they are damaged or removed. Those in priority one are the most critical ones, followed by the second, third and the fourth priority signs.

- *Tables 4 and 5 present a summary of pavement markings and messages.* These are also critical to road users because they communicate the intended travel path for short range operations and roadway alignment for long range delineation. These markings need to be detected, recognized and classified by CAVs. The order of priority for replacement when they are damaged or removed is not yet known. However, the research team has checked some markings and messages for inclusion in the future DTCD system.

Table 2. Example Prioritized list for Traffic Signs - Intersections

Type	Static/Dynamic Signs	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory Signs	STOP	x		
	ALL WAY Sign	x		
	YIELD Sign	x		
	YIELD Sign;			
	-To Pedestrian and stop here for Pedestrians	x		
	-In-street and overhead Pedestrian Crossing	x		
	Speed Limit	x		
	Variable Speed Limit*	x		
	Movement Prohibition Signs	x		
	Intersection Lane Control Signs		x	
	Mandatory Movement Lane Control Signs	x		
	Optional Movement Lane Control Signs:		x	
	DO NOT PASS Sign		x	
	Selective Exclusion Signs			
	-WRONG WAY,	x		
	-DO NOT ENTER	x		
	Wrong-Way Traffic Control at Interchange Ramps	x		
	ONE WAY SIGNS	x		
	LOCATION SIGNS		x	
	Parking, Standing, and Stopping Signs (R7 and R8 Series)		x	
	Emergency Restriction Signs		x	
	WALK ON LEFT FACING TRAFFIC and No Hitchhiking Signs			x
	Traffic Signal Signs	x		
	Headlight Use Signs			x
	Rest Area Directional Sign		x	
	Commercial Vehicle Lane Restriction Signs		x	
Warning Signs	BUMP and DIPS	x		
	Warning Signs and Plaques for Motorcyclists			x
	Intersection Warning Signs		x	
	Non-Vehicular Warning Signs		x	
	Playground Sign		x	
	Watch For Children		x	
Guide Signs	Design of Route Signs			x
	Route Sign Assemblies			x
	Design of Route Sign Auxiliaries			x
	Location of Distance Signs			x
	Street Name Signs			x
	Advance Street Name Signs			x

Note: Dynamic Signs = (*)

Table 3. Example Prioritized list for Traffic Signs – Roadway Links

Type	Static/Dynamic Signs	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory	Speed Limit and End XX mile speed signs	x		
	DO NOT PASS Sign	x		
	Variable Speed Limit*	x		
	Dynamic Message signs*	x		
Warning	Horizontal Alignment Warning Signs			
	(a) Truck Rollover Warning Sign	x		
	(b) ONE LANE BRIDGE Sign	x		
	Low Clearance Signs	x		
	BUMP and DIP Signs	x		
	Warning Signs and Plaques for Motorcyclists		x	
	Reduced Speed Limit Ahead Signs		x	
	Vehicular Traffic Warning Signs		x	
	Merge Signs		x	
	STEEP GRADE AHEAD Plaque		x	
Guide Signs	Overhead Arrow per lane Guide sign			x
	Guide Sign Spreading			x
	Pull-Through Signs			x
	Diagrammatic Guide Signs			x
	EXIT ONLY SIGNS			x
	EXIT DIRECTION SIGNS			x
	Route Signs and Trailblazer Assemblies			x
	Interchange Signs			x
	Advance Guide signs			x
	Other Supplemental Guide Signs			x
	Next Exit Guide Signs			x
	EXIT DIRECTION SIGNS			x
Toll Roads	Electronic Toll Collection (ETC) Account-Only			x
	Auxiliary Signs (M4-16 and M4-20)			x
	Toll Payment Regulatory Signs		x	
	Preferential And Managed Lanes Signs			x
	Preferential And Managed Lanes Signs*			x
	Guide Signs For Priced Lanes			x

Note: Dynamic Signs = (*)

Table 4. Example Prioritized List for Pavement Markings

Types	Details	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Pavement And Curb Markings	Yellow Center Line Pavement Markings	x		
	No Passing Zone Pavement Markings	x		
	Other Yellow Longitudinal Pavement Markings	x		
	White Lane Line Pavement Markings	x		
	Edge Line Pavement Markings	x		
	Extensions through Intersections or Interchanges		x	
	Lane Reduction Transition Markings		x	
	Approach Markings for Obstructions		x	
	Raised Pavement Markers		x	
	Stop and Yield Lines	x		
	Do Not Block Intersection Markings	x		
	Crosswalk Markings	x		
	Parking Space Markings		x	
	Pavement Word, Symbol, and Arrow Markings		x	
	Speed Measurement Markings		x	
	Speed Reduction Markings		x	
	Curb Markings	x		
	Chevron and Diagonal Crosshatch Markings	x		
	Speed Hump Markings	x		
	Advance Speed Hump Markings		x	
Roundabout Markings	White Lane Line Pavement Markings for Roundabouts		x	
	Edge Line Pavement Markings for Roundabout Circulatory Roadways		x	
	Yield Lines for Roundabouts		x	
	Crosswalk Markings at Roundabouts		x	
	Word, Symbol, and Arrow Pavement Markings for Roundabouts		x	
	Markings for Other Circular Intersections		x	
Markings For Preferential Lanes		x		
Markings For Toll Plazas				x
Delineators				x
Islands				x
Rumble Strip Markings				x
Bicycle lanes		x		
Shared lane markings		x		

Table 5. Example Prioritized List for Pavement Messages

Types	Details	DTCD Inclusion		
		1st Priority	2nd Priority	Exclude
Regulatory	STOP	x		
	YIELD	x		
	RIGHT (LEFT) TURN ONLY	x		
	25 MPH	x		
	Lane-use and wrong-way arrows	x		
	Diamond symbol for HOV lanes		x	
	Other preferential lane word markings		x	
Warning	STOP AHEAD	x		
	YIELD AHEAD	x		
	YIELD AHEAD triangle symbol	x		
	SCHOOL XING	x		
	SIGNAL AHEAD	x		
	PED XING	x		
	SCHOOL	x		
	R X R	x		
	BUMP	x		
	HUMP		x	
	Lane-reduction arrows		x	
Guide	Route numbers (route shield pavement marking symbols and/or words such as I-81, US 40, STATE 135, or ROUTE 10)			x
	Cardinal directions (NORTH, SOUTH, EAST, or WEST)			x
	TO			
	Destination names or abbreviations thereof			x

General Transit Feed Specification—Model for the DTCD Data Service

The research team reviewed existing surface transportation-focused data services to serve as a model for a foundation for the DTCD data service. Most of these services focused on the provision of real-time system status information. For example, the Regional Integrated Transportation Information System (RITIS) operating in the Washington, D.C., region. RITIS data feeds are services that provide direct access to real-time incident, event, detector, probe, weather, transit, and other data sources including ITS device status. Given the need to provide both static and dynamic data with a strong spatial component, it was determined that the General Transit Feed Specification (GTFS), which supports public transportation data services world-wide, would serve as the most appropriate model. The GTFS refers to a common data format for public transit information (Google, 2018). Through GTFS “feeds”, public transit agencies are able to share their data with third-party developers. The “feeds” include information such as routes, fare, and bus stop locations. The GTFS technology was created by Google in 2005 to satisfy the requirement of online transit trip planners from TriMet in Portland. After a successful partnership between TriMet and Google, more agencies developed an interest in using GTFS to share their transit information with the public. It was estimated that in January 2016, 1,026 transit agencies globally were using this service, of which 864 agencies are in the United States. Currently, GTFS datasets are being used by third party vendors for trip planning, maps, timetable creation, mobile data, visualization, accessibility, analysis tools for planning, and real-time information systems.

GTFS Data Creation and Maintenance

Before transit agencies publish their data, they first convert the data into the GTFS format. The conversion process involves (1) understanding the GTFS data format and fitting their data into the GTFS format and (2) formatting of the GTFS data, which can be done either in-house or through outsourcing. Agencies have several ways to execute these tasks depending on their technical support and financial abilities.

- *In-house Formatting:* This is conducted by agencies with enough technical expertise. They often use industrial standard software packages such as: Trapeze, HASTUS, Connexionz, and TripSpark for creating and maintaining GTFS data. Although these packages comparatively produce better data format than some open-source tools, technical support from agencies is needed to ensure better data quality.

- *Outsource Vendors:* They provide full service from data formatting to database maintenance. While less technical support is needed, the cost of such service is higher.

GTFS Data Dissemination.

After generating the GTFS data, the transit agencies make the data available to application developers as well as the general public. Agencies usually maintain GTFS data on agency-owned websites, global directories, and regional directories.

GTFS Real-Time Feeds

GTFS real-time refers to a feed specification that allows public transportation agencies to provide real-time information or updates about their fleet to application developers as well as consumers. The following information is currently supported by GTFS real-time feeds:

- *Trip updates:* delays, cancellations, changed routes.

- *Service alerts:* stop moved, unforeseen events affecting a station, the route or the entire network.

- *Vehicle positions:* information about the vehicle location and congestion level.

GTFS real-time feeds may combine with other entities of varying types. They are served through the hypertext transfer protocol (HTTP) and updated as often as possible. Since the file is a regular binary file, any type of web server is capable of hosting and serving the file. Web application servers can as well be used as a response to a valid “HTTP” for “GET” (requests data from a specified resource) request to return the feed. Although there are no restrictions on the frequency and the exact method of updating or retrieving the feed, the feeds need to be updated regularly to help determine the actual status of the fleet.

Vision of Future Traffic Control Device System

The results from the previous tasks document the massive amount of information that is conveyed to drivers by VDOT's existing physical TCD infrastructure. The results also demonstrate that this information is essential for the safe and efficient operation of automated vehicles. Finally, the results also reveal that rapid development in the national connected vehicles program, as well as in commercial wireless networks, makes viable the creation of sophisticated driver awareness assist systems that complement physical signage to allow for improved driver safety. Based on these results, the research team has developed a vision in which VDOT creates a DTCD data service that will (a) support driver awareness assist systems to complement the physical TCD infrastructure in the near term, and (b) provide a foundation for automated vehicle operation for Virginia in the long term. In addition, the vision includes development of national standards to guide DTCD data services that are consistent nationwide.

This section presents the vision for a DTCD Data Service to be created, maintained, and operated by VDOT.

DTCD Data Service Architecture

In 2017, VDOT launched a cloud based data portal initiative called the Smarter Roads Data Portal to support CAV technology. The system provides free and widespread access to VDOT information to anyone interested in developing transportation applications and products for end users. This system contains 22 different feeds of primarily dynamic operational data for public use. The envisioned DTCD Data Service can build on this existing data portal to add a database of TCDs (signs and markings) and their attributes.

These digital representations of signs and markings will focus on providing the information content of these physical TCDs, not on trying to replicate the signs themselves. In this study, a GTFS-like database system of signs and markings information is proposed for this new DTCD Data Service. This DTCD Data Service would be a potential replacement of the physical signs in the future when both AVs and the DTCD Data Service are fully developed.

The recommended critical signs and markings for inclusion in the DTCD system are classified as priority level one in Tables 2 through 5. As shown in Figure 1, the future DTCD data Service will consist of the following:

- *Static Signs and Pavement Markings Database:* These TCDs have been grouped together because they will not require continuous updates since their location will change very infrequently over time. The static signs and markings and their data elements will be stored online at a dedicated VDOT website for public use.

- *Dynamic Signs Data Feed:* This data requires regular updates whenever needed especially in work zones. This data is already partially available on the existing VDOT cloud database portal.

In the future DTCD Data Service, third party developers and automakers can download the static data (signs and markings) from the portal and subscribe to the dynamic data feed. Initially, VDOT will develop a GTFS-like data service format to begin prototype development. In parallel, VDOT will work with the Federal Highway Administration (FHWA) to initiate an effort to create a national standard data format for the dissemination of TCD information to the general public, which will take the form of a GTFS-like national standard for traffic control devices. A recommended architecture diagram of the new DTCD Data service is shown here. It is envisioned that this architecture will support both DSRC and connected vehicles as well commercial wireless networks.

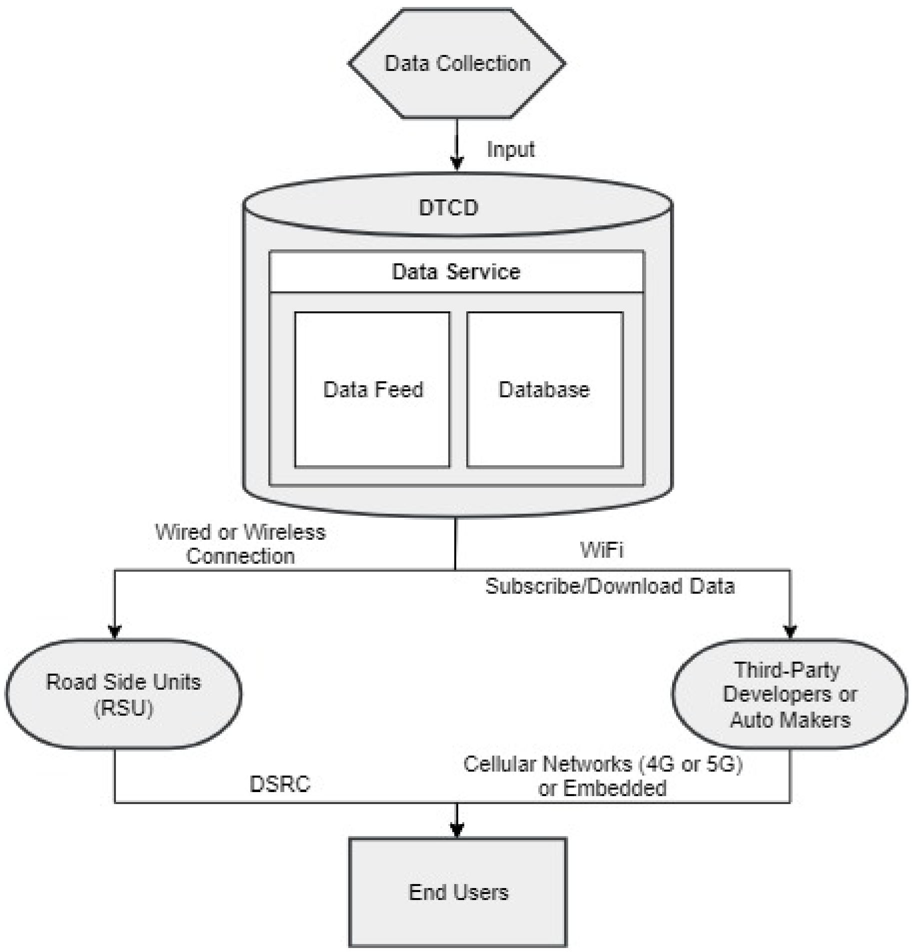

Figure 1. Recommended DTCD Data Service Architecture

Data Content

In 2011, VDOT's Traffic and Safety Asset Community of Interest (COI) developed a consensus on a standard set of data elements for signs. This set is the ideal starting point for a future DTCD data service database. Unfortunately, no such standard data set was found for pavement markings and messages. Most logically, this data will include both a spatial component (i.e. the location of the information to be presented) which in some cases will be a single point (such a stop sign) and in other cases as a linear zone, as well as attribute information to provide the information related to the location.

It is important to note while the existing TCD infrastructure and the future DTCD data service provide the same information to the users of the transportation system, the difference between the users is significant and results in important differences. Today's human drivers must derive the necessary information based on seeing and interpreting physical signs and markings. On the other hand, future automated vehicles will be able to act on the information content directly without the visual interpretation step. As a result, in many cases simply replicating a physical sign in a database for a DTCD data service is not advisable. For example, capturing the location of existing physical skip lines to delineate lanes may not be as useful as providing a lane's centerline location along with a lane width attribute in a DTCD data service. Thus, it will be critical to look beyond pure replication of physical signs and markings in a DTCD data service.

Expected Evolution of the Role of the DTCD Data Service

It is certainly not feasible to move directly from the current state-of-the-practice to a comprehensive DTCD data service. Rather, the following evolutionary approach is envisioned.

1. *Prototype Phase.* Develop prototype for a test corridor and test on driver performance.

2. *Data Service Development.* Develop based on emerging national standards and experience in prototype phase.

3. *Driver Awareness Support.* In this phase, third party developers such as Google or Waze can integrate the DTCD data service into their applications to develop transportation applications to support human drivers. Third party developers could also subscribe to the dynamic signs database and use proper application programming interface (API) to support their own mobile applications. Here, TCD information would be sent out by means of cellular networks to end users.

4. *Automated Vehicle Support.* In the long term when the level of automation is from levels 3-6, a prototype DTCD database will be connected to RSU through wired/wireless means and shared with vehicles using MAP message. Priority level one TCD (dynamic and static) and vehicle to infrastructure (V2I) related applications will be installed in the RSUs in advance. Since the DTCD database information (particularly dynamic information) will be updated continuously to include all

accurate TCD data, the system will be able to send out TCD and warning information of collisions on the roadways in advance directly to CAVs through DSRC.

End users will be able to receive TCD information by using the products provided by the third-party developers. In addition, TCD information can be shared directly between the CAVs and the RSU through DSRC/Cellular networks. These RSU will then process the data and send out messages to nearby vehicles. It will serve as input data to support CAV applications, such as Curve Speed Warning and Stop/Yield Sign Violation Warning.

5. *Possible Discontinuation of the Existing Physical TCD Infrastructure:* Finally, since the TCD data will be provided directly to the CAVs, it will be possible to consider discontinuation of the existing physical TCD infrastructure.

DISCUSSION

VDOT's Transitioning From Physical TCD to Digital TCD System

While the results of this research indicate that there is a need to initiate development of a DTCD data service, full implementation to completely replace the current physical TCD system is decades away. Thus, VDOT must retain the current physical infrastructure and its TCD managerial processes such as planning, installation, maintenance and replacement. The DTCD data service will operate concurrently with the physical system, hence the VDOT state of practice for current physical TCDs will not change.

Potential Issues/Challenges and Recommendation for the Future System

The development and implementation of the DTCD data service will create a number of issues/challenges for VDOT to address. The following are some potential issues/challenge that would result from the DTCD development and implementation:

- *Cyber-security Threat.* Transportation systems that utilize wired and wireless communications for roadway management are at a growing risk from cyberattacks. The use of smart devices and communications systems also introduce new risk due to their new features and functionalities. Therefore, in the future DTCD system where data storage and transmission will solely be done using wired and wireless network such as DSRC, 4G, etc., the system will not be an exception. While the use of smart devices and communications provides new features and functionality, they also introduce new risks. There is therefore the need to develop a real-time threat monitoring system to continuously check the system to ensure that it functions properly.

- *Data Validation and Change Management.* Data validation refers to the checking of accuracy and quality of data before using it. . The goal here is to create a consistent, accurate, up-to-date data service. This step is necessary and critical since the DTCD data will apply to infrastructure owned and maintained by different agencies (i.e., city, county, state DOTs). To ensure the data quality of DTCD service, it is important for these agencies to follow a consistent procedure of providing and updating TCD information. This procedure as well as data related standards need to be developed. In addition, the feedback data generated from CAVs could also be very valuable for data validation. For example, if vehicle cameras detect a missing sign, the vehicle could report back to DTCD database for correction.

- *Staffing.* The DTCD data service will require staff comfortable with information technology, as well as having a thorough knowledge of traffic engineering. Knowledge and ability in sign fabrication and marking material will become less important over time. VDOT will need to consider this in long-term staff planning.

  Developing the necessary staff for the DTCD data service will be a significant budgeting consideration. During the transition period, VDOT will need both staff for the traditional physical TCD infrastructure, and for the DTCD data service. Over time, the staff can transition to purely personnel for the DTCD data service. Thus, the budget implications will be short term – but must be considered.

CONCLUSIONS

- *A comprehensive DTCD data service has the potential to improve the safety and efficiency of CAVs.* Investigation of the current development of automated vehicles shows a large amount of effort devoted to identifying and interpreting TCDs using automated vision systems. Given that VDOT is responsible for providing this information to drivers through the use of TCDs in the current state-of-the-practice, this role should translate to providing this information digitally to CAVs. This has the potential to improve the safety of CAVs by providing an authoritative data source to compare vision system derived data. With redundant data, vehicles will be less likely to make inappropriate control decisions.

- *There is a need for a national standard for DTCD data services.* Experience in the public transportation industry has shown that the GTFS standard has led to the ubiquitous availability of static and dynamic transit data. In order to make this a reality for DTCD data services, a national standard must be created that will support all transportation agencies.

- *A portion of the data needed to populate a DTCD data service exists in VDOT database systems and private map databases.* A portion of the data necessary to create a DTCD data service exists in various VDOT database systems. This provides a starting point for creation of such a service. In addition, private mapping companies have created databases that may be purchased to supplement existing VDOT data.

- *The complexity of creating a comprehensive DTCD data service cannot be fully understood without direct experience gained in the development of a prototype system.* Creation of an effective DTCD data service will be a significant and complex undertaking. Experience in similar systems (for example, in much of the past development of intelligent transportation systems) has shown that smaller scale prototype development is essential to support more effective production systems.

RECOMMENDATIONS

1. *VDOT's Connected and Automated Vehicle Program Manager and/or VDOT's Traffic Engineering Division (TED) should be actively involved in efforts with national organizations such as AASHTO to create national standards that are "GTFS-like" to govern the provision of DTCD data services for all transportation agencies in the United States. This effort should be initiated within 1 year of the publication of this report.*

2. *The Virginia Transportation Research Council should develop and test a prototype DTCD on a corridor in Virginia. This effort should be initiated within 1 year of the publication of this report.*

IMPLEMENTATION AND BENEFITS

Implementation

- *Recommendation 1 will be implemented by VDOT's Connected and Automated Vehicle Program Manager and/or Traffic Engineering Division (TED) by participating in efforts with appropriate national organizations including SAE, AASHTO, and the National Committee on Uniform Traffic Control Devices (NCUTCD).* The CAV Program Manager is a member of various CAV committees and working groups and TED staff are involved in the NCUTCD, which should facilitate VDOT's action on this recommendation.

- *Recommendation 2 will be implemented by the Virginia Transportation Research Council by establishing a project to build and test a prototype DTCD system on a corridor in Virginia.* It is suggested that the project take place on one of the Virginia Connected Corridors (VCC). The research team has worked with the FHWA's Turner-Fairbank Highway Research Center to scope a test in Northern Virginia that will allow for parallel human subject testing of drivers using a driver awareness assist system "fed" by the prototype DTCD data service called for in this recommendation. For this reason, it is suggested that Recommendation 2 be implemented in the Northern Virginia testbed of the VCC.

Benefits

- *The benefits of implementing Recommendation 1* are to take the leadership in developing a future DTCD system in the nation, and to provide a foundation for technology developers to create applications to enhance driver awareness and automated vehicle performance.

- *The benefits of implementing Recommendation 2* are to demonstrate interim benefits to justify the investment in a DTCD data service, and for VDOT to gain necessary understanding and knowledge to prepare for the opportunities as well as the challenges of providing DTCD data services in a CAV environment. This allows VDOT to look ahead and prepare for a rapidly approaching future with significant differences from the current state-of-the-practice.

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