Title

Current and Future Transportation Management High-Level Requirements Technical Memorandum

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Current and Future Transportation Management High-Level Requirements Technical Memorandum

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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1. INTRODUCTION

This document presents a review of the current and future requirements for information exchange between traffic management centers, with emphasis on the changes expected due to the changing nature of transportation and the advances in technology that are becoming prevalent in the transportation ecosystem. The intent of this document is to provide a look at the source of changes required within center-to-center communication and new requirements that will need to be addressed as transportation undergoes significant change due to new transportation modes, technology advances in connected and automated vehicles, advances in infrastructure elements, and other changes that are expected in the future.

1.1. PURPOSE OF DOCUMENT

This document is one of three initial technical memorandums designed to accomplish the following:

- Review the current Traffic Management Data Dictionary (TMDD) standard.
- Review the information technology landscape, specifically regarding information exchange mechanisms, tools and techniques, and exchange protocols currently available. Review new and upcoming technologies suitable for exchange of information.
- Review current and future transportation information exchange needs and technologies, specifically related to center-to-center information requirements (this document).

This document will include the review of current and future transportation information exchange needs and technologies.

1.2. INTENDED AUDIENCE

The primary audience for this document includes:

- Caltrans DRISI sponsors of the project
- Caltrans operations managers at headquarters and the district level
- Vendors with products that incorporate center-to-center communications capabilities
- ITE committee for the TMDD standard
- University of California, Berkeley Connected Corridors program personnel

1.3. DOCUMENT ORGANIZATION

The remainder of this document is organized as follows:

- **Section 2** presents a general description of TMC operations including monitoring, controlling, and informing.
- **Section 3** provides a review of the National ITS Architecture and explores three cases of integrated corridor management deployments.
- **Section 4** explores future trends in transportation and investigates various influencing factors.

- **Section 5** studies the centers demand for collaboration.
- **Section 6** provides a review of existing standards related to various interface classes of the National ITS Architecture.
- **Section 7** investigates the requirements for future C2C communications.
- **Section 7** provides a summary of findings.

2. EXISTING TMC OPERATIONS

Transportation management centers (TMCs) aim to manage various aspects of transportation networks to enhance safety and efficiency of the systems. According to the Federal Highway Administration (FHWA), a TMC performs [1]:

> *"... monitoring, collecting, processing and fusing transportation system data; disseminating transportation information to outside entities; implementing control strategies that affect changes in the transportation system; and coordinating responses to traffic situations and incidents."*

Based on this definition, operations of a full-scale TMC include three main functions: monitoring, controlling, and informing. This section explores these three functions in more detail.

2.1. MONITOR

TMCs monitor and collect data of traffic incidents, state information including traffic signal timings and performance measures (e.g., traffic flow condition, average travel time), weather condition, work zones, and special events. Each of these items can use various technologies and tools to collect the required information. Table 1 lists examples of such tools and technologies.

Table 1 - TMC monitoring items and tools (*source*: adopted from [2])

Monitored Item	Tools
Incidents	• Closed-circuit television (CCTV) • Communication with local law enforcement and 911 dispatchers • Computer-aided dispatch (CAD) and similar systems • Third-party reporting (i.e. Waze) • Video incident detection
Traffic State Information: • Travel time • Speed, Flow, Density • Delays and congestions • Traffic signal status • Ramp meter status	• CCTV • Loop, acoustic, radar detectors • Probe vehicle • Traffic signal plans • Wide-area wireless communications • Dedicated short-range (DSRC) communications • Safety/service patrols, police report • Ramp meters and metering rates/plans
Weather	• Automated roadway detection including road weather information systems (RWIS)
Work Zones	• CCTV • Communications with crews • Intrusion alert devices

	• Sensors in barrels or cones
Special Events	• CCTV • Communications with authorities

2.2. CONTROL

TMCs can apply various controls to manage available infrastructure, optimize system performance, and ensure safe operations. Controls can be applied individually or in conjunction with other controls. Table 2 lists TMC controlled items and tools.

Table 2 - TMC controlling items and tools (*source*: adopted from [2])

Controlled Item	Tools
Traffic Signals	• Coordinated signal systems • Adaptive traffic signals • Adjusting traffic signal splits • Transit signal priority / emergency vehicle preemption
Ramps	• Ramp metering • Ramp gates • Priority access • Interchange metering • Mainline metering (bridge, toll, etc.)
Speed Limit	• Variable speed limit
Lane Access/Usage	• Vehicle restriction • Lane use/road closure
Work Zones	• Road closure management • Speed enforcement
Messages/Warnings	• Variable message signs
Pricing and Tolling (e.g., congestion pricing, tolling, parking, transit)	• Radio frequency identification (RFID) • Barcodes • Smart cards
Incidents	• Safety/service patrols • Access restriction • Physical barriers • Warning system

2.3. INFORM

TMCs gather information and data through their monitoring tools. In addition to real-time and historical information, TMCs gather transportation network information (e.g., physical assets). The collected data can be shared with the public to provide information regarding traffic conditions. Moreover, TMCs can collaborate with other agencies and organizations and exchange information. Table 3 lists examples of tools that TMCs use to exchange information with the public and other agencies.

Table 3 - TMC information exchange tools (*source*: adopted from [2])

Information Type	Tools
Shared with the public: ● Travel time ● Incident ● Advisory/Emergency Messages ● Local traffic condition ● Local weather condition	● Variable Message Sign (VMS) ● Highway Advisory Radio (HAR) and Low-Power FM Radio ● In-Vehicle Communications (e.g., IntelliDrive, Sirius XM radio traffic channel) ● CV On-board Unit displays/TIM messages ● 511 Traveler Information Systems ● California QuickMap Information Service ● Third-Party Communications (e.g., Traffic.com) ● Email, pager, fax, short message service (SMS)
Shared with other Agencies: ● CCTV feeds ● Traffic sensor data ● Weather sensor data ● Incident and congestion ● Work zones, special events ● Probe vehicle data ● Traffic signals, ramp meters, lane controls, VMSs ● Public transit data ● Public alert and warning system data	● C2C communications

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3. CURRENT SOURCES OF INFORMATION

This section explores existing sources of information based on the National ITS Architecture. In addition, three integrated corridor management projects in the US are outlined.

3.1. NATIONAL ITS ARCHITECTURE

The Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) provides a detailed list of activities, functions, and objects supported by typical TMC operators. The ARC-IT is a framework for planning, defining, and integrating the variety of objects in intelligent transportation systems [3]. Figure 3-1 shows the physical view of the ARC-IT presented in Version 8.3 [3].

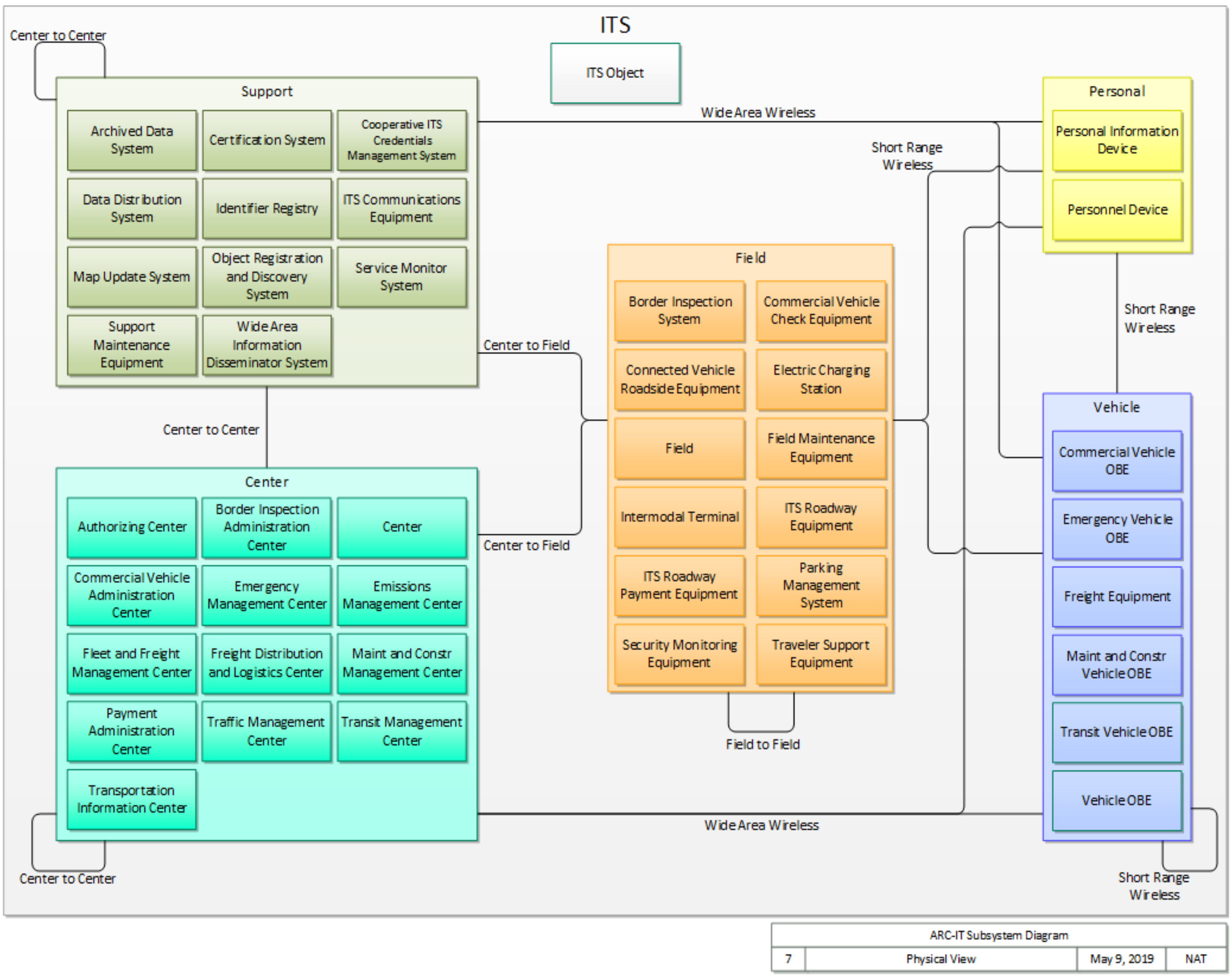

Figure 3-1 - Physical view of the Architecture Reference for Cooperative and Intelligent Transportation (*source*: [3])

Information exchange occurs between source and destination physical objects. ARC-IT identifies five groups of physical objects based on their behavior and interactions with other physical objects. The classes of physical objects include:

- **Field**: such as Field Maintenance Equipment and Parking Operator
- **Personal**: such as Cyclist, Pedestrian, Traveler, and Personal Device
- **Vehicle**: such as Commercial Vehicle OBEs, Driver, and Emergency Personnel
- **Support**: such as Archive Data System and Service Monitor System
- **Center**: such as TMC, Vehicle Service Center, and Emergency Management Center

TMCs exchange information with several subsystems in each class of physical objects. The class of physical objects determines the type of interactions with other subsystems. For instance, a Center interacts with a Field object through *Center to Field* communication while it exchanges information with a Personal or Vehicle object via *Wide Area Wireless* communication. A Center interacts with another Center through a *Center to Center* communication.

3.2. EXAMPLE INTEGRATED CORRIDOR MANAGEMENT DEMONSTRATION SITES

There are several Integrated Corridor Management (ICM) demonstration sites that illustrate more advanced examples of communication needs for Center-to-Center information exchange. The four sites mentioned below provide a reasonable and generally consistent view of the variety and volume of data exchanged, as well as the usage of the information exchanged for ICM operations. Each of these programs utilized TMDD for their Center-to-Center communications. San Diego and Dallas sites were federally funded ICM demonstration sites, while the I-210 Connected Corridors program is the first state-funded ICM demonstration in the United States. Other ICM programs do exist at varied levels of complexity, including the I-80 corridor in the California San Francisco Bay Area.

Additional information can be found on-line for each of these three representative programs at:

San Diego:

- https://www.sandag.org/index.asp?projectid=429&fuseaction=projects.detail
- https://rosap.ntl.bts.gov/view/dot/32035

Dallas:

- https://trid.trb.org/view/1400202

Florida Department of Transportation District 5

- http://www.cflsmartroads.com/projects/ICM.html

Connected Corridors:

- https://connected-corridors.berkeley.edu/

3.2.1. SAN DIEGO ICM

The San Diego ICM site corridor is a 21-mile long segment of I-15 between San Diego and Escondido [4]. The corridor is one of the two main freeways connecting commuters and cargo movements between San Diego, Orange, and Riverside counties. Key strategies used in the ICM includes [4]:

- Improvements of selected traffic signal systems
- Active Decision Support System
- Coordinated incident management
- Freeway coordinated ramp metering
- Actionable traveler information
- Alternate route wayfinding signs.

Figure 3-2 shows various components of the San Diego ICM system. The ICM system interfaces with a variety of systems which are managed by different agencies. The sources of information include:

- **Freeway Systems** (shown in turquoise) including Lane Closure System, Ramp Meter Information System, Advanced Traffic Management System, Congestion Pricing System, Express Lanes Control System
- **Arterial Systems** (shown in yellow) including Regional Arterial Management System
- **Transit Systems** (shown in lavender) including Regional Transit Management System, Smart Parking System)
- **Public Safety** (shown in purple) including Regional Event Management System
- **Advanced Traveler Information Systems (ATIS)** (shown in orange) including Arterial Travel Time System, Traveler Information Systems, Weather Information System.

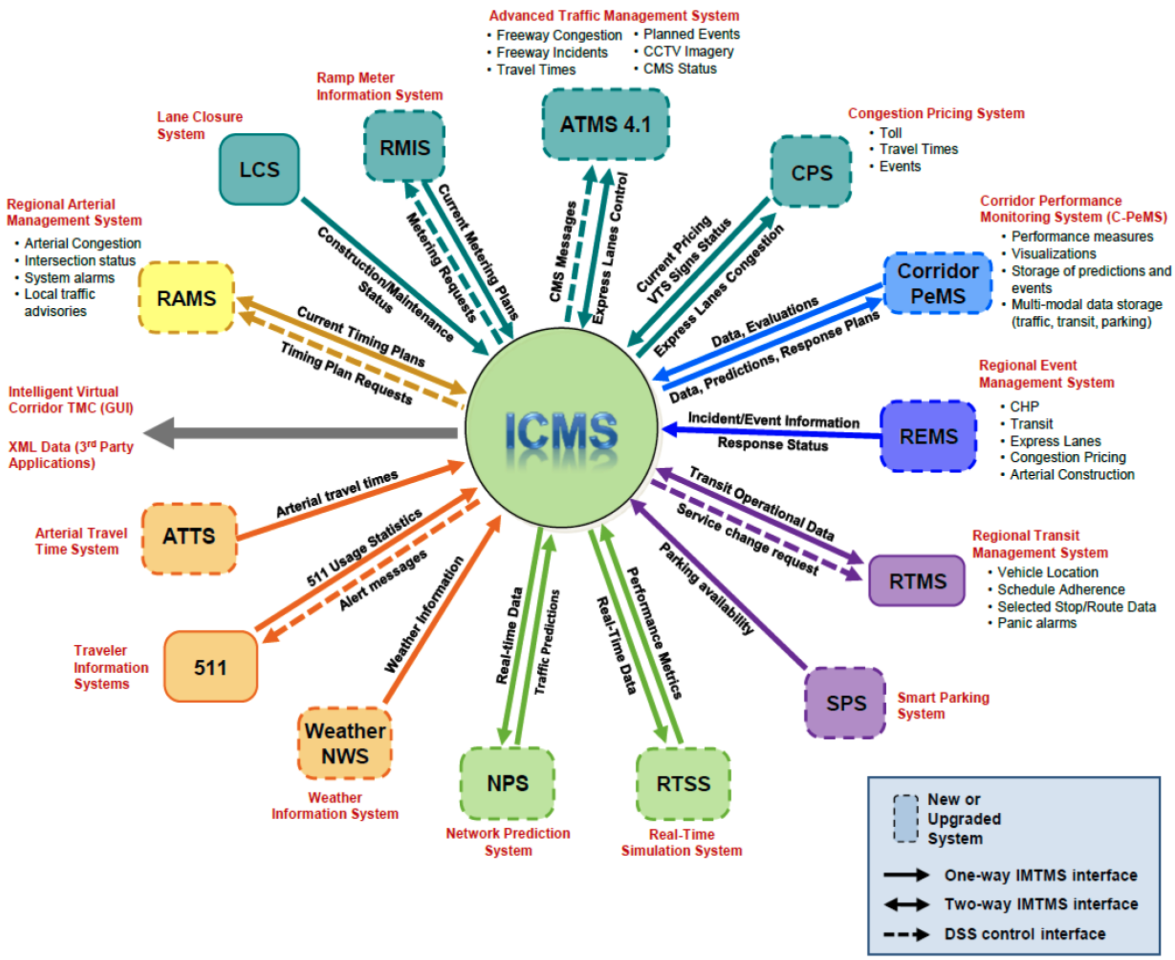

Figure 3-2 - San Diego I-15 ICM system (*source*: [4])

3.2.2. DALLAS ICM

The US-75 Integrated Corridor Management System (ICMS) supports corridor management through sharing information including special event, construction, transit, incident, and traffic flow data [5]. The US-75 ICM uses the obtained data to provide operational planning and evaluation.

Th Dallas ICM system has three main subsystems [6]:

- Information Exchange Network User Interface (SmartNET)
- Information Exchange Network Data Layer (SmartFusion)
- Decision Support System (DSS)

Sources of information in the Dallas ICM system include:

- Weather information
- Parking information
- Navteq data (freeway and arterial traffic information)
- Regional C2C

- TxDOT XML (provides detailed information that C2C does not provide)
- Dallas Area Rapid Transit (DART) AVL & APC data
- DART Events
- DART GTFS

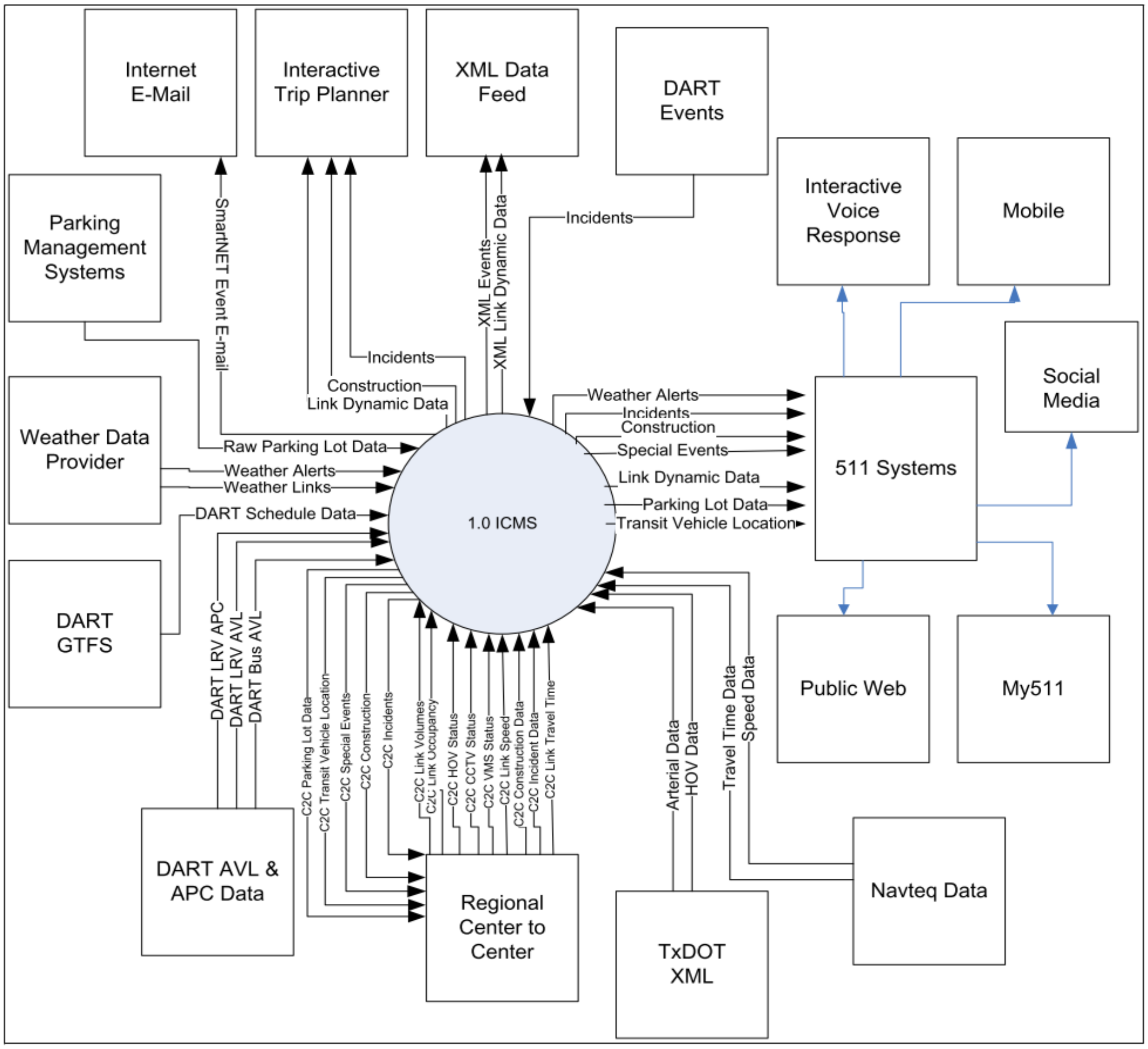

Figure 3-3 - Dallas US-75 Integrated Corridor Management System (*source*: [6])

3.2.3. FLORIDA DOT DISTRICT 5 ICM

The Florida DOT District 5 ICM is located in the Orlando area with operations along the I-4 freeway and surrounding communities. It coordinates the operations of eight Transportation Management Centers and includes state, county, city, rail, bus, park and ride, and toll operations. Primary goals of the system, in priority order, include improving information sharing across the corridor, improving travel time reliability, enabling intermodal travel decisions, improved incident management, increased corridor throughput, and improve infrastructure coverage. The District 5 regional TMC hosts a data fusion system, ATMS, and Decision Support System along with center-to-center communications with other agency's systems to distribute response plan requests and coordinate regional signal and ramp meter actions. Traveler information is provided via 511, DMS, agency websites, media, and mobile applications.

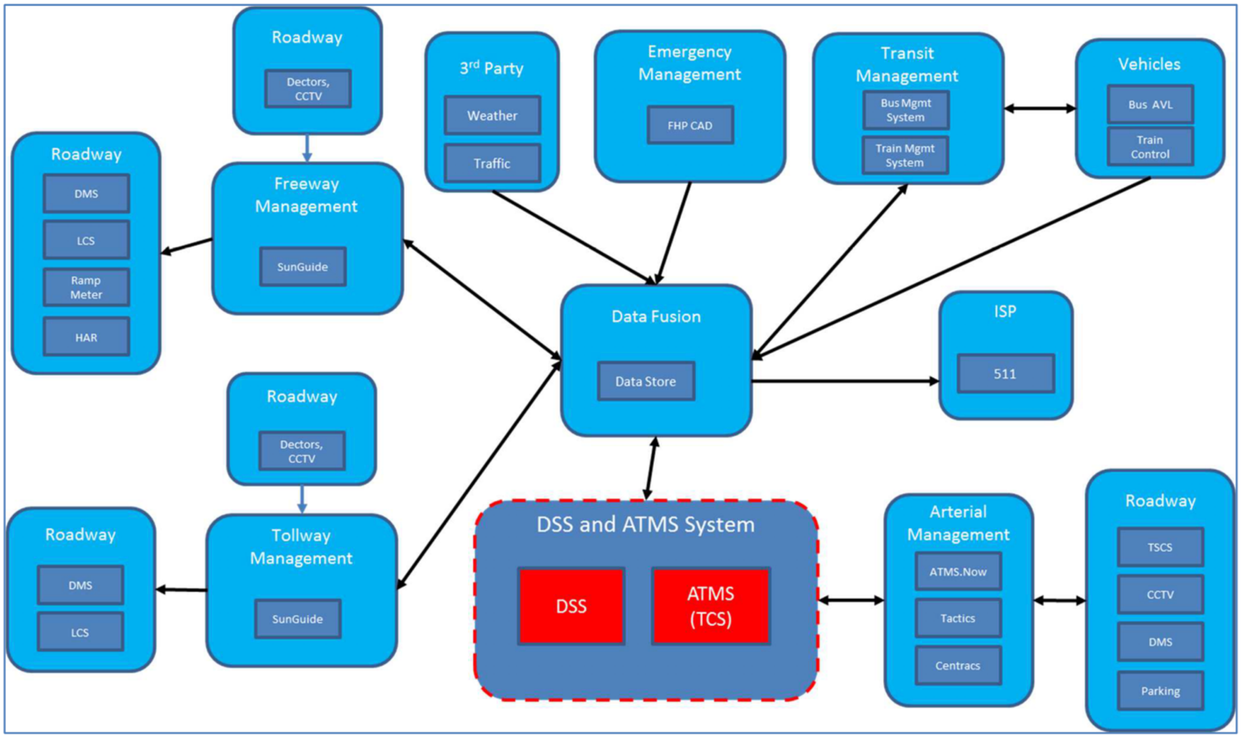

Figure 3-4 FDOT I-4 Baseline Operations Diagram *(source: Florida DOT District 5)*

3.2.4. I-210 PILOT

The I-210 Pilot is located on a 22-mile section (from the SR-134/I-210 interchange near downtown Pasadena to the Foothill Boulevard interchange in La Verne) of the I-210 freeway in the San Gabriel Valley in Los Angeles County [7]. The I-210 Pilot network includes the most heavily congested sections of the freeway. ICM strategies considered in the I-210 Pilot include [7]:

- Integration of freeway ramp meters and arterial signal systems
- Arterial signal coordination
- Traffic rerouting due to incidents or events with support from dynamic message signs and 511
- Transit signal priority on arterials and on-ramps (future)
- Parking management (future)
- Traveler communication of traffic conditions, transit services, parking, alternate route/trip/mode options (future)
- System coordination/communication between Caltrans and local jurisdictions

Sources of information in the I-210 Pilot ICM include:

- **Roadway operators** (shown in blue) including freeway detectors, freeway CMS, ramp and connector meters, lane closure system, traffic signals, bluetooth devices, changeable message signs, and cameras
- **Transit operators** (shown in green) (future)

- **Law enforcement and first responders** (shown in red) including Freeway Service Patrol, call boxes, local dispatch systems, CAD system
- **511 services/Information providers** (shown in purple) including traveler information applications, radio, weather, 511 systems
- **Other data suppliers** (shown in gray) including probe vehicle data, crowdsourcing, and PeMS dataset

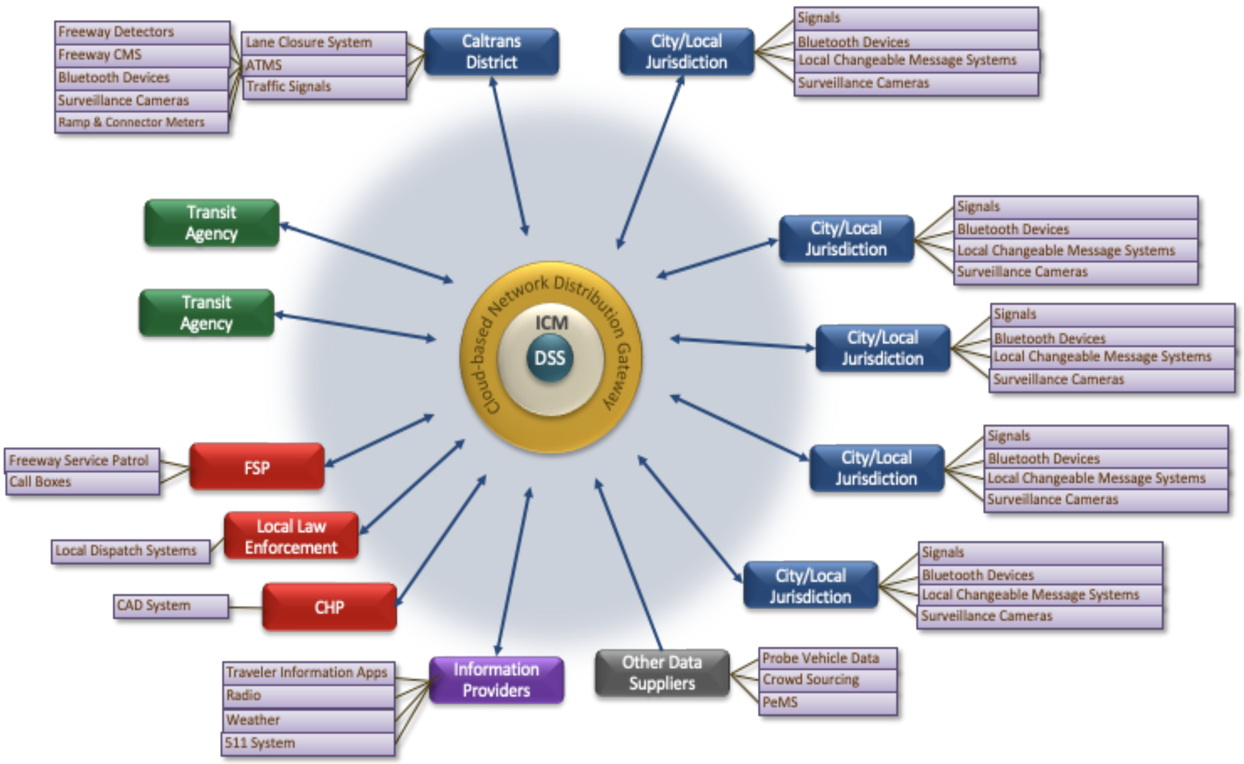

Figure 3-5 - The I-210 ICM System High-Level Architecture

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4. FUTURE TRENDS

The advent of the Internet of Things, ride-hailing, micromobility services, and connected autonomous vehicles are changing how travelers behave in transportation systems. The emerging technologies and business models will be creating massive new businesses, disrupt existing models, change cities, and impact quality of life [8].

4.1. INFLUENCING FACTORS

4.1.1. INTERNET OF THINGS

Internet of Things (IoT) is a concept based on the integrations of different processes including sensing, identification, networking, and computation [9]. IoT enables value-added services and technological innovations by providing interactions with various processes.

IoT is increasingly deployed in intelligent transportation systems to improve the efficiency, safety, and security of the transportation systems. Embedding IoT sensors in transportation networks allows TMCs to better collect data, estimate current state information, and respond to varying traffic conditions. IoT sensors and technologies can be utilized for various purposes including [10]:

- **Traffic monitoring:** devices such as Global Positioning System (GPS), Radio Frequency Identification (RFID), vehicle accelerometers, detectors, and cameras can be used to monitor and estimate traffic condition
- **Driver safety:** devices such as gyroscope, GPS, accelerometer, eye movement detector, face detector, can be utilized to monitor driver's behavior
- **Parking guidance and information (PGI)**: devices such as message signs, cameras, and sensors detecting parking occupancy status, can be used to help drivers find parking spaces
- **Traffic signals:** devices such as traffic volume detectors, emergency vehicle detectors, transit vehicle detectors, and cameras can be used to improve efficiency of traffic signals and provide emergency preemptions as well transit signal priorities.

4.1.2. AUTOMATION AND CONNECTIVITY

The connected and autonomous vehicles (CAVs) market is currently growing at a fast pace, and many driverless cars are expected to be on our roads in large numbers. Numerous companies are manufacturing level-2 autonomous cruise-controlled (ACC) vehicles and full autonomous vehicles (level-5) are expected to enter the market. Currently, more than 136 cities around the world are piloting or preparing for CAVs (Figure 4-1).

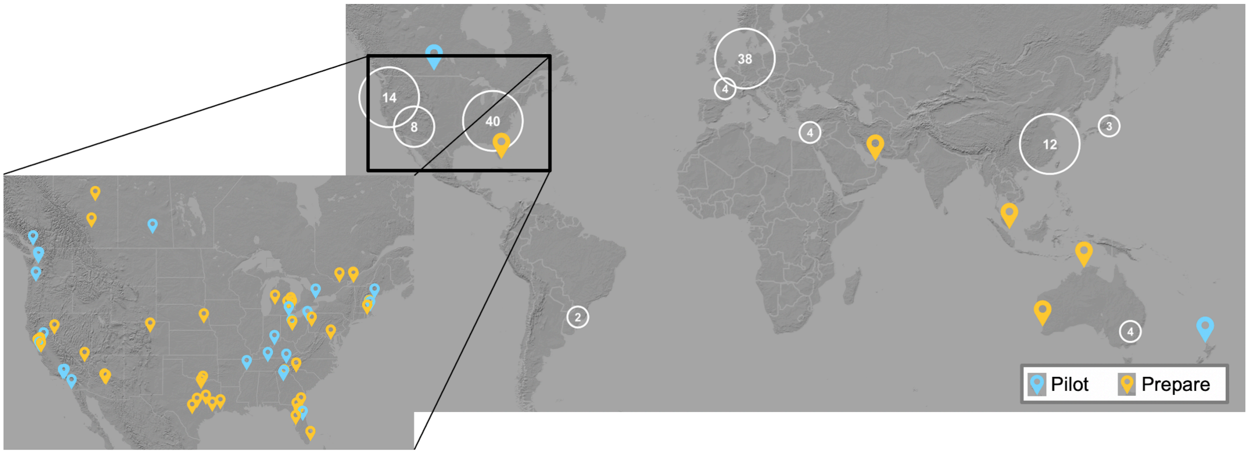

Figure 4-1 - Cities piloting or preparing for CAVs (*source*: adopted from [11])

Poor human driver behavior, such as abrupt lane-changes, along with limited human reaction times and lack of coordination with other drivers can disturb traffic flow and lead to traffic waves [12]. The emergence of CAVs has provided significant opportunities since CAVs fundamentally change the way traffic flows and enable traffic systems to eliminate human error and improve safety. In addition, CAVs provide connected and integrated transportation environments which offer an opportunity to mitigate weaknesses in human driving.

TMCs traditionally utilize infrastructure-based controls, such as traffic signal control, ramp metering, and lane access control, to manage traffic systems. With the advent of CAVs, a new paradigm is emerging where TMCs can utilize CAVs to manage traffic. Recent research efforts have indicated that even a small percentage of CAVs can significantly reduce traffic energy footprint and improve safety [12], [13].

Furthermore, connected vehicle environments enable TMCs to directly communicate with CAVs. This enables TMCs to distribute information directly to these vehicles.

4.1.3. Shared MicroMobility

Shared micromobility services such as dockless scooters, bicycles, and mopeds have been growing at a fast pace. Over the past decade, the shared micromobility industry has grown to an ecosystem with a wide variety of vehicle types, ownership configurations, and system models [14]. Micromobility is becoming an integral part of transportation systems providing a mode that contributes environmental, public health, and equity goals.

In 2019, more than 292 cities across North America had bikeshare or scooter systems [14]. Several cities are collaborating with operators to provide micromobility data streams. For instance, Chicago has made its scooter data stream open source, which provides real-time information of scooters available for rent [15]. In order to effectively manage mobility policies, TMCs will need to interact with micromobility companies who operate in the public right-of-way.

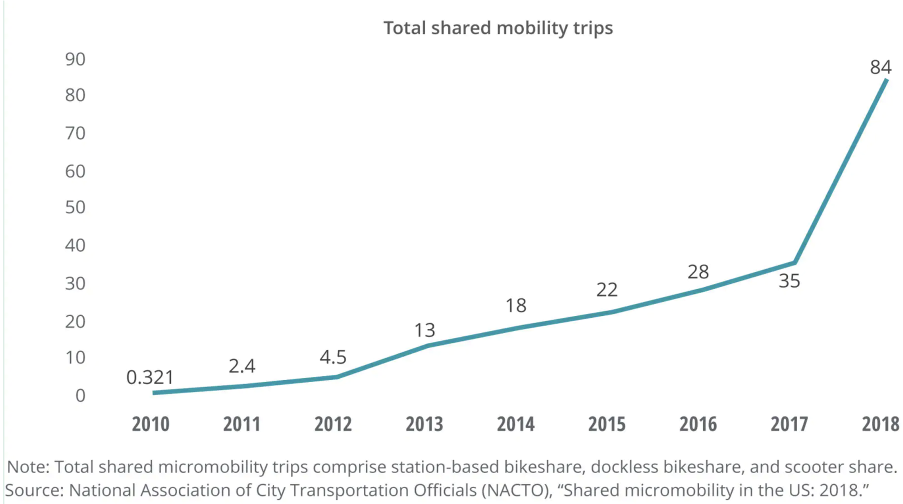

Figure 4-2 - Trend of shared micromobility tips in the US, in millions (*source*: [16])

Micromobility industry was accelerating until the COVID-19 pandemic which dramatically reduced the use of micromobility services. It is expected that the pandemic will shift consumer behavior and travel preferences [17]. Micromobility is considered less risky than other shared mobility modes, such as public transit, and consequently more people are using the micromobility services for the first time and average travel distance is increasing. By 2030, it is estimated that passenger-kilometers traveled using micromobility services will increase 5 to 10 percent [17].

4.1.4.Ride-hailing

Ride-hailing, also known as ride-sourcing, refers to prearranged and on-demand transportation services for compensation that provide connection between drivers of personal vehicles and passengers [18]. The ride-hailing services often use mobile applications for booking, payment, and rating. Uber, which was founded in 2009 in San Francisco, California [19], is one of the pioneers of the ride-hailing industry. Since then, several other companies, such as Lyft, have entered the market. According to the 2017 National Household Travel Survey, nearly eight percent of the U.S. population used a ride-hailing service at least once in the last 30 days [20].

The total available market (TAM) of transportation, which is currently estimated to be more than $7 T [8], is set to change dramatically. It is expected that ride-hailing services will significantly disturb multiple existing markets, such as taxi services, car ownership, and public transportation. By 2030, Goldman Sachs predicts the ride-hailing market to reach around $400 B which will account for about five percent of the transportation market (Figure 4-4). It is estimated that global ride-hailing miles will expand at a 5-year compound annual growth rate of 15%, while personal vehicle miles will increase by 2% over the same period [8].

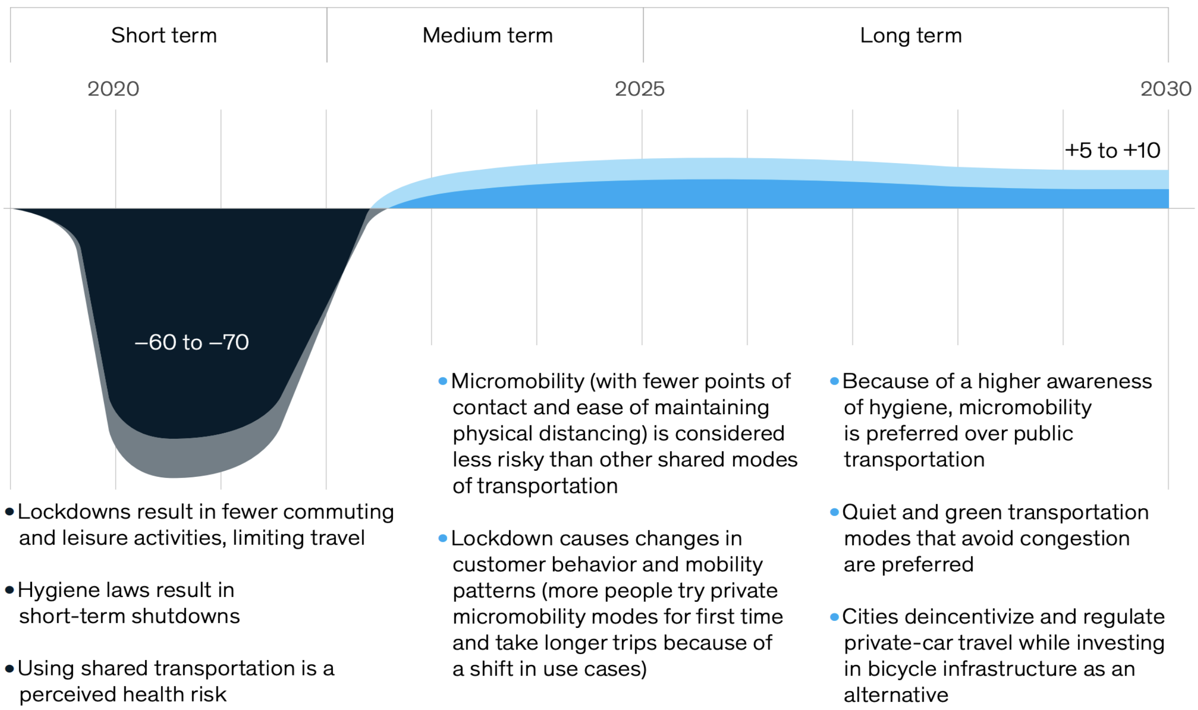

Figure 4-3 - Global micromobility growth based on the 2019 market, % passenger-kilometers traveled (*source*: [17])

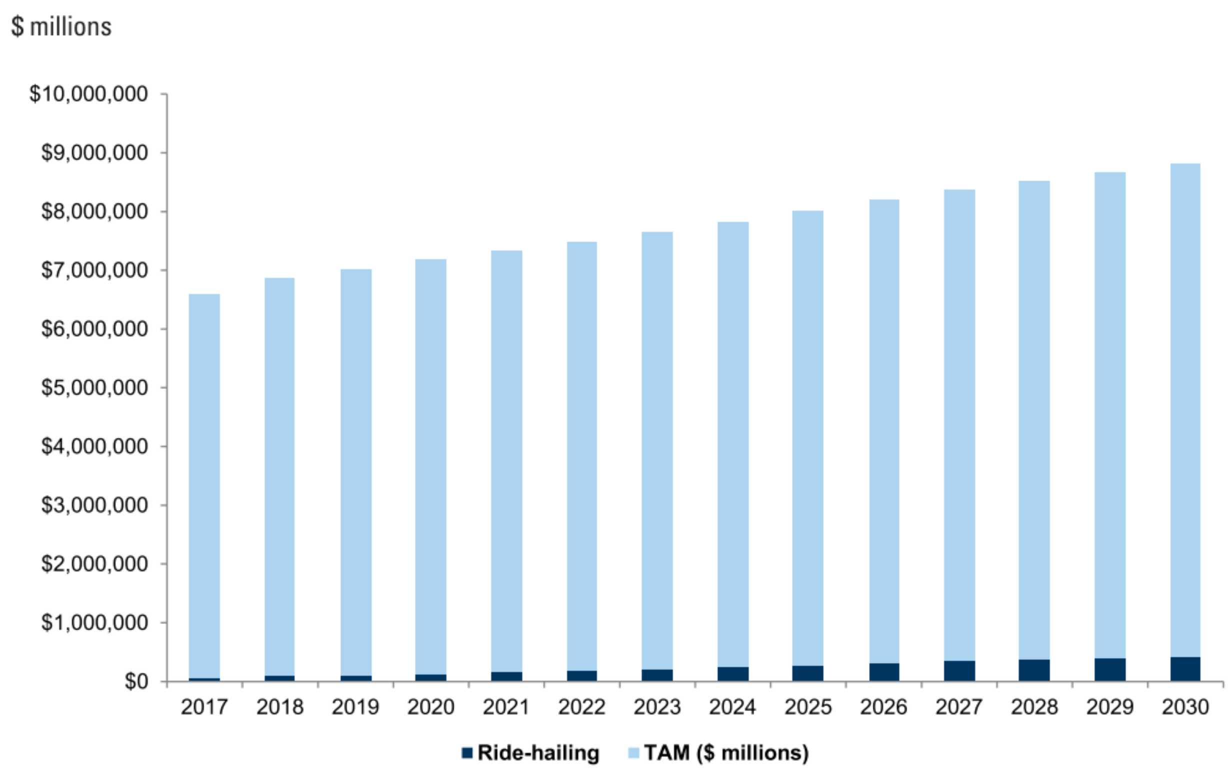

Figure 4-4 - Trend in ride-hailing and total available market of mobility (*source*: [8])

Ride-hailing services are affecting transportation systems around the world. From 2013 to 2019, ride-hailing daily trips in New York City jumped from 20,000 to more than 700,000 [21]. A study of Manhattan traffic indicated that about 30% of traffic in Manhattan were For-Hire Vehicles (FHVs), which mainly included ride-hailing vehicles, and that 41% of the time, these vehicles were driving without a passenger [21].

4.1.5.Multimodal

The advances in technology have paved the way for optimizing the performance of existing infrastructure through the implementation of multimodal transportation systems. Multimodal transportation refers to systems that integrate more than one mode to transport goods between an origin and destination. Emerging technologies enable travelers to plan, access, and pay for multiple shared mobility services, such as ride-hailing, scooter, bicycles, and public transit.

A recent empirical study analyzed multimodal connections between dockless bikesharing and ride-hailing in New York City [22]. The results indicated that the multimodal system in comparison to the single-mode system served the same number of travelers with 40% fewer taxis. The study concluded that multimodal bikesharing and ride-hailing services decrease travel times and reduce road congestion.

4.1.6.Data Collection and Information Sharing

Transportation management and control requires data sources describing the state of the system such as weather condition, traffic counts, and signal status. The rapid advancements in data collection and communication technologies has brought a unique opportunity for TMCs. With better data qualities and more sources, TMCs can add to their capabilities improved estimation and prediction models and apply more efficient controls.

Data generation over the past decade has been exploding and will continue to increase in the next decade. According to International Data Corporation (IDC) [23], in 2010 1.2 zettabytes data was generated in the world, while 33 zettabytes data was created in 2018. IDC predicts that 175 zettabytes will be generated in 2025.

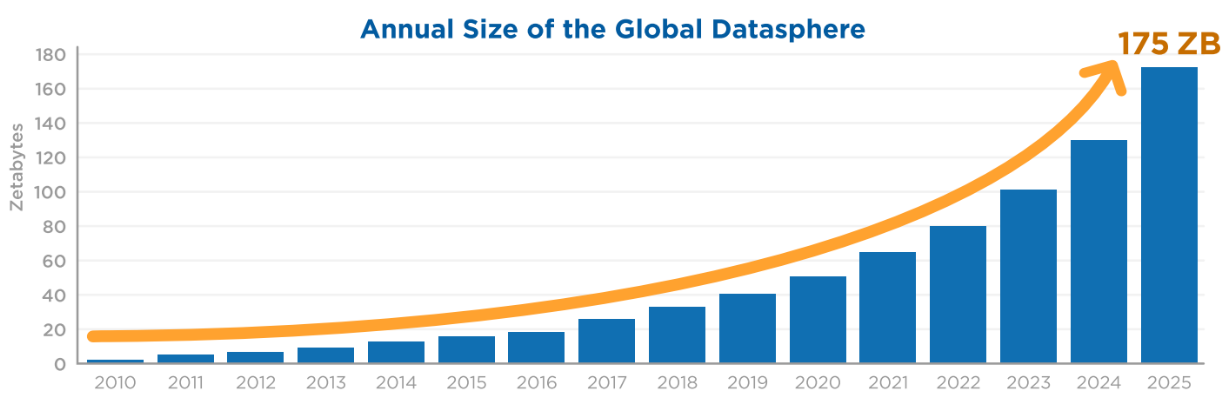

Figure 4-5 - Size of global datasphere (*source*: [23])

CAVs are expected to generate considerable amount of data by their systems including sensors and cameras. As the level of autonomy increases, the amount of generated data increases (Figure 4-6). It is estimated that Level-5 CAVs will generate 25 gigabytes of data every hour [24].

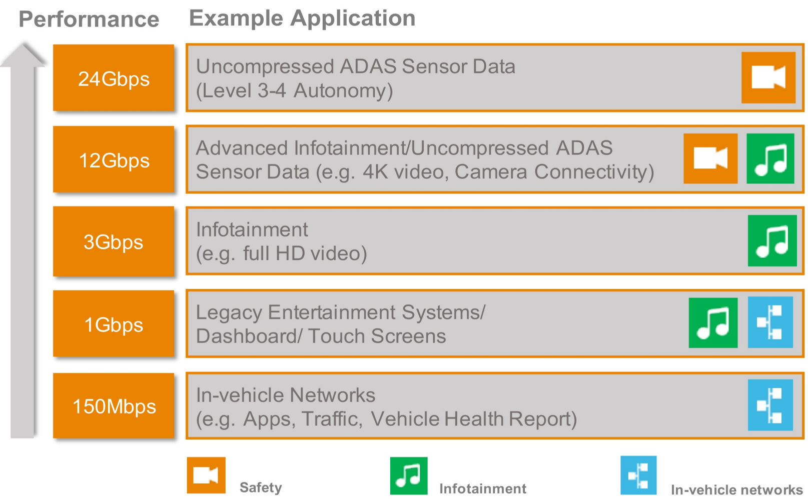

Figure 4-6 – Vehicle data generation by various systems (*source*: [24]**)**

The trend in data generation will require partnerships of public and private transportation organizations to share, secure, and standardize data. Through these partnerships, TMCs can benefit from diverse sources as well as higher coverage, data types, and resolution.

4.1.7.New Modes

New transportation modes are expected to enter the market. TMCs will need to plan for the introduction of the new modes in order to effectively manage their systems. Hyperloop, air taxi, and drone delivery are examples of the new modes that might enter the market.

Hyperloop

Hyperloop is an idea for long distance transportation mode which would move passengers or goods through tubes [25]. Hyperloop potentially may provide faster, cheaper, and more environmentally friendly services in comparison to other modes such as trains, airplanes, and cars. Several companies, such as Hyperloop One, are planning to build hyperloops in the US, India, and United Arab Emirates [25]. If successful, hyperloop can enter the transportation market in the next few years.

Air Taxi

Air taxies, which are small commercial aircrafts, are being designed for short flights on demand. The Uber Elevate team is working on Uber Air that would provide aerial ridesharing at scale [26]. The first phase of Uber's shared air transportation, which is planned for 2023, would fly between cities and suburban areas.

Air taxies are on track to become a reality in the near future [27]. In order to enable mass-scale urban air transportation, the battery life needs to be improved, required infrastructure such as ports should be built, and regulatory requirements should be address [27].

Drone delivery

Drone delivery is an autonomous unmanned aerial vehicle used for transporting goods such as packages, food, and medical supplies [28]. Amazon, United Parcel Service (UPS), and Domino's are among companies that are developing drone delivery services [29]. In 2020, Amazon received federal approval for implementing drone delivery [30].

4.1.8.Social Media for traveler information

Since early 2000s, social media platforms have been increasingly used [31]. Figure 4-7 displays trends in several social media usages. The increase in social media usage enables TMCs to use these platforms to directly communicate with travelers. TMCs can provide information such as such as incident, emergency, and routing messages to the travelers.

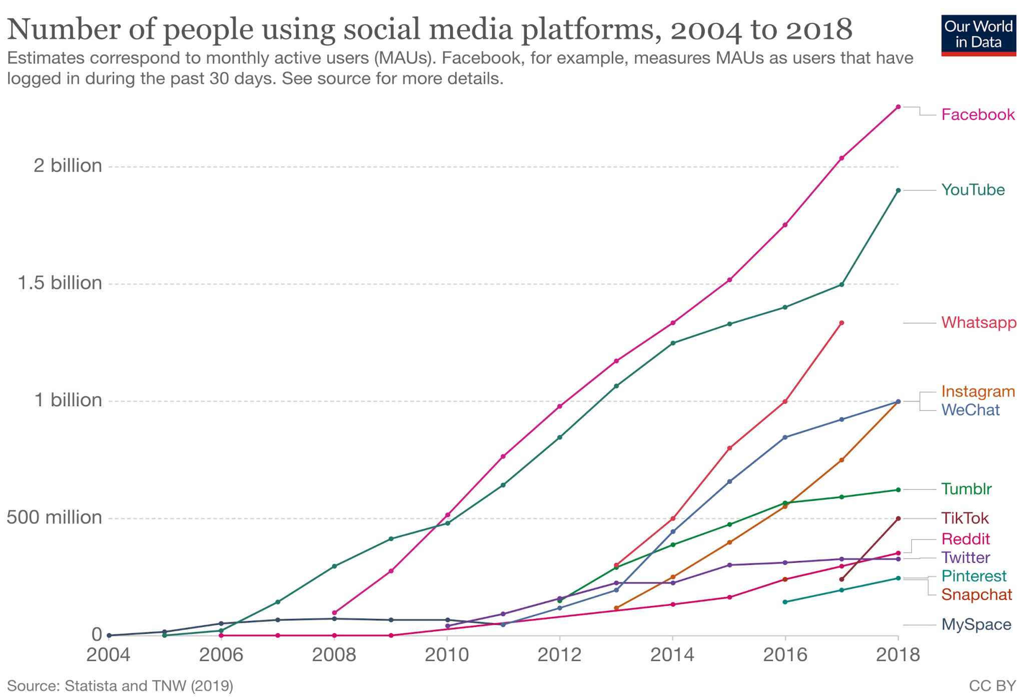

Figure 4-7 - Social media platforms usage (*source*: [31])

4.2. HORIZONS

The influencing factors explored in Section 4.1 would potentially affect transportation systems over different time periods. This section investigates future trends over short-term, medium-term, and long-term horizons.

4.2.1. SHORT-TERM (0-5 YEARS)

- **Monitor**: In the next five years, limited increase in the IoT services is expected due to limited 5G infrastructure. Information sharing with other agencies and third-party private data will increase, but be limited. There will be an increasing need to collect ride-hailing and micromobility data.
- **Control**: Very limited vehicle-based control will be implemented due to low CAV penetration rates. Increasing capabilities for controlling infrastructure such as traffic lights, speed limits, and lane use will enable more infrastructure-based control strategies. Applications of active traffic management to apply demand-side control is expected.
- **Inform**: Limited use of social media for informing the public. Information sharing with other agencies will be mainly limited to local agencies.

4.2.2. MEDIUM-TERM (5-10 YEARS)

- **Monitor**: In the next five to ten years, increase in the data collected from IoT devices is anticipated due to improvements in 5G infrastructure. Information sharing with other agencies and third-party private data will significantly increase and limited data from regional collaborating agencies. There will be a significant increase in data obtained from ride-hailing and micromobility data.
- **Control**: Increasing capabilities for vehicle-based control due to increasing CAV penetration rates. Improvements in infrastructure-based control and applications of active traffic management.
- **Inform**: Significant use of social media for informing the public. Limited use of CAVs to directly communicate with drivers. Improvements in information sharing with local agencies. Limited information sharing with regional agencies.

4.2.3. LONG-TERM (MORE THAN 10 YEARS)

- **Monitor**: Significant data collected from IoT devices and information sharing with other agencies and third-party private data. Significant data gathered from other local agencies and third-party private data. Significant data from regional collaborating agencies. Significant data obtained from ride-hailing and micromobility data. Significant data collected from new modes such as air taxi.
- **Control**: Significant capabilities for vehicle-based control. Significant improvements in infrastructure-based control and deployment of active traffic management strategies such as pricing.
- **Inform**: Significant use of social media for informing the public. Significant use of CAVs to directly communicate with drivers.

Figure 4-8 - Trends in TMCs Operations

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5. DEMAND FOR COLLABORATION

Existing TMC operations are mainly concerned with the movements of vehicles (including passenger cars, trucks, and transit vehicles). This paradigm mainly focuses on the ground transportation movements and rarely takes into consideration other modes of transportation. With the advent of micromobility services, and new transportation modes, TMCs will need to take into account more players in urban transportation systems.

Over the next decade, traffic and congestion will continue to grow in urban areas. Recent migration trends from urban to sub-urban and rural areas is also occurring at an increased rate, particularly with the move to remote work practices with the COVID-19 epidemic. This, along with reductions in the use of mass transit as a result of the epidemic, is likely to change traffic and congestion patterns permanently. Transportation subsystems will likely be more interrelated and interconnected. Transportation managers will likely incorporate monitoring and control information from broader regional areas to provide a more robust plan for the total transportation network in a region. It is expected that communications costs will fall, and the range of data coverage will increase, which can help grow the scope of TMC operations.

In addition to more regional operations, multi-jurisdictional operations of TMCs are likely to increase. In a single jurisdiction plan, a TMC has sole discretion and autonomy to manage its network, while in a multi-jurisdictional plan, TMCs are required to coordinate their efforts. Traffic will be managed more cooperatively, as opposed to independently.

In the near future, it is expected that transportation managers will integrate more multi-modal operations to more effectively manage the transportation system. Integration of multiple travel modes such as public transit, ride-hailing, and micromobility services can improve the efficiency of transportation systems. To perform multi-modal operations, TMCs will require broader cooperation between stakeholders.

TMCs will likely deploy more advanced traffic management technologies and utilize more IoT devices. The data gathered from these devices can provide valuable information for other agencies to improve their services. Enhanced communication systems between various agencies will help the agencies to more effectively utilize outside information.

A center might share data obtained from a third-party source with other centers to improve their predictions and enable higher quality proactive management. It is expected that TMCs will have access to more third-party data made available from various sources, such as navigational applications and factory-installed vehicle sensors. Third-party data can include vehicle location, environmental information, and incident data.

Increasing penetration rates of CAVs along transportation networks provides an opportunity for effective vehicle-based control. Level-2 autonomous vehicles have already entered the market and Level-5 (full autonomy level) are on the horizon. The emergent behaviors from CAVs introductions can affect traffic behaviors in different ways from increasing traffic capacity to enhancing safety. In addition, numerous sensors installed on CAVs can provide valuable information for managing transportation systems. Governments, universities, research institutions and car manufacturers are conducting a broad range of studies on CAV technologies. Collaboration between various centers can help TMCs to more effectively benefit from CAVs data and deploy vehicle-based control.

6. EXISTING STANDARDS

As shown in Figure 3-1, ARC-IT identifies five classes of interfaces for the interactions of physical objects including center-to-center (C2C), center-to-field (C2F), center-to-vehicle/traveler (C2V/T), field-to-field (F2F), and field-to-vehicle (F2V). Each of these interface classes has various application areas which are listed in Table 4.

Future trends of the influencing factors (e.g., CAVs, IoTs), as well as the growing need for collaboration between centers, will significantly affect all of the interface classes. For instance, the IoT improvements might add new data fields to all interface classes while the introduction of CAVs in transportation systems can provide new data fields for C2V, F2V, and C2C communications.

Table 4 - ITS Standards Application Areas Table (source: [32])

Interface Class	Standards Application Areas	Example Standards
Center-to-Center: Includes interfaces between various transportation management centers.	Data Archival Incident Management Rail Coordination Traffic Management Transit Management Traveler Information	**ITE TMDD 3.3 ITE TMDD** Traffic Management Data Dictionary (TMDD) Standard for Center to Center Communications; **NTCIP 1104** Center-to-Center Naming Convention Specification; **NTCIP 2306** Application Profile for XML Message Encoding and Transport in ITS Center-to-Center Communications (C2C XML); **IEEE 1512** -2006 Standard for Common Incident Management Message Sets for use by Emergency Management Centers; **SAE J2354** Message Set for Advanced Traveler Information System (ATIS);
Center to Field: Includes interfaces between a center and its field equipment such as: ● traffic monitoring ● traffic control ● environmental monitoring ● driver information ● security monitoring ● lighting control	Data Collection/Monitoring Dynamic Message Signs Environmental Monitoring Lighting Management Ramp Metering Traffic Signals Vehicle Sensors Video Surveillance	**ASTM E2259** - 03a(2011) Standard Guide for Archiving and Retrieving ITS-Generated Data; **ATC 5201** (ITE ATC Controller) Advanced Transportation Controller (ATC); **ITE ATC API** Application Programming Interface (API) Standard for the Advanced Transportation Controller (ATC); **NTCIP 1103** Transportation Management Protocols (TMP); **NTCIP 1206** Object Definitions for Data Collection and Monitoring (DCM) Devices;

Interface Class	Standards Application Areas	Example Standards
		NTCIP 1209 Data Element Definitions for Transportation Sensor Systems (TSS); **NTCIP 2301** Simple Transportation Management Framework (STMF) Application Profile; **SAE J2266** Location Referencing Message Specification (LRMS);
Center-to-Vehicle/Traveler: Includes interfaces between a center and the devices used by drivers or travelers.	Mayday Transit Vehicle Communications Traveler Information	**APTA TCIP-S-001** 4.0.0 APTA Standard for Transit Communications Interface Profiles; **SAE J2266** Location Referencing Message Specification (LRMS); **SAE J2354** Message Set for Advanced Traveler Information System (ATIS); **SAE J2540** Messages for Handling Strings and Look-Up Tables in ATIS Standards; **SAE J2540/2** ITIS (International Traveler Information Systems) Phrase Lists;
Field-to-Field: Includes interfaces between field equipment.	Highway Rail Intersection (HRI)	**IEEE 1570-2002** Standard for the Interface Between the Rail Subsystem and the Highway Subsystem at a Highway Rail Intersection;
Field-to-Vehicle: Includes wireless communication interfaces between vehicles and field equipment.	Probe Surveillance Signal Priority Toll/Fee Collection	**ASTM E2213-03** Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems - 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications; **IEEE 1609.2-2016** Standard for Wireless Access in Vehicular Environments - Security Services for Applications and Management Messages; **IEEE 1609.3-2016** Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services; **IEEE 1609.4-2016** Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation; **NTCIP 1211** Object Definitions for Signal Control and Prioritization (SCP);

Interface Class	Standards Application Areas	Example Standards
		PTA TCIP-S-001 4.0.0 APTA Standard for Transit Communications Interface Profiles; **SAE J2735** Dedicated Short Range Communications (DSRC) Message Set Dictionary;

For each application area, the potential impacts of the future trends can be addressed in various existing standards. As an example, new data fields in F2V and V2V communications which arise from the introduction of CAVs, can be addressed in standards including SAE J2735. SAE J2735 specifies a message set, as well as its data frames and data elements, which can be used in applications that use vehicle-to-everything (V2X) communication systems [33]. SAE J2735 Messages include [33]–[36]:

- **BasicSafetyMessage**: conveys vehicle state information such as position, motion, and brake system status
- **CommonSafetyRequest**: designed to allow a per vehicle request for supporting data elements in V2V safety exchanges
- **EmergencyVehicleAlert:** designed to announce the presence of emergency vehicles in the area; however, has been largely replaced by a section in the BasicSafetyMessage
- **IntersectionCollisionAvoidance:** informs nearby users that a dangerous condition exists, or is likely to exist
- **MapData:** provides intersection and roadway lane geometry data
- **NMEAcorrections**: designed to wrap NMEA-183 formatted messages
- **PersonalSafetyMessage:** conveys messages similar to a BasicSafetyMessage for at-risk pedestrian users
- **ProbeDataManagement:** controls probe data that vehicles collect and report to roadside unit (RSU) devices using ProbeVehicleData messages
- **ProbeVehicleData:** reports details of prob data to RSU devices in vehicle-to-infrastructure exchanges
- **RoadSideAlert:** designed to support simple, quick, ad hoc messages for ATIS-like informational use
- **RTCMcorrections:** wraps RTMC correction messages
- **SignalPhaseAndTiming:** provides the current signal/phase timing data
- **SignalRequestMessage:** used to request services from intersection signal controllers
- **SignalStatusMessage:** used to reflect current state of the signal controls
- **TravelerInformation:** contains a variety of advanced traveler and traffic condition messages

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7. REQUIREMENTS FOR FUTURE C2C COMMUNICATIONS

The scope of this study contains C2C communications and the main objective is to provide a specification proposal for the modernization of the TMDD. In order to address the requirements of the future trends in transportation, different standards will need to be updated. The parts that TMDD might absorb are related to traffic management and incident management application areas. Specifically, the areas in which TMDD and C2C communications can be used are [37]:

- Providing traffic/travel information to other centers
- Providing status of and remote control of traffic controllers
- Helping coordinate operations within C2C network
- Providing event information to other centers

7.1. PROVIDING TRAFFIC/TRAVEL INFORMATION TO OTHER CENTERS

C2C communication can be used by centers to transfer traffic and travel information between the centers. Future trends can impact this area by:

- **Affecting existing sources:** It is expected that higher data resolutions and quality will be available from the existing resources. Current SOAP-based services recommended by TMDD cannot handle the future growth in data sizes. Replacing SOAP-based services with RESTful and more advanced communication services is inevitable.
- **Introducing additional modes:** Trends in micromobility, ride-hailing services, and the introduction of new modes such as air taxi will require TMCs to collect their data and plan accordingly. Existing systems, which mainly focus on cars, will need to be revised.
- **Providing new third-party data**: Third party data including probe vehicle timestamps, macroscopic traffic data from navigation applications, shared mobility information, and hail-riding data will become increasingly available. Sharing third-party data can help centers to better estimate network state information and provide more accurate action plans; however, the legal issues regarding data privacy should be taken into consideration.
- **Introducing more IoT devices:** With the improvements in 5G network, additional IoT devices will be introduced along the transportation network. TMCs will see an increasing variety in the types of information available as well as significant increases in the volume of information available. Use of this information will be critical for improving decision making without making critical infrastructure dependent upon cellular networks.
- **Introducing CAVs:** It is expected that the penetration rate of CAVs provides an opportunity for TMCs to obtain real-time vehicle information. However, not all data generated by CAVs is useful for TMCs. CAVs V2V or V2X communications include many data elements (see SAE J2735 discussed in section 6) which are necessary for CAVs operations; but do not benefit TMCs. TMCs collect data to get a better estimate of the transportation system state to better manage the system. Information from CAVs communications that can be useful for TMCs can include:
    - **Microscopic traffic information:** including speed, position, and acceleration which can be used to estimate traffic conditions such as traffic flows, densities, and travel times
    - **Environment information:** from CAVs sensors such as weather, light, and road condition
    - **CAV-Infrastructure interactions:** including communications with signals and other control elements

It should be noted that collecting data from CAVs can be performed by a single centralized center. A single center, which can also be a third-party provider, can collect and process data and share the information with other centers.

7.2. PROVIDING STATUS OF AND REMOTE CONTROL OF TRAFFIC CONTROLLERS

TMCs may operate various controllers (e.g., traffic signals, lane access, etc.) to manage transportation systems. C2C communications can enable other centers to apply required controls. Future trends can affect remote controlling by:

- **Enhancing existing controllers:** More advanced controllers with additional capabilities are expected in the near future. TMCs may require real-time exchanges between centers.
- **More pricing and tolling controls:** More active traffic management strategies including tolling and pricing strategies will be implemented.
- **Vehicle-based control (CAVs)**: In the long-term, TMCs can be expected to apply vehicle-based traffic controls (such as longitudinal control of CAVs) to improve system performance. Current TMDD does not provide guidance on C2C communications for CAVs controls.

7.3. HELPING COORDINATE OPERATIONS WITHIN C2C NETWORK

Communications between different centers are crucial for coordinating operations within C2C networks. Future trends and the need for collaboration will require more regional level collaborations in which overlaps between several jurisdictions are expected. In a decentralized system, TMCs will need to collaborate with other centers in different jurisdictions, which can limit operations. However, a cooperative centralized system (regional or district level) can remove the technology barriers for multi-jurisdictional collaborations and potentially improve operations.

In addition, a center might send a request to another center to communicate with their resources. For instance, a TMC might ask another center to provide dynamic routing guidance or speed recommendations to vehicles within their network. TMDD needs to enable such communications between centers.

7.4. PROVIDING EVENT INFORMATION TO OTHER CENTERS

Centers share event information such as incidents, construction activities, public events, holidays, and seasonal events with other centers. With the improvements in data collection and event detection systems, it is expected that the frequency of event information exchanges will increase. Furthermore, more regional level event information will be shared as regional collaboration increases.

CAV data, such as incident detection systems, is expected to provide valuable information for TMCs. Once a TMC detects an incident using CAV data, it can implement models to estimate the incident size.

8. SUMMARY

Future trends in transportation systems will be shaped via the influencing factors (e.g., IoTs, CAVs, micromobility services) over various time periods. These trends will affect the main operations performed by full-scale TMCs including monitoring, controlling, and informing.

To effectively address future trends, TMCs need to be more cooperative, and be part of transportation solutions:

- **Paradigm shift in TMC operations:** TMCs will need to operate their systems to consider various modes of transportation, in contrast to the traditional approach which is primarily focused on automobile and freight transportation.
- **Regional level impacts:** TMCs will take into account regional impacts, in comparison to existing operations which are mainly concerned with single jurisdictional impacts.
- **Multi-jurisdictional operations:** TMCs will not operate as a sole autonomy; therefore, cooperative traffic management is expected.
- **Multi-modal operations:** Cooperation with various stakeholders and integration of various transportation modes such as public transit, micromobility services, and ride-hailing will allow TMCs to more effectively manage their assets.
- **Data augmentation:** Information handled by a TMC can assist and enhance fulfillment of another center's missions. Future applications of IoT devices and other data sources, will provide an opportunity for TMCs to cooperate and exchange information.
- **Third-party data:** Centers will likely have access to more third-party data such as navigational applications or factory-installed vehicle sensor data. Exchanging third-party information with other TMCs can help centers improve their plans.
- **Impact of CAVs:** Numerous organizations are collaborating on CAV technologies. TMCs will need to collaborate with other agencies and centers to use CAV data and apply effective vehicle-based controls.

Future trends of the influencing factors and the growing need for collaboration between centers will affect all interface classes of the National ITS architecture. For each application area, the potential impacts of the future trends can be addressed in various existing standards (e.g., SAE J2735). TMDD, as a standard for C2C communications, needs to address future trends related to traffic management and incident management application areas.

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