

Sharing and Using Connected Device Data to Improve Traveler Safety and Traffic Management—Review of Current Practice

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FOREWORD

New and emerging sources of data generated from travelers using mobile devices, vehicles, infrastructure, and other sources provide agencies with opportunities to change how they manage traffic and their transportation systems. These sources of data offer agencies an incentive to enhance or develop the capabilities of their transportation management systems to collect, compile, save, use, and share these data.

This report provides information and strategies that may assist agencies as they evaluate, plan, or explore efforts associated with electronic message sharing to improve the safety, mobility, and experience of travelers using mobile devices. This report may be of interest to representatives from State departments of transportation, local agencies, metropolitan planning organizations, regional authorities, toll authorities, and other groups that may benefit from sharing and using data from connected mobile devices to improve traveler safety and traffic management.

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Operations Research and Development

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16. Abstract The ability to exchange electronic messages with mobile devices in realtime has the potential to improve travel safety, mobility, and the experience for users of the surface transportation systems. Intelligent transportation system devices and traffic management systems using information derived from sharing electronic messages with travelers, vehicles, and other sources using mobile devices offer new options for agencies to consider how to improve how they manage traffic and share information with travelers. This report provides information and strategies that can assist agencies as they evaluate, plan, or develop efforts associated with the sharing of electronic messages with mobile devices. The report provides an overview of the components involved with sharing and using these electronic messages and the needs of travelers to process and use this information. This report may be of interest to representatives from State departments of transportation, local agencies, metropolitan planning organizations, regional authorities, toll authorities, and other groups that may benefit from sharing and using data from connected mobile devices to improve traveler safety and traffic management.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1,000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS AND ABBREVIATIONS

3G	third generation
3GPP	Third Generation Partnership Project
4G	fourth generation
5G	fifth generation
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
API	application programming interface
ATCMTD	Advanced Transportation and Congestion Management Technologies Deployment
ATIS	Advanced Traveler Information Systems
ATTRI	Accessible Transportation Technologies Research Initiative
BIM	basic information message
BSM	basic safety message
C-V2X	cellular vehicle-to-everything
CAM	Cooperative Awareness Message
CAV	connected and automated vehicle
CCTV	closed-circuit television
CDMA	code division multiple access
CMS	changeable message signs
CV	connected vehicle
D-RIDE	dynamic ridesharing
D2X	device-to-everything
DENM	decentralized environmental notification message
DSRC	dedicated short-range communications
ETA	estimated time of arrival
ETC	electronic toll collection
ETSI	European Telecommunications Standards Institute
GNSS	global navigation satellite system
GPS	Global Positioning System
GTFS	general transit feed specification
HOV	high-occupancy vehicle
ID	identification
IDTO	integrated dynamic transit operations
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
IT	information technology
ITS	intelligent transportation systems
LTE	long-term evolution
MAC	media access control
MAP	MapData
MMP	multimodal trip planner
MoD	mobility on demand
MUTCD	Manual on Uniform Traffic Control Devices
NFC	near-field communications
NTCIP	National Transportation Communications for ITS Protocol

OBU	onboard units
PDM	probe data management
PMM	personal mobility message
PMM-ARRIVE	personal mobility message arrival
PMM-CANCEL	personal mobility message cancel
PMM-RSP	personal mobility message response
PSM	personal safety message
PVD	probe vehicle data
RFID	radio frequency identification
RTCM	Radio Technical Commission for Maritime Services
SAE	SAE International
SPaT	signal phase and timing
SPM	signal performance metrics
SRM	signal request message
SSM	signal status message
T-CONNECT	connection protection
T-DISP	dynamic transit operations
TIM	traveler information message
TMC	transportation management center
TMS	transportation management system
TSMO	Transportation Systems Management and Operations
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VRU	vulnerable road user
WAVE	wireless access in vehicular environments
Wi-Fi®	wireless fidelity

CHAPTER 1. INTRODUCTION

PURPOSE

The purpose of this report is to capture information on the use of mobile devices in managing traffic in the surface transportation space. The ability to exchange electronic messages with mobile devices in realtime has the potential to improve travel safety, mobility, and the experience for travelers using the device. Intelligent transportation system (ITS) devices and traffic management systems using information derived from sharing electronic messages with travelers, vehicles, and other sources using mobile devices offer new options for agencies to consider how to improve how they manage traffic and share information with these travelers.

A mobile device is a computer that can connect to the Internet, is small enough for a traveler to hold and operate in the hand, has the same capabilities and features of a smartphone, but has the added ability to communicate via other wireless communications protocols. Mobile devices expand connectivity options by incorporating direct methods of communication into today's standard connected smartphones, tablets, and wearable devices, expanding the utility and commensurate benefits of the devices and the connected vehicle (CV) environment. These devices can be carried by a traveler on foot, on a bicycle, by a passenger on a transit vehicle (or ride-source or rideshare vehicle), or by a driver of a personal vehicle. Further, mobile devices can enable electronic message sharing, where data elements may be extracted from these messages, allowing the data elements to be used by software applications installed on these devices to convey various types of information to travelers carrying the device.

This report provides insight and information into the safety and decisionmaking needs of travelers for different types of trips and methods of providing data to travelers using mobile devices connected to the Internet. Current practices are documented and, as applicable, how mobile devices can be leveraged to improve travelers' decisionmaking. The deficiencies and gaps between user needs and the capabilities of existing mobile device technology are also identified, including the need for additional data elements currently unavailable in existing standardized message sets.

Specific goals of this report are as follows:

- Identify examples of where a mobile device can benefit travelers using one or more modes of transportation.
- Provide an overview of current methods for delivering information to travelers.
- Describe the capabilities of currently available mobile devices and supporting communications technologies, software applications, and standards to support information sharing with these devices.
- Undertake activities that enable electronic message sharing with mobile devices.

Intended Audience

The intended audience for this report is primarily transportation operations professionals involved in managing, participating in, and supporting efforts to collect or share messages, compile data, and use this information in operating transportation management systems (TMS), transit applications, or transit management systems. Although the range of users may be large, the primary audience is anticipated to be the following types of audience groups:

- Transportation agency information technology (IT) staff—IT staff involved with supporting the data management and security issues surrounding the data exchange.
- Transportation agency project managers—Research and project managers charged with delivering a framework for the data exchange.
- TMS leadership—Managers of the TMS who operate and oversee the data exchange.

Each of these audience groups have different roles, responsibilities, and concerns, and each agency's project or use case differs.

Context of Sharing Information with Mobile Devices

Detailed descriptions of both mobile devices and CVs are described later in this report, but for purposes of this introduction, a CV environment consists of the technologies and messages that allow direct device-to-device wireless communications—most commonly vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). Mobile devices expand connectivity options by incorporating direct methods of communication into today's standard connected smartphones, tablets, and wearable devices, expanding the utility and commensurate benefits of both the devices and CV environment.

The use of mobile devices in the CV environment continues to emerge as many traveler's needs can be addressed using mobile device applications. In addition to the many smartphone applications that currently are available to improve traveler mobility, many more valuable ways exist that mobile devices can be used to foster safety and mobility. Of particular interest is integrating CV communications technology with smartphones or other devices so that pedestrians and other vulnerable road users (VRU) can receive safety-critical warnings and mobility information from vehicles and ITS infrastructure using low-latency communications.

When mobile device research was initiated, the primary technology used to implement CV was based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11p, known as dedicated short-range communications (DSRC).⁽¹⁾ Recently, however, cellular vehicle-to-everything (C-V2X)—based on the Third Generation Partnership Project (3GPP) (Release 14)—has become a viable option for future device integration, and other emerging technologies will continue to emerge.⁽²⁾

Travelers' Needs

The information needs of each type of traveler are inherently different. In support of the diverse traveler information needs, mobile devices can provide travelers with directions for walking,

biking, driving, or using transit to get to their chosen destination safely and efficiently. Mobile devices can inform travelers when the next bus will arrive at a stop, where there are traffic delays, or what time of day is best to travel. In short, mobile devices have become entwined in our daily routines, specifically in our daily transportation routines.

Report Organization

This report includes four main chapters organized as follows:

- **Chapter 1. Introduction.** This chapter presents the purpose of the report, intended audience, foundational information on mobile devices, and the overall organization of the report.
- **Chapter 2. Use Cases and User Needs for Sharing Electronic Messages with Mobile Devices.** This chapter presents examples of how mobile devices supporting decisions made for different types of trips can provide benefits to travelers of various modes of transportation. Descriptions and the information needs of different travelers are presented, as well as methods of delivering information and how travelers may use that information.
- **Chapter 3. Mobile Device Technologies.** This chapter provides a detailed definition of a mobile device, which is typically a smartphone commonly used by travelers. Types of situations where information may be shared and used by software applications installed on mobile devices are discussed, as well as messaging conventions and wireless communications technologies available to different types of mobile devices.
- **Chapter 4. Enabling Technologies, Prototypes, and Pilot Deployments.** This chapter provides information about development efforts to enable communications with mobile devices, mobile device prototypes, and deployments.
- **Chapter 5. Impacts During Development.** This chapter discusses issues to consider when deploying equipment to enable the generation and sharing of electronic messages with mobile devices. Information is also provided on limitations with the sharing and use of electronic messages to support travelers using these devices.

CHAPTER 2. USE CASES AND USER NEEDS FOR SHARING ELECTRONIC MESSAGES WITH MOBILE DEVICES

The basic premise of mobile devices is that electronic messages are shared and the software on the devices converts these messages to data elements. These data elements can then be used by other software applications installed on the device to convey information to travelers using the device to support decisions they make for their trips. This chapter identifies possible uses and corollary user needs that may be satisfied by sharing information with a traveler via a mobile device. This chapter considers examples in which travelers use data received via a connected mobile device to make informed decisions and perform transactions that support the needs of their trip.

Data can originate from a variety of sources, including but not limited to roadside ITS devices, a traffic management center, trip planning services, or a ride-sourcing/ridesharing service. This chapter discusses the type of information travelers may need to complete trips, the various data types used by travelers to make decisions both before and while traveling, and the associated challenges they may encounter. This chapter also provides information on issues to consider with disseminating this information to travelers, and methods for capturing decisions made by travelers during a trip.

Examples are provided of the range of information users of mobile devices may use to support their decisionmaking while completing different types of trips. Travelers' potential needs for information for these trips are by no means exhaustive. The examples provide a representation of how the information needs of travelers using mobile devices may be satisfied and provide a foundation from which agencies can begin to elicit more specific information to meet local needs and use cases.

Sharing electronic messages with users of connected mobile devices does not come without specific challenges, which also are identified in this chapter. Finally, this chapter provides agencies with a range of issues to consider when delivering information to travelers using mobile devices and how agencies can use information from these devices to develop and deploy systems that communicate with mobile devices. This chapter includes the following:

- An outline of use cases where mobile devices can be used to address traveler safety and mobility needs.
- Discussion of issues and challenges to consider (specific to mobile devices) when developing user needs and use cases for specific implementation.
- Considerations on how information is delivered to travelers specifically related to the location and time information needed by the traveler.
- Considerations on how local agencies can leverage information obtained from travelers to ascertain decisions made by travelers and how this information can be used for management activities.

Use Cases and Traveler Information Needs for Decisionmaking

A review of current practices provides several use cases for the range of information for different types of trips that may be enhanced by mobile devices providing trip specific information to travelers. Mobile devices are expected to be able to address these needs because of their utility and versatility of communications. Mobile devices also enable travelers to share information with existing systems that can help to enhance the safety and mobility of their specific types of trips. While individually, many of these use cases provide some level of functionality, many other user needs can be met by combining the functionalities of various applications, using different communications media to support existing applications, and/or using new messages (or modifications to existing message sets) that currently are not standardized.

The Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) is one resource that can be leveraged to begin identifying mobile device-based use cases.⁽³⁾ The ARC-IT is based on a set of applications that have been defined by various CV programs. Certain applications were identified for inclusion in the use cases presented in this section, including personal information devices, which are mobile device applications that provide safety, mobility, or other convenience benefits to a traveler.

The primary focus of the high-level use cases is to meet the needs of mobile device users. As a result, the use cases are framed from a mobile device user perspective. In particular, the use cases capture how travelers will use data that can be received by a mobile device to affect their actions and to make decisions throughout a trip.

The use cases demonstrate the following:

- How mobile device users may make decisions during typical types of trips from beginning to end.
- How the information travelers need can be packaged and sent as electronic messages by traffic management systems and others.
- How to use temporal and spatial data to determine what messages are delivered to mobile device users and when.
- How this information can be used and sent to meet the information needs of mobile device users before these decisions are made during trips.

A common starting point for grouping use cases is by a mode of travel. Typically, modes of travel include walking, bicycling, using transit and sharing mobility services, and using personal vehicles. Travelers using the same mode of transportation are expected to have similar needs that are captured in each use case and interact with mobile devices in the same fashion throughout the course of their trip.

A traveler using a particular mode may exhibit one or more needs associated with that mode over a given leg of a trip. Travelers' mode of transportation may change throughout any given trip. When mode changes occur, the traveler's needs (and use cases embodying those needs) are expected to change as they can interact with the transportation environment changes. While not

specifically discussed in this report, there may be unique considerations for multimodal travelers. Furthermore, travelers with disabilities may have needs that are crosscutting in nature, independent of the use case or mode of transportation, including scheduling trips, reaching the vehicle, knowing that the vehicle is the desired vehicle, boarding, paying the fare, riding and exiting the vehicle safely, and knowing when to request a stop to deboard.

Pedestrian Use Cases

Place Pedestrian Phase Call

When crossing the roadway at signalized intersections, pedestrians typically must use push buttons to activate the pedestrian phase of the signal. Mobile device applications have been designed that allow travelers to activate the pedestrian phase, but many of these applications rely on the pedestrian manually inputting the leg of the intersection that they intend to cross. The applications also do not provide information about the signal state to the traveler and do not adjust operations based on the pedestrian's walking speed.

It would be advantageous to enable pedestrian phase activation through a mobile device to support the needs of pedestrians with disabilities. A pedestrian could access a trip planner on a mobile device and define a trip based on their needs. As the pedestrian progresses on the trip, pedestrian signals would be activated as the pedestrian approaches intersections along their route. The mobile device would know which crosswalk to request activation based on the route initially selected by the pedestrian (the trip planning service may have to be accessed to find a new route if the pedestrian deviates from route).

Furthermore, a pedestrian with visual and/or audio disabilities may not be able to readily observe (through infrastructure-based audio or visual cues) the current walk signal status. An intersection also may not be equipped with a pedestrian signal head or audio equipment. The mobile device can provide crosswalk signal state information specific to the pedestrian's route via screen, speaker, or haptic feedback. Crosswalk signal state information would be helpful to the pedestrian to know when to start walking in the crosswalk, when to wait, or how much time is left to cross.

In summary, this use case allows a pedestrian to request a pedestrian phase at an intersection via the mobile device, eliminating the need to locate and use a pushbutton located at the intersection. The pedestrian also may need wayfinding information to know which crosswalk to use, where the crosswalk is, and when to start crossing. This use case is also based off the pedestrian mobility application in the ARC-IT.

User needs associated with the place pedestrian phase call use case are as follows:

- A pedestrian needs to know when a signalized intersection crosswalk is being approached.
- A pedestrian needs to activate a pedestrian crosswalk phase.
- A pedestrian with visual and/or audio disabilities needs wayfinding and navigation solutions for a complete trip between an origin and destination in the public right-of-way

(Note that traveler needs for wayfinding and navigation information prior to starting a trip must be updated throughout the trip to account for changing conditions—e.g., a pedestrian signal).

Pedestrian in Crosswalk Intersection Safety

The presence of vehicles at intersections introduces some level of risks to pedestrians, especially in locations where the pedestrian and vehicle share the same space, such as a crosswalk. Vehicles are often permitted to drive across a crosswalk while a walk phase or interval is provided at a traffic signal for a pedestrian to cross the same crosswalk. The pedestrian's safety depends on the driver's observation of the pedestrian.

However, there are instances when a driver may not readily observe the pedestrian, which places the pedestrian in imminent danger. Improving pedestrian safety can be accomplished if the driver is provided notification of the presence of a pedestrian in the vehicle's potential path, especially if the pedestrian is in a signalized crosswalk. A mobile device can send real-time data on the location of the pedestrian in the roadway environment so that other CVs can receive the information to provide notification to the driver.

Another aspect of creating safer environments for pedestrians using a crosswalk is to provide adequate time for the pedestrian to complete crossing the street. Pedestrian clearance intervals are often based on a design minimum walking speed; however, certain pedestrians may walk at a lower speed and not clear the roadway during the pedestrian interval. Drivers that may be crossing the crosswalk during the subsequent phase need to be aware of the pedestrian's presence to preserve their safety.

However, the mobile device enables the pedestrian's walking speed to be communicated to the intersection so that the intersection could adjust the clearance interval on a one-time basis to accommodate the pedestrian. Alternatively, the mobile device could provide the pedestrian's location to the intersection so that the intersection could extend the pedestrian clearance phase to prevent the subsequent phase from activating until the pedestrian has cleared the intersection.

In summary, equipped vehicles receive and process messages from mobile devices to provide advisories and warnings to the driver. Similarly, the mobile device receives and processes messages from equipped vehicles to alert the pedestrian when a vehicle is approaching and there may be a risk of collision unless immediate action is taken. This use case is based on the Pedestrian in Signalized Crosswalk Warning application in the ARC-IT and focuses on direct mobile device-to-vehicle connectivity to accomplish the communication required with intersection roadside equipment and vehicles.⁽³⁾

User needs associated with the pedestrian in crosswalk intersection safety use case are as follows:

- A pedestrian needs additional time to complete crossing a crosswalk if still in the crosswalk and the pedestrian phase clearance time will imminently expire.
- A pedestrian needs to be in a crosswalk to be known to approaching drivers.

Bicyclist Use Cases

Place Bicycle Phase Call

This use case is a natural extension of the place pedestrian phase call use case. However, rather than addressing the needs of pedestrians at crosswalks, this case addresses the needs of bicyclists in the roadway as they approach intersections. Bicyclists may have issues actuating sensors (typically embedded in the roadway or other mounted sensing equipment) at intersections. This issue may result in the bicyclist waiting for an extended period at the intersection or proceeding through the intersection when not permitted to do so.

Similarly, at intersections where a multipurpose trail crosses a roadway, a bicyclist may be required to push a button to activate a warning beacon to alert traffic on the roadway that a bicyclist is about to cross. A mobile device could communicate directly with the traffic signal or warning device to place a call for a phase on the controller, or to activate warning lights to simplify the interface between the bicyclist and the traffic control device at an intersection.

In summary, this use case allows a bicyclist to request a phase at an intersection via the mobile device, eliminating issues associated with bicycle detection and/or the need to locate and use a pushbutton located at the intersection to activate a warning device.

User needs associated with the place bicycle phase call use case are as follows:

- A bicyclist needs to activate a phase call at a signalized intersection.
- A bicyclist needs his or her presence in the roadway to be known to approaching drivers.

Driving Use Cases

En Route Adjustment for Driving Trip

Smartphones provide a means of trip planning and enroute adjustment to assist drivers in wayfinding, avoiding traffic, and finding the fastest route. This use case considers use of these popular functionalities but considers an open mobile device-based solution. Traffic conditions continuously change, and congestion caused by incidents or other events impacting the normal operation of the roadway may result in additional delays to a planned vehicular trip. Under these circumstances, an alternate route may be available that provides better travel time than the original route. Drivers would need real-time comparative data to identify the alternate route and make the decision to reroute.

Mobile devices could provide access to a multimodal trip planner (MMTP) service that considers current roadway conditions and user location to develop route options while en route. The MMTP service would obtain information from the mobile device about current location, ultimate destination, and any vehicle characteristics or preferences that could limit (or provide) access to certain roadway facilities. The MMTP also could provide alternative transportation options (park-and-ride to fixed-route transit or carpool) to give the traveler a choice on how to proceed to the final destination.

The driver would then be provided with the travel time for the most efficient driving route and for the transit route and may decide to change to transit. Continuously receiving updates from this service throughout a trip would essentially support flexible and tailored operational strategies and control plans, based on specific origins, destinations, and needs of each traveler. Periodic updates could also be applied to transit trips to provide alternative options to transit riders in the case that transit vehicles get ahead of or behind schedule.

The user need associated with the en route adjustment for driving trip use case is as follows: a driver needs access to alternative route information to potentially minimize travel time when conditions along the current planned route change.

Driving Wayfinding—Tailored Roadway Signage

One of the biggest drawbacks of the *Manual on Uniform Traffic Control Devices* (MUTCD) (and the use of static signs in general) is the presentation of information does not account for the real-time dynamics of the vehicle when the traveler encounters a sign.⁽⁴⁾ The placement of static signs is dependent on the expected amount of time it takes a driver to travel a given distance given a designated speed limit. However, if the vehicle is moving at a speed that is greater than the speed limit, then the driver will have less time to react to that sign than intended. Alternatively, at slower speeds, there may be too much time, resulting in expectancy issues. Ideally, information on the sign is displayed to the driver at a time and location that corresponds to their current speed.

Another drawback of static signage is that drivers may have to read and interpret information that may not be applicable to them. For example, a driver may pass by a school zone sign at a time when the school zone is not active. In this case, the need for the driver to read the information on the school zone sign is unnecessary. Another example is the use of guide signs on freeways. Drivers do not need guide signs that apply to routes that they do not intend to take. Ideally, only guide signs applicable to the driver's route are provided to the driver as they proceed on their trip. Regulatory and warning signs should be used conservatively because these signs, if used to excess, tend to lose their effectiveness. However, if these signs are only displayed to the driver, when necessary, then increased compliance may result.

Changeable message signs (CMS) also are important to consider, as they may communicate customized information to drivers. One of the greatest differences between a mobile device and CMS is that CMS are only able to provide messages to drivers at specific locations on the roadway where it is deployed. A mobile device can help resolve this issue because the driver can receive verbal messages via their mobile device when conditions warrant. The mobile device also allows for longer messages to be conveyed verbally to the driver. However, the downside to this method is that longer messages can create a distraction from other vehicle operation tasks.

This use case provides real-time and adaptive signage information to a driver traditionally placed according to the MUTCD. Traveler information communications is detailed in the National ITS Reference Architecture in the In-Vehicle Signage application.⁽⁵⁾

In summary, a mobile device connected to the Internet can provide real-time information (e.g., of traffic incidents, temporary weather impacts such as flooding, detours, or congestion) to the

driver based on prevailing conditions in the immediate area. Information is provided at a time and location far enough in advance for the driver to effectively receive, process, and act on the information.

User needs associated with the driving wayfinding—tailored roadway signage use case are as follows:

- A driver needs spatially and temporally relevant roadway signage information.
- A driver needs traveler information that is customized to a predetermined route (i.e., does not need information that does not pertain to the situation).

Provision of Toll Facility Information

A large amount of information must be displayed to drivers to navigate toll lanes. If the driver's route is known in advance, a mobile device could be used to tailor the information that is presented to the driver so that only the travel time and tolling information relevant to that trip is presented to the driver. Furthermore, a mobile device would allow all information to be arranged and displayed simultaneously to reduce the burden on the driver to remember information placed periodically along the freeway.

In cases where the drivers' route is not known to the mobile device, the mobile device could display the toll for several downstream segments, as well as the toll amount that the driver has accumulated thus far on their toll lane trip. This application could logically be combined with the toll payment application (discussed in the section Pay for Tolls/Parking) to facilitate the toll payment after the trip that uses a toll lane is taken.

If the driver decides to use the managed lane, conditions in the general-purpose lanes may change during the trip that result in the driver reevaluating his or her decision to use the managed lane and may want to leave the managed lane at the next egress location. If travel time information for the downstream segment is not available, then the driver is not able to make an informed decision. Conversely, if the driver decides against use of the managed lane at first, but downstream conditions change (e.g., traffic builds due to high demand or an incident), the driver may want to enter the managed lane at the next access location. When traveling on a freeway with a managed lane, this information could be displayed to the driver so the driver has the ability to periodically evaluate the decision to use or not use the managed lane facility.

This use case provides signage information to a driver that is traditionally placed according to the MUTCD but focuses specifically on providing toll information that is specific to a driver's trip. It is a specialized extension of the in-vehicle signage application.

In summary, the mobile device delivers tailored toll information so that the driver clearly understands the tolling information specific to the planned route. Mobile devices allow tolling information to be arranged and displayed in various dynamic modes to reduce the burden on the driver to remember information that is placed only periodically along the freeway.

User needs associated with the provision of toll facility information use case are as follows:

- A driver needs tolling information for toll facilities that could be used to get to the destination when using a personal vehicle.
- A driver needs a method of knowing travel time savings by using a toll facility.

Pay for Tolls/Parking

This use case is derived from the electronic toll collection (ETC) application in the National ITS Architecture.⁽⁶⁾ In summary, the mobile device uses a common interface for parking payments and integrates with the various fare collection systems. This interface would enhance traveler convenience when using multiple systems and allow fare transfers if multiple trips are taken within a given timeframe.

User needs associated with the pay for tolls/parking use case are as follows:

- A driver needs a method by which to pay for tolls.
- A driver needs a method by which to pay for parking.

Transit and Shared Mobility Use Cases

Adjust Transit Operations and Connection Protection

Travelers on a multileg transit trip depend on reliable and efficient connections to arrive at their destination in a timely manner. If the traveler misses the connection, waiting for the next transit vehicle to service the stop may drastically increase travel time. Connection protection is the coordination between intersecting transit lines to protect the rider's transfer. However, a transit agency may require certain conditions to be met to allow connection protection (e.g., a threshold on the number of travelers needing to make the transfer or a requirement for the connecting route to be low frequency in nature).

MMTPs provide a valuable service, combining and processing multiple data sources to provide complex multimodal routes that cater to a traveler's individual preferences. However, these services do not enable functionality, such as connection protection for transit.

A mobile device could be used to facilitate connection protection by communicating a traveler's anticipated transfer location and arrival time to the transit agency en route. This process could apply to connections within a single transit agency or across multiple agencies. While the notification could be completed through user input, it would be beneficial if the actions were automatic and generated from a planned route to eliminate distractions if the user is multimodal.

Connection protection could be provided for travelers using a mobile device-based MMTP when using transit. At the beginning of a trip, the traveler uses the mobile device to select a transit itinerary that contains two or more contiguous transit legs. The mobile device reports this trip (and its connections) to the appropriate transit agencies, and periodically provides the traveler's location to the transit agency so that the transit agency can confirm that the traveler is adhering to the selected itinerary. The transit agency can assess its transit service to determine if the

traveler will be able to make the transfer. If the arriving vehicle arrives later than intended, or the connecting vehicle arrives earlier than intended, the connecting vehicle can be held to accommodate the traveler's transfer need.

Another function that can be added to an MMTP to allow travelers to make better decision while traveling is transit trip updates. A mobile device could periodically query the MMTP to determine if changing service conditions warrant taking a different route than the originally planned route. A transit route could be updated as the traveler is making the trip. This function could be useful if connection protection cannot be accommodated. In addition to proposing other transit options, this function could suggest other travel modes, such as biking, walking, car sharing, or ride sourcing, to provide the traveler with as many options as possible.

This use case provides a method of ensuring a traveler can make a planned connection between two transit routes. This method is detailed in the National ITS Reference Architecture in the transit connection protection application and provides alternative route information if connection protection cannot be accommodated.

In summary, the mobile device facilitates connection protection by communicating a traveler's anticipated transfer location and arrival time to the transit agency while en route. The transit agency on the connecting link can hold a bus for a certain amount of time so that the traveler can make the connection.

User needs associated with the adjust transit operations (connection protection) use case are as follows:

- A transit user needs to notify a transit manager (or transit management system) when they intend to make a scheduled connection.
- A transit user with disabilities needs wayfinding and navigation solutions for a complete trip between an origin and destination in the public right-of-way.

Transit Stop Notification

A traveler taking transit needs to be able let an approaching transit vehicle know he or she intends to board the vehicle, and when the transit vehicle is approaching so they can prepare to board. Transit vehicle operators typically rely on the visual presence of the traveler on the roadside to know when to stop to service the passenger. However, certain conditions may make this more difficult, such as during nighttime hours when it may be difficult to see a waiting passenger. A waiting passenger unfamiliar with the transit services may not know which vehicle to board (when a stop is served by multiple vehicles) or may not be able to perceive when the transit vehicle is approaching.

MMTPs provide a valuable service, combining and processing multiple data sources to provide complex multimodal routes that cater to a traveler's individual preferences. However, these services do not enable functionality, such as automated communication with the operator of the transit vehicle to notify when the traveler intends to board and alight the vehicle.

This use case is derived from the transit stop request application in the National ITS Architecture.⁽⁷⁾ The use case provides transit information (arrivals and wayfinding) to a traveler specific to a trip the traveler is taking via a mobile device. Accessible Transportation Technologies Research Initiative (ATTRI)-specific considerations for this use case are discussed in the section Travelers with Disabilities. The provision of corollary information from travelers to transit vehicle operators is used to enhance the communication of passenger intention to board and alight.

In summary, the mobile device, with knowledge of the traveler's route, communicates with the transit vehicle operator to ensure that the transit vehicle stops when needed to pick up the traveler and ensures the traveler boards the correct route.

Similarly, while on the bus, the mobile device, with knowledge of the traveler's route, can communicate with the transit vehicle to ensure that the traveler get off the transit vehicle at the correct location.

User needs associated with the transit stop notification use case are as follows:

- A transit user needs to be able to view the amount of time until the next arrival or locations of nearby transit vehicles occur.
- A transit user needs to know information about approaching transit vehicles when waiting at a transit stop.
- A transit user needs to notify the transit vehicle operator when they intend to enter or exit from the transit vehicle.
- A transit user needs wayfinding and navigation solutions for a complete trip between an origin and destination in the public right-of-way.

Reserving Use of a Shared Mobility Device

While not specifically included in the ITS Architecture, this use case is pertinent in today's transportation environment given the rapid expansion of shared use bicycles, scooters, and other mobility devices.

In summary, the mobile device uses a common interface for shared mobility services to integrate with any existing reservation systems. This integration could allow users the option to locate shared mobility devices from competing services. The mobile device also uses a common interface for (shared mobility) payments and integrates with the various fare collection systems. This integration would not only add convenience for a traveler when using multiple systems but also could allow fare transfers if multiple trips are taken within a given timeframe.

One high-level user need associated with the reserving use of a shared mobility device use case is travelers who need to reserve a shared mobility device when they have planned a trip that uses a shared mobility device.

Fare Payment

Integrating fare payment capability into a MMTP would allow travelers to use a mobile device to pay for the fare for the trip they select. Today's system would require the traveler to make individual fare payments for each system used, which can be cumbersome, time consuming, and confusing because different transit systems in the same region typically use different payment systems. The institutional arrangements that must be made to allow common fare payment could be leveraged to provide payment services through a MMTP.

Integrating fare payment into the MMTP would provide a single point of payment that is consistent for the traveler. When selecting an itinerary, the traveler is presented with a fare for each transit service used on the trip. Fares are paid to each respective agency as the traveler activates each trip when boarding.

This use case is derived from the transit fare collection management application in the National ITS Architecture.⁽⁸⁾ Mobile devices use a common interface for payments to integrate with various fare collection systems. This interface would add convenience for a traveler using multiple systems but could allow fare transfers if multiple trips are taken within a given timeframe.

User needs associated with the fare payment use case are as follows:

- A transit user needs to know the fare to take a trip using transit (or other shared mobility device).
- A transit user needs a method by which to pay for a trip taken using transit (or other share mobility device).

Travelers with Disabilities

The ATTRI program studied applications that improve mobility options for all travelers, particularly those with disabilities. These applications are crosscutting in nature and can often be integrated with existing applications to enhance the user experience. In 2016, the ATTRI program undertook research to understand the needs and barriers to mobility for travelers with disabilities that can be solved by leveraging technology in these five areas: wayfinding and navigation solutions, assistive technologies, automation and robotics, data integration, and enhanced human services transportation.⁽⁹⁾ Research indicates that with the notable advancement in mobile and portable computing power and the continued rise of continuously connected mobile devices, many of the technology solutions that were identified as solutions for gaps in information are very realistic for implementation within the next 3 to 5 yr.

A traveler with a visual disability may have issues knowing where they are while they are traveling, due to a lack of signs and waypoints that are readily accessible for persons with a visual disability. Technology-based solutions to provide real-time assistance to travelers with disabilities include the use of a virtual electronic guide dog, wearable devices to provide course corrections, and even semiautonomous technologies that detect when a traveler has departed from their expected path and automatically begin to provide real-time guidance assistance through an "on-demand virtual concierge service," "mobile application," or other method.

Technologies involving “text-to-speech” or “speech-to-text,” mobile wayfinding and navigation applications, and enhanced “assistance” technologies, such as “on-demand assistance” or virtual assistants, are frequently identified as potential solutions. Technologies that would reduce the level of information needed by travelers with disabilities, such as autonomous vehicles with preprogrammed door-to-door service, also are frequently cited.

Disabled travelers also need additional travel options. Systems of information integrated into a single database across multiple agencies that can be accessed by a single piece of technology unique to the traveler would enable personalization of services and support individual travel needs. For example, if payment and information systems were integrated with fixed-route transit services across both public and private providers, a traveler could be informed of alternative travel routes that are suitable for their mobility needs. These options could then be provided automatically based on their current location and transaction with the payment system. The traveler’s individual mobility needs also could be conveyed.

Wayfinding and navigation show significant potential to improve mobility. Information prior to and during a trip is consistently cited as the greatest need, and wayfinding and navigation technologies can help address this need. For example, electronic orientation aids use radio frequency identification (RFID) tags and mobile devices to determine a person’s location more precisely, which is used to assist vision-impaired individuals in navigating a route to a destination.

The strength of the application is its ability to annotate the route a user wants to take and invite trusted sources (individuals or organizations) to enhance urban navigation decisions by blind or vision-impaired travelers. Table 1 provides a summary of the traveler’s and mobile device information needs for the use case presented.

Table 1. Needs based on ATTRI research findings.

Need Type	Need Description
Traveler’s needs	(High-level) wayfinding and navigation solutions, text-to-speech or speech-to-text, course correction, travel options, trip planning information.
Mobile device information needs	Step-by-step directions (to be output to the traveler as he or she progresses on a trip), data that can be output in visual or audio format to the traveler, RFID tag information.

Implementation Considerations

The use cases and user needs presented in the section Use Cases and Traveler Information Needs for Decisionmaking provides a representation of the use cases by which mobile devices can provide benefits to travelers of various modes. It is expected that when developing a mobile device-based system for a specific local deployment, there will be specific local conditions and local stakeholder needs that will need to be considered. This section identifies some of the issues and challenges associated with the derivation of user needs and the development of use cases. As user needs and use cases are developed for specific implementations, it is important to consider how to meet or supplement the information provided to travelers (based on current and evolving conditions) and the decisions that travelers need to make while completing a trip. The following

list summarizes a range of specific issues that should be considered for sharing and facilitating the use of electronic messages by mobile devices:

- Developing effective methods of determining travelers' needs for information and decisionmaking.
- Establishing when and where that information needs to be provided to traveler for them to make the most effective use of it.
- Adhering to communications and messaging standards as they potentially evolve throughout the development process. A brief discussion of issues to consider regarding messaging conventions is provided in the section Issues to Consider.
- Providing the availability of hardware and software on mobile devices to enable the designed system (e.g., C-V2X or DSRC).
- Establishing the availability of existing systems (e.g., transit management systems, traffic management systems, shared use device management systems, and payment systems) that could provide data to mobile devices.
- Providing the availability of application programming interfaces (API) on external systems that the mobile device will interact with where external systems exist.
- Establishing a communications network for applications that require constant or frequent connectivity and better coverage.
- Considering equity issues related to the accessibility of paid mobile Internet networks.

Delivering Information to Support Traveler Decisionmaking

As the quantity of emerging data sources available to transportation operations managers continues to grow, an increasing number of traveler needs can be met. This section discusses approaches for delivering information to travelers as well as current practices and research on the delivery of information to drivers, including the MUTCD, managed lane information delivery, CMS message delivery, and positive guidance methodology for providing information to users of traffic control devices within the public right-of-way. The delivery of transit information to travelers also is discussed along with the concept of positive guidance, which provides a more holistic view of strategically providing information to a traveler.

The methods discussed in this section, regardless of if they are specific to driving, transit, or otherwise, are transferrable to the delivery of electronic messages to travelers in the transportation environment in situations where timely delivery of information is essential and provides a benefit. In addition to providing information about each method, each subsection concludes with an explanation of how the method at hand is transferrable to provide efficient and timely delivery of information to travelers via a mobile device-based application.

Sources are not specific to the dissemination of information through mobile devices but are expected to be transferrable. Methods for displaying static and dynamic signage in the current

transportation environment will be studied and considerations will be made to determine how these concepts can be transferred to mobile devices.

Methods of Delivering Information to Travelers

The primary methods of delivering data to travelers includes signage, smartphones, and mobile devices (CV-enabled smartphone). The placement and use of static signage and dynamic signage along roadways is typically governed by the MUTCD. Many States tailor the MUTCD to a State-specific version of the MUTCD, while some States use the Federal version.⁽¹⁰⁾ At transit stations, electronic signage (like CMS used on a roadway) are used to display real-time arrival information for one or more transit lines that service a stop.

A more recent development in transportation technologies allows for dissemination of information to travelers through smartphones. Smartphones are used by drivers (within the scope of the law of using a smartphone in a vehicle), passengers, and pedestrians to accomplish any number of mobility-related tasks. This use could be accessing a walking, cycling, driving, transit trip planning application, a ride-sourcing or ridesharing service, or 511 system (discussed in detail in the section Wireless Communications Technologies and Methods).

Given that smartphone functionality is most useful while a traveler is en route, access to a mobile form of Internet is highly desired. Communication of information to and from smartphones requires an Internet connection (short-range wireless communications or cellular).¹ However, use of a cellular communication network requires a paid subscription to a data plan from a data provider. This requirement is often viewed as an equity issue for people who cannot afford to subscribe to such data plans. To help overcome this issue, many transit agencies provide free access to Wi-Fi[®] (at transit stations or stops and in vehicles) so that travelers can access trip planning services while en route. However, this access limits the number of locations where a traveler can connect to the range of the Wi-Fi network established by the transit (or other) agency.

Recent research has indicated that there are use cases that can be satisfied by integrating CV communications technology with the functionality of today's smartphones. As noted earlier, this combination of technologies makes up what we are calling a mobile device. In addition to the features that are provided on today's smartphones, the mobile device's CV radio allows for the communication of safety-critical information at low latency to support mobile device-based traveler safety applications.

A CV radio located on the roadside (aka roadside unit) can be connected to roadside ITS devices and to a transportation management center (TMC) to communicate information from these devices to mobile device users to further support traveler safety and mobility needs. Furthermore, the use of CV provides an alternative pathway for allowing travelers to access travel services—like how the smartphone uses traditional Wi-Fi and/or cellular data to access mobility services. A mobile device could potentially communicate through a roadside CV device

¹Cellular encompasses all active network types that which support data exchange, including third-generation (3G)/fourth-generation (4G), long-term evolution (LTE), and fifth-generation (5G).

to access a travel service data. Applications available to mobile devices are discussed in detail in the section Wireless Communications Technologies and Methods.

Accessing data by smartphones afforded by CV is like access provided by Wi-Fi—it is limited to regions where roadside CV devices are deployed. The relative advantage of communicating via CV (as opposed to Wi-Fi) is that CV has a lower overhead when negotiating a connection with another device (i.e., lower latency), which allows for quicker feedback to the mobile device user. However, it is important to note that data communicated via CV are constrained to messages that are defined by SAE International (SAE) J2735 to promote interoperability between devices and regions.²⁽¹¹⁾ The research assessed the need for CV messages to meet travelers' needs to make decisions that cannot be met using existing messages.

Human Factors in Delivery of Information to Travelers

Travelers use information to become aware of surrounding conditions that may influence their actions or planned trip and then react to the condition. The decisions made by travelers has the potential to be influenced by the information presented before or during travel. To understand the methods by which a mobile device may present information to travelers to impact their decisions, current methods of information delivery need to be studied.

Recently, much consideration has been given to the information that is presented to drivers as they complete a trip. Guidance exists for the size and placement of freeway signs and markings, managed lane information, and the text that is displayed on CMS. Aspects of positive guidance, which provides insight into spatial and temporal consideration for providing drivers with information, are part of those considerations. While much of the existing research of displaying information to travelers focuses on drivers, it is anticipated that this research can be extended to the provision of information to mobile device users. Finally, the provision of transit information at transit stops and on transit vehicles is discussed.

MUTCD

The MUTCD (2009) provides guidance on the size, spacing, and layout for roadway signage.⁽¹⁰⁾ Signs in this manual are shaped and colored, based on the type of information they are attempting to convey to the driver. Furthermore, these signs are sized per the design speed of the roadway. Drivers traveling at a higher rate of speed need larger signs so they have time to comprehend the information. Word messages on signs are specified to contain standardized wording, letters, and font. A list of acceptable abbreviations also is specified. Table 2 provides descriptions and examples of how colors are used in signs specified in the MUTCD.

²CV is primarily composed of standardized messages exchanged between devices, which promotes broad interoperability. DSRC presently does and C-V2X is expected to support a means to directly access remote services over a traditional Internet Protocol-based connection.

Table 2. Sign colors used in the MUTCD.⁽¹⁰⁾

Color	Description	Example
Black/White	Regulatory.	 <p>R2-1 R3-8b</p>
Blue	Road user services guidance, tourist information, and evacuation route.	 <p>D12-5* D5-2a</p>
Brown	Recreational and cultural interest area guidance.	
Fluorescent Pink	Incident management.	 <p>W3-4 W4-2!</p>
Fluorescent Yellow-Green	Pedestrian warning, bicycle warning, playground warning, school bus and school warning.	 <p>S1-1 W16-7P S4-5</p>

Color	Description	Example
Green	Indicated movements permitted, direction guidance.	
Orange	Temporary traffic control.	
Purple	Lanes restricted to use only by vehicles with registered ETC accounts.	 <p data-bbox="1029 995 1365 1041">1. Pictograph on a purple or other non-contrasting background</p>
Red	Stop or prohibition.	
Yellow	Warning.	

Several methods are provided for improving the conspicuity of signs. These methods are used in special circumstances when it is especially important to make sure a driver notices the posted signage. When considering delivery of output to mobile device users, the techniques applied though the MUTCD are important. Outputs should be consistent so that a driver can expect how to react in each situation. While MUTCD signage is visual, for a mobile device, consistency in

visual, audio, and haptic output needs to be considered. When visual output is provided to the driver, ideally, it should conform to the sign colors and shapes that are specified by the MUTCD.

Roadway signage also is sized and located based on the speed limit on a given roadway. The signage gives the driver sufficient time to interpret the sign at a point that is not too early or too late for the driver to react. However, vehicles traveling above or below the speed limit and drivers moving at different speeds will have different amounts of time to interpret and react to roadway signage. For a mobile device, the size of signage no longer needs to vary as a function of vehicle speed, as the mobile device is with the driver.

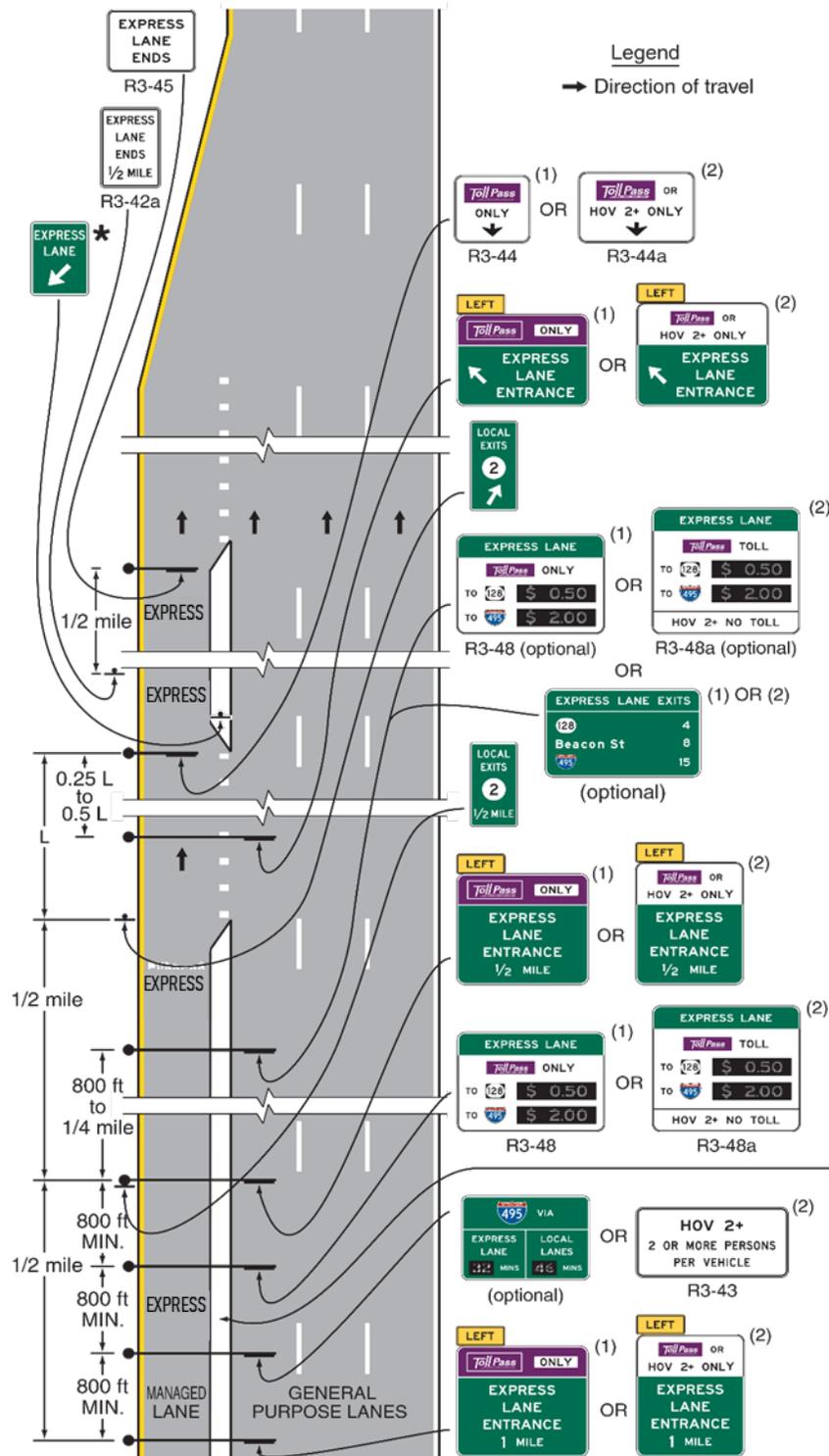
However, ensuring the information displayed or conveyed on a mobile device takes up a similar amount of space as roadside signage in the driver's field of view is appropriate so the driver can comprehend. The mobile device's screen size may constrain the total amount of information displayed to the driver at a time. The mobile device also will be able to tailor the location and time at which information is displayed to a driver. This customization is especially important when drivers are moving at different speeds and ensures that the message is provided an adequate amount of time prior to the driver reaching a specific downstream location. Messages would be provided sooner (at farther upstream locations) to drivers moving at higher speeds and later (at farther downstream locations) to drivers moving at lower speeds.

Managed Lane Information Delivery

Regulatory signs must address pricing, vehicle eligibility, hours of service, and possibly enforcement. The possibility of information overload is great with guidance signs, especially if a complicated operational strategy is in place. Design choices concerning priority of guide signs compared to regulatory signs also is necessary.

The National Cooperative Highway Research Program Research Report 835 describes the challenges of displaying toll information to drivers in advance of a managed lane access point.⁽¹²⁾ The placement of managed lane toll information must consider the amount of time it takes for a driver to decide whether to use the managed lane based on the costs and benefits of using the facility. The report states that one of the major reasons drivers do not use managed lanes is that they are not sure where they go. The report recommends several signing strategies to help the driver understand where the next entrance or exit point is, the location of downstream entrance or exit points, the travel times for general purpose lanes and the tolled express lane for various segments or destinations, and the amount of the toll for various segments (between entrance and exit locations).

To convey all this information to the driver, signage must be spaced to allow the driver to process the information required to make an informed decision. Because the information is spaced, the driver must be able to link pieces of information, such as the travel time and toll amount, from one sign to the next. Further complicating the information needs of drivers is that managed lane access points are generally intermittent, and managed lanes may have special access to certain off-ramps that are not available for use by vehicles in the general-purpose lanes. A standard configuration of express lane signage is provided in figure 1.



Notes:

1. Geometry is for illustrative purposes only; use locally applied geometric criteria.
2. The minimum vehicle occupancy requirement and hours of operation on the sign may vary for each facility.
3. See Chapter 3D of the MUTCD for pavement markings.
4. Warning signs are not shown.

- (1) All vehicles must have a registered ETC account. Toll discounts or exemptions through a registration program might be applicable for certain vehicles.
- (2) All vehicles except HOV must have a registered ETC account. If registration is required for non-toll travel by HOV traffic, case (1) signing shall be used.

Barrier, buffer, or contiguous access prohibition.

* Barrier-separated facilities only

Source: FHWA.

HOV = high-occupancy vehicle; L = distance from the end of the first segment of barrier to the start of the second segment of barrier.

Figure 1. Diagram. MUTCD express lane signage example layout.⁽¹⁰⁾

This guidance can also be used to display managed lane information to mobile device users. Mobile devices provide a method for simplifying information that is displayed to drivers in advance of a managed lane access location. Traditional signage limitations can cause ingress, egress, travel time, and toll amount information to be placed in several locations along the roadway; however, on a mobile device, this information can be displayed to the driver all at one time. In addition to having all information in one place, the driver will have more time to view information on the screen of the mobile device.

The amount of information that can be displayed at once will be limited by the size of the screen of the mobile device. It is important to note that not too much information should be displayed at once so the driver is not distracted from the driving task. Furthermore, if the travel path of the mobile device user is known, only managed lane information relevant to that path needs to be provided to the driver.

CMS Message Delivery

CMS are programmable traffic control devices that can display any combination of characters and symbols to present messages to motorists. These signs are either permanently installed above or on the side of the roadway or portable devices attached to a trailer or mounted directly on a truck and driven to a desired location.

CMS have limited space, and the text that is displayed on them must be chosen carefully to ensure that information is conveyed to the driver in a precise fashion. Furthermore, a driver only has a limited amount of time to read and interpret the message that is written on the CMS. This limitation is further complicated when a message must be split into multiple parts due to message size limits of the CMS. Due to the demand of other driving tasks (especially on busy roadways), it may not be possible to read all parts of the message at once, or the driver possibly may not be able to read the message at all.^(13,14,15)

Information delivered on CMS may be used for the display of similar information to mobile device users. Mobile devices do not have the same text limitations as CMS, so there are fewer limitations to the amount of information that can be displayed to the driver. However, like fixed-location CMS signage, only a certain length of message can be easily comprehended as a vehicle is moving and as a driver is engaged in the task of driving. Messages displayed on a mobile device must remain concise so that too much information is not displayed to the driver at once, allowing the driver to focus primarily on the driving task.

Positive Guidance

The concept of providing drivers with appropriate information about hazards and inefficiencies at strategic locations and times is known as positive guidance. The goal is to use knowledge rooted in human factors and traffic engineering to improve highway safety and operations.

One of the more comprehensive resources available in determining when to provide information to travelers to improve their ability to make decisions is called *A User's Guide to Positive Guidance*.⁽¹⁶⁾ This publication provides a high-level overview of the positive guidance concept.

And while the guidance in this report focuses on the presentation of information to drivers. The same concepts can be adapted to include the presentation of information to mobile device users.

Specifically, drivers gather information while driving primarily through visual means, including other vehicles, signs, and obstacles in the driver's field of view. For a driver to receive information via visual means, the driver must be capable of noticing the information, the information must be in the driver's field of view, and the information must be comprehended by the driver in a location that provides the driver with an appropriate amount of time to perform the requisite maneuvers safely and efficiently.

Drivers often filter the vast number of visual inputs that are received to prioritize and react to the most immediately important events. The short-term memory trace lasts from 30 s to 1 or 2 min, with a span of approximately five to nine information sources. The reaction time of a driver must be considered in the placement of information. This reaction time varies according to whether the event is expected (less reaction time) or unexpected (more reaction time) and the amount of information that must be processed. As the amount of information increases, so does the required reaction time. This same logic applies to driver expectancy. If the driver's expectancy is violated, the driver's reaction time increases, resulting in possible confusion, inappropriate responses, and errors as follows:

- Control expectancies (highest importance)—pertain to vehicle handling and response.
- Guidance expectancies (medium importance)—involve highway design, traffic operations, hazards, and traffic control devices. Most Positive Guidance concepts focus on guidance.
- Navigation expectancies (low importance)—affect pretrip and in transit phases and relate to routes, service, and guide signs.

Drivers tend to prioritize information, placing the most emphasis on information that affects control, followed by guidance and navigation. Maintaining consistency in the use of signage and control devices helps to eliminate expectancy issues. Recognizing that different drivers exhibit variability in sensory-motor capabilities is important. As drivers age, they experience sensory-motor impairments that affect their vision, hearing, and memory, and ultimately, their reaction time when presented with information.

Drivers must be able to classify and process and avoid hazards, which, if not responded to properly, could lead to system inefficiencies or crashes. Adequate sight distance provides sufficient time for drivers to gather information, process it, perform the required control actions, factor in the vehicle's response time, and evaluate the appropriateness of their response in a feedback process.

Stopping sight distance is the distance that a vehicle traveling at the highway design speed will cover between the time a driver receives information to when the vehicle comes to a complete stop. Decision sight distance is the distance that is covered while a driver is deciding based on complex or simultaneous pieces of information and must be considered in the calculation of stopping distance. However, other inputs could include audible alerts from other vehicles, such

as a siren or horn, or tactile feedback from the roadway surface, such as raised pavement markers or rumble strips.

Positive guidance also involves information presentation principles and techniques. General principles of positive guidance attempt to address the various considerations associated with the process of receiving and reacting to information. It is important to accommodate target groups, such as older drivers, and be sensitive to driver sensory-motor attributes. All needed information about hazards, routes, and services should be displayed when needed, where required, and in a form best suited to the driver and task. Information should be compatible where expected to receive and in a fashion that does not surprise the driver.

Overload and underload should be avoided so that the driver does not become confused or miss important information. A lack of information could lead the driver to miss new information due to lack of vigilance. A steady pace of information will assist in avoiding overload and underload of information.

In cases where multiple pieces of information need to be displayed to the driver at the same time, primacy should be used to determine which piece of information should be displayed. This practice corresponds to the greatest threat to the driver but can generally be ordered by information related to control, guidance, and navigation.

Information display techniques can be used to improve the likelihood that a driver will receive information that is needed without overloading or underloading the driver. Spreading is a technique that involves the spacing of information longitudinally on a freeway to reduce the chance for overload at high processing demand locations. Coding is another concept that translates verbal information into a symbol that is understood by drivers. When multiple codes are merged into larger units, it is known as chunking. In some cases, it may be advantageous to repeat information so that the driver is more likely to remember and act on it. Redundancy is a technique that is used to ensure consistency in language, color, and shape, to reduce ambiguity and increase the number of drivers able to use the information.

Although the positive guidance concept is primarily oriented toward drivers, it also can be applied to connected travelers or mobile device users as they complete a trip. Positive guidance concepts can be applied to the dissemination of information to mobile device users as they complete a trip. While these concepts generally refer to the placement of information on freeways, which is predominately visual in nature, it is important to recognize that in addition to visual information, mobile devices also can provide audible information to users as well as haptic feedback.

The visual and haptic aspects of mobile devices are especially important to consider, as a traveler generally does not have the screen of the mobile device in immediate view. In vehicles, mobile devices may be located outside of the driver's primary field of view, requiring the driver to temporarily change their focus from the roadway to the mobile device, which could result in an unsafe situation. Furthermore, pedestrians and bicyclists are not constantly looking at a mobile device as they complete their trip.

In fact, in certain jurisdictions, it is illegal to engage in smartphone activity during certain travel activities, such as using a crosswalk. Many pedestrians carry their smartphone in a pocket or a tote such as a purse or backpack. The concept of positive guidance should be a consideration in the design of audio and haptic outputs from mobile devices to account for the differences between the design of placement of freeway signs and information provided through mobile devices.

One of the major differences between the design of placement of freeway signs and information provided through mobile devices is that highway signage is static and is placed based on a generic design driver and the speed limit of a roadway. A mobile device can consider specific traveler characteristics (e.g., reaction time) and needs to tailor the time and location a piece of information is provided to the traveler. The mobile device can determine the speed of the traveler so that the location where information is provided can be adjusted to the driver's stopping distance. Also, if the mobile device knows the driver's route, it can eliminate the output of unnecessary guidance information that must be included on freeway signs to meet specific guidance and navigation needs of all drivers.

Provision of Transit Information

Travelers use signs located at transit stops to determine which vehicle will arrive at the stop next, the time it will arrive, or to identify the locations of their desired bus or train routes. This type of signage is considered an amenity for transit users because it reduces passenger stress and perceived waiting time. Generally, the following types of information displayed on electronic signs were the most prevalent: current time and date, route number and final destination of the vehicle, waiting time (countdown or arrival time), and service disruptions or other service messages.

Figure 2 provides an example of signage used at transit stops. The sign indicates the route number, destination, and the amount of time or the arrival time of the next four buses to serve the stop.⁽¹⁷⁾ The information that is used to populate these digital signs is often made available to application developers and the public so that travelers can access this information via a smartphone. While no specific guidance exists for displaying this information on a smartphone, Many of the same principles apply.



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Figure 2. Photo. Tri-Met (Portland, OR) bus stop electronic real-time bus information.⁽¹⁷⁾

Many transit vehicles also provide audible and visual information about the next stop along the transit route. This information is extremely helpful to individuals with visual, hearing, and cognitive impairments and assists people who are unfamiliar with the service area. To adhere to the Americans with Disabilities Act regulations, agencies are required to provide onboard announcements on fixed-route service so people with visual and other disabilities know where they are and when to alight.⁽¹⁸⁾ Furthermore, when boarding, people need to know which fixed-route vehicle to board. The agency must identify bus route (via operator verbally or automated system) when a stop or station serves more than one route or line.⁽¹⁹⁾

Capturing Traveler Decisions

The capture and use of traveler data has become a topic of increasing interest among management agencies (traffic and transit). As an increasing number of mobile devices communicate with center-based components, access to high-quality, real-time, multimodal transportation data will become increasingly available. This information allows the current status of, and decisions made by travelers to be ascertained as the traveler completes a trip. Concepts of data capture and management, ITS traffic detection equipment, CV probe data collection, Traveler Information (Advanced Traveler Information Systems (ATIS) 2.0 Precursor System), and private service providers are discussed.⁽²⁰⁾

Data Capture and Management

The Data Capture and Management program focuses on the creation and expansion of access to high-quality, real-time, multimodal transportation data captured from CVs, mobile devices, and infrastructure.⁽²¹⁾ Management and control of transportation systems are dependent on data sources describing the performance of the system (e.g., measured average facility speed) and the state of system controls (e.g., the currently active signal timing plan). Probe data will become increasingly available as the number of vehicles and handheld mobile devices that can communicate this probe data increases.

Traffic Detection Equipment and Probe Data Collection in a CV Environment

Throughout the past several decades, ITS equipment has provided a means for traffic managers to monitor roadway conditions. Traffic managers can then implement any number of traffic

management strategies at their disposal to help improve traffic conditions. ITS data collection equipment may include, but are not limited to loop detectors, radar or video detection, and closed-circuit television (CCTV) cameras. Traffic managers may implement solutions, including but not limited to posting a message or travel times on CMS, adjusting a variable toll, adjusting a variable speed limit, adjusting traffic signal timing, or adjusting ramp meter timing (depending on the availability of these solutions). Similarly, a transit service operator may increase the frequency of its service in realtime depending on traffic conditions and real-time transit vehicle occupancy levels if this data is available and the transit agency has the flexibility to add fixed-route service in an on-demand fashion.

Using CV data for traffic management is a growing area of interest amongst traffic managers to supplement traffic conditions data collected from other existing ITS equipment. Such applications are contained in the concept of the Smart Columbus CV Environment and in the Minnesota Department of Transportation Connected Corridor.

ATIS 2.0 Precursor System Concept

The general concept behind the ATIS 2.0 Precursor System is the capture of data exchanged between travelers and services, such as trip planning services.⁽²⁰⁾ Data input by travelers is sent to and processed by the service, which generates intent data that is considered a by-product of user-service interactions. For instance, travelers input a desired origin and destination into a mobile travel planning application and receive route information for navigating between the origin and destination. This information is captured by the ATIS 2.0 Precursor System and is the input to a process that transforms disaggregate data collected from all travelers using the travel planning service (along with other real-time and historic data sources) into an advanced prediction of traffic congestion (alerts).

When these alert predictions are issued, traffic managers may choose to implement any number of management strategies at their disposal. As it relates to capturing traveler decisions, intent data that is generated by the travel planning service provides insight into the decisions made by travelers as they make a trip. In some cases, a traveler may repeatedly use the trip planning service throughout the course of their trip to assess changes in roadway conditions that may warrant the use of an alternative route. Assessing a series of these trip requests provides further insight to the choices made by drivers, and the evolution of route options available to drivers as they complete trips.

Private Sources

Numerous applications developed for existing smartphones and tablets implement location and behavior tracking capabilities available from the device. These capabilities enable advanced traveler support and targeted information. Typical smartphone applications implement these features for travelers. Access to this information outside of the applications themselves however varies, but as providers look to increase revenue opportunities, purchasing traveler behavior data from private sources such as these may become more realistic.

CHAPTER 3. MOBILE DEVICE TECHNOLOGIES

This chapter provides a closer look at various aspects of mobile devices, mainstream smartphone applications, message sets that are typically used to convey information in a standardized format, and communications media. The capabilities and functionalities of mobile devices and smartphones (in practice and in research) is important for understanding how they will support travelers in the transportation environment.

An agency can use the information in this chapter to better understand what a mobile device is, the types of applications it may support, and communications and messaging standards that it may use. Because most people are familiar with smartphones and the mobile devices are essentially smartphones with some feature enhancements, the smartphone is used as a foundation for defining a mobile device. This naturally leads into a discussion of the types of communications media available to mobile devices and the benefits of how each can be used for the communication of electronic messages.

The types of applications that currently are available are discussed to provide insight into how handheld technologies are predominately used by travelers in today's transportation environment. Considering the use cases provided in chapter 2, this discussion of applications begins to set the stage for considering how a mobile device has the potential to enable and enhance these applications to provide benefits to travelers. Finally, there are nearly limitless amounts and types of information that can be communicated with a mobile device to enable these applications. One of the potential benefits of a mobile device is the ability to communicate using standardized message sets to promote interoperability. To provide an understanding of what messages are available and how they might be used, a description of these standards and messages are provided at the end of this chapter.

The content in this chapter is arranged into the following aspects of mobile device technologies:

- **Mobile Device Definition and Background.** Provides a definition of a mobile device in the context of today's available technologies. A definition and description of today's smartphones is provided and built on to understand the additional capabilities that a mobile device provides.
- **Wireless Communications Technologies and Methods.** Wireless communications options available to mobile devices use are described. These media ultimately enable the transmission of electronic messages.
- **Applications to Enable Mobile Devices Sharing and Using Travel Management and Traffic Control Messages.** The types of applications that can be enabled by mobile devices are discussed. Examples of applications in use by today's smartphones are provided.
- **Current Mobile Device Messaging Conventions.** Current messaging standards are discussed. Open message standards are important to consider promoting interoperability between mobile devices and infrastructure-based components in different locations.

Understanding characteristics of smartphones and mobile devices provides insight into what they are capable of so that how a mobile device may be used in the context of use cases defined in chapter 2 can be envisioned.

Mobile Device Definition and Background

What typically comes to mind when “mobile device” is referenced is a smartphone. Smartphones are characterized as hand-held computers exhibiting a set of standard features, such as an operating system, access to various communications technologies, and hardware and software sensors. Applications (apps) are the software that is installed on the smartphone, which take advantage of the smartphones features to provide a service to the user. The user interacts with the smartphone typically using a touchscreen.

All components of the smartphone are contained in a mobile form factor (designed to be carried on the person) and are powered by a rechargeable battery. Smart phones have become increasingly sophisticated. Improvements in recent years focus on software and hardware improvements that allow the device to communicate according to the latest standards and take advantage of the latest technological advancements (e.g., screen, battery, processor, memory).

The operating system manages the smartphones’ hardware (processor, memory, sensors) and software (application) resources. The market share of smartphone operating systems in the United States is dominated by iOS™ (58.12 percent) and Android™ (41.55 percent).⁽²²⁾ Less than 1 percent of smartphones use an operating system that is not Android or iOS. Smartphones use a variety of communications media, including third-generation (3G)/fourth-generation (4G) long-term evolution (LTE), fifth-generation (5G), satellite, Wi-Fi, near-field communications (NFC), or other wireless communications technologies, which are discussed in the section Wireless Communications Technologies and Methods.

Many of the sensors that detect movement and proximity have been carried over from previous generations of smartphones. The accelerometer and gyroscope detect linear and angular acceleration along three axes. A magnetometer is used to detect direction with respect to the smartphones’ reference axis. A proximity sensor determines if there is an object within a certain distance of the face of the phone (this is typically used during phone calls to determine when the screen should automatically turn off). Also, ambient light sensors are included (typically used to auto-adjust screen brightness to enhance usability). However, sensors such as the barometer and ambient temperature sensor are no longer commonplace in today’s smartphones.

A mobile device refers to a device that has the same capabilities and features as a smartphone, but also can communicate via a CV radio. Smartphones do not have CV accessibility, and therefore external hardware must be used to provide this feature. In the initial mobile devices research prototype project, a mobile device was composed of a smartphone tethered to a mobile battery-powered CV radio via short-term wireless communications. Both the mobile device and the radio would contain a platform around which processes can be carried out. The CV radio unit typically hosted an open-source computing platform and has the ability receive messages that can be provided to the smartphone.

Similarly, the API on the smartphone operating system provides access to the smartphone's features and communications media. Processing functions supported on a mobile device could occur on either the smartphone or the CV radio. The smartphone platform hosts other smartphone applications and provides a user interface to allow the user to interact with the specific functions being supported. The demand for a tethered mobile device has not materialized outside of the research community; however, with the move toward C-V2X as the predominant technology for CV applications, its coexistence in the same microprocessor chip with the regular cellular features allows for a single device to exhibit both smartphone and CV capabilities, eliminating the need for tethering.

Wireless Communications Technologies and Methods

This section provides an overview of various communications technologies used in the transportation environment. One of the most important aspects of any CV system is the wireless medium through which devices communicate with each other. This section is not intended to focus on backhaul connectivity of devices, but rather the communications between the roadside and vehicles/mobile devices and communication between multiple vehicles/mobile devices. This section is also not intended to recommend or specify communications media that will be used in future systems, but to outline communications media available and the benefits and drawbacks of each. Note that not all communications listed are necessarily found on smartphones that are commonly available.

DSRC

DSRC is a two-way short- to medium-range wireless communications capability that permits remarkably high data transmission critical in communications-based active safety applications. Such applications require near-instant transmission of data (from one vehicle to another or from the roadside to a vehicle) to alert a driver when immediate action is required to prevent a crash or a potential unsafe maneuver. DSRC can be used to transmit several message types (standardized in SAE J2735 and SAE J2945/1) that enable applications to improve traveler safety and mobility.^(11,23) Another major benefit of DSRC is that it allows devices to communicate directly with each other (as opposed to relying on a network backbone) while ensuring message authenticity and preserving user anonymity.

DSRC is characterized by low-latency transmission of data and has been a major focus of CV research over the past several years. One of the major benefits of DSRC is the secure and trusted communication of information between two parties that have never encountered each other before.

Radios are typically installed on the roadside, in vehicles, and recently tethered to smartphones on mobile devices. A security and credentials management system is required to ensure secure communications between devices.

DSRC is used for direct device-to-device communications technology used to enable safety and mobility applications. It is a well-tested technology that has been deployed primarily on vehicles at and intersections in a handful of small- and medium-scale projects throughout the country. DSRC technology is not a feature included in mainstream smartphones, although a U.S.

Department of Transportation (USDOT) project has prototyped a mobile device that consisted of a smartphone tethered with a DSRC antenna to demonstrate mobile device capabilities. The use of DSRC is expected to plateau or decrease as current and future deployments shift to C-V2X communications technologies.

The following standards apply to the transmission of data via DSRC:

- IEEE 802.11p—Wireless Access in Vehicular Environments.⁽¹⁾
- IEEE 1609.2—Wireless Access in Vehicular Environments—Security Services for Applications and Management Messages.⁽²⁵⁾
- IEEE 1609.3—Wireless Access in Vehicular Environments (WAVE)—Networking Services.⁽²⁶⁾
- IEEE 1609.4—WAVE—Multichannel Operation.⁽²⁷⁾

C-V2X

C-V2X is an emerging communications technology based on 3GPP Release 14 that, like DSRC, allows data to be transmitted directly from V2V, V2I, and vehicle-to-pedestrians (mobile devices).⁽²⁾ 3GPP, the standard for LTE cellular communications, defines two interfaces: one which allows it to communicate with the network using traditional cellular means (known as the Uu interface), and one which allows it to directly communicate to other devices independent of the cellular network (known as the PC5 interface). The PC5 interface is referred to as C-V2X. This direct communication between devices presently uses 20 MHz of the ITS Safety spectrum to allow for low-latency communications that supports safety-of-life applications.⁽²⁸⁾ Recent Federal Communications Commission actions have secured this 20 MHz for exclusive use by C-V2X, and have initiated the process to allow C-V2X to replace DSRC.⁽²⁹⁾

C-V2X, like DSRC, can be used to enable many of the same applications. C-V2X is becoming increasingly accepted as the successor of DSRC and is expected to be the primary means of communications in future CV deployments. Mainstream smartphones are increasingly becoming equipped with the hardware and firmware to support C-V2X device-to-device communications. However, traveler-focused transportation applications that leverage this C-V2X device-to-device communications are not yet prevalent—though this is expected to change as C-V2X continues to proliferate. Many of the same messaging standards that are applicable to DSRC also are applicable to C-V2X.

3G and 4G LTE Mobile Network

4G LTE remains one of the most popular methods of transmitting traveler information to travelers. Through in-vehicle systems, or smartphones, travelers can receive roadway travel times, information on roadway closures, or real-time transit data. One of the major benefits of 4G LTE is its coverage area, particularly on highly traveled corridors. However, because communication between devices on a 4G network are routed through fixed-location transceivers, communications latency may become an issue, which can preclude a system network relying on 4G LTE from supporting safety of life applications. Furthermore, since the 4G LTE network is managed through wireless telecommunications providers, a subscription to a mobile data plan is required for individuals to use 4G LTE, which may be a barrier of entry for some roadway users.

Communication of data via 4G LTE is specified by the code division multiple access (CDMA) A2000 and 3GPP families of standards.^(30,2)

Some agencies using 4G LTE to backhaul connected roadside devices to a TMC. 4G LTE is commonly used by transit agencies to run transit management activities (such as fare payment). 3G and 4G LTE are available to mobile devices that have the proper radio equipment and often require a data subscription plan.

3G and 4G LTE have been the primary means of providing smartphone connectivity with cellular network for many years. As 5G continues to become more ubiquitous, it is expected to become increasingly leveraged where available.

5G Mobile Network

5G is the latest version of what is commonly known as cellular technology. It was originally based on 3GPP Release 15 and was finalized in Release 16.⁽³¹⁾ While still limited to major markets, availability of 5G is quickly growing and will eventually surpass 4G as the primary cellular technology. Similar to 4G LTE, 5G enables travelers to receive roadway travel times, information on roadway closures, or real-time transit data.

Two of the major benefits touted for 5G are higher speeds and lower latency, however, for those to be realized, clear line-of-sight and close proximity to the “tower” are required. When those conditions cannot be met, 5G can still be fully functional, albeit at speeds and latency that are only incrementally better than 4G LTE. 5G’s range also is much shorter than 4G LTE, and as such, requires significantly more infrastructure to be installed before the same coverage is achieved. When built out however, 5G promises reliability, speed, and latency that could potentially serve safety-of-life applications.

Agencies currently using 4G LTE to backhaul connected roadside devices to a central traffic management center will likely remain for some time, but in addition to the speed and latency afforded mobile devices, roadside equipment also could benefit from these enhanced capabilities. C-V2X has a forward compatible evolution path to the technology underlying 5G as well. Known commonly as C-V2X new radio, this generation is expected to enhance the available features of V2X, but that has not been developed outside of the laboratory environment. Smartphone technology is expected to progress to eventually support 5G device-to-device communications.

Global Navigation Satellite System (GNSS)

GNSS is a generic term for systems that are available for satellite geolocation. The four primary GNSS systems include the Global Positioning System (GPS) (United States), GLONASS (Russia), Galileo (European Union), and BeiDou Navigation Satellite System (China). (See references 32–35). The GNSS is generally considered to provide position, speed, and time information for receivers, which can be placed in or on a vehicle, on the roadside, or on mobile devices. Mobile device-based applications rely on pedestrian, bicycle, and vehicle positioning. It is important to note that this information exhibits varying degrees of accuracy depending on conditions, such as the number of satellites and interference.

Smartphones are typically equipped with some form of GNSS technology. GNSS is considered to be a mature technology that will continue to be available for smartphone and mobile devices to leverage for the foreseeable future. Furthermore, antennas to receive GNSS data also are typically found in vehicles (used by vehicle telematics systems) and are frequently contained in devices that also contain DSRC radios.

Wireless Network

Wireless network allows mobile device users to access the Internet when in range of wireless routers. Travelers that do not have access to cellular data typically use wireless when it is available to access the trip planning services they may need. Private wireless networks are generally password protected and cannot be accessed by unauthorized mobile devices, meaning connectivity is further limited to locations where public access is provided. Some transit systems have begun to install free access to wireless at stations and in-transit vehicles as an amenity to riders. A wireless network is considered to be a mature technology that will continue to be available for smartphone and mobile devices to leverage for the foreseeable future.

The following standards apply to the transmission of data via a wireless network: IEEE 802.11a,b,g,n,ac, ax—Wireless Local Area Network Medium Access Control and Physical Layer Specifications.⁽³⁶⁾

Short-Range Wireless Communications

Short-range wireless communication is supported on most modern smartphones. Many smartphones support different short-range communication standards, which allow smartphones to communicate with other low-energy devices. The target market for short-range wireless communication devices have uses related to healthcare, sports, and fitness, among others. Short-range wireless communication is a mature technology that will continue to be available for smartphone and mobile devices to leverage for the foreseeable future.

NFC and RFID

RFID is widely used in ETC, or tracking of goods, and in sporting events that are timed (such as a running or bike race). NFC is a specialized subset of RFID technology that supports secure communications and is characterized by devices of being capable of being a tag and a reader. NFC is nearly ubiquitous in smartphones sold in recent years.

Tolling networks use passive RFID transponders in vehicles and active RFID transponders on the roadside to send a unique identifier to the roadside as the driver passes through tolling points throughout the network. That unique identifier is associated with account information, which is used to debit a prepaid account or bill the driver for the toll.

Compared to other methods of wirelessly exchanging information, NFC is preferred for transmitting information due to its low latency, and low power consumption. Although its range is much smaller (approximately 4 inches), this could be considered a security benefit, as this physically limits the potential of other unintended devices to receive payment information. The use of secure channels further improves the likelihood that only authorized devices (the intended recipient) are able to receive the payment information.

NFC is a mature technology that will continue to be available for smartphone and mobile devices to leverage for the foreseeable future. Today's smartphones primarily leverage NFC to exchange payment information. However, smartphones are not traditionally used in the tolling space, where RFID devices are still used in vehicles to facilitate tolling information.

The following standards apply to the transmission of data via RFID and NFC:

- International Organization for Standardization (ISO) 15693—Identification cards—Contactless integrated circuit cards—Vicinity cards.⁽³⁷⁾
- ISO 14443—Identification cards—Contactless integrated circuit cards—Proximity cards.⁽³⁸⁾

Applications to Enable Mobile Devices Sharing and Using Travel Management and Traffic Control Messages

This section discusses an inventory of smartphone applications that are available today to enable information sharing and travel management/traffic control function. This section describes five different application types that indicate how mobile devices could be used in today's transportation environment using smartphone technology.

Combined Public-Transit Planning and Fare Payment

Mobility on demand (MoD) is an innovative transportation concept where consumers can access mobility, goods, and services on demand by dispatching or using shared mobility and public transportation solutions. The most advanced forms of MoD passenger services incorporate trip planning and booking, real-time information, and fare payment into a single user interface.

Mobile fare payment applications allow a traveler to use a mobile device to pay for a transit trip, and to use the mobile device as a method to prove a fare was paid. Quite often, these fare payment applications also contain a trip planner, which allows a user to input an origin, destination, and departure or arrival time and is provided with one or more route options. Such a feature is beneficial because it also may specify the fare for each trip.

This feature reduces the need for the traveler to understand every facet of the fare structure of one or more services and provides an easy method for the traveler to purchase a fare for the specific trip they intend to take. An alternative to the trip-based method is the traveler could purchase a single- or multiple-day pass, while still using the app for travel planning purposes. Though the traveler has paid for the fare, the trip is not active until the traveler is about to start the trip.

Prior to boarding the first transit vehicle, the traveler activates the trip through the smartphone application. While the trip is active, the screen displays a proof of payment. Depending on system operations, this proof of payment may be shown to the transit vehicle operator when boarding the vehicle or provided to enforcement agents onboard a transit vehicle when proof of payment is requested.

After a predetermined period, the trip deactivates, and the traveler can no longer show the proof of payment. For a single trip, the active period typically lasts 2–3 h. This period is given to allow the traveler to make transfers to other routes in the same network. For single- or multiple-day passes, the active period lasts for the specified period. Once the pass expires, the traveler cannot use that pass to board another transit vehicle. At this point, another trip or pass must be activated, or an additional trip(s) or pass must be purchased.

Examples of transit agencies that allow mobile fare payment include the following:

- Metro Transit (Minneapolis-St. Paul Metropolitan Area).
- Greater Cleveland Regional Transit Authority.

The downside of transit trip planning and payment applications is that in some regions, each transit agency or system has its own trip planning application and separate payment systems. Payment for a fare for a trip with a given transit agency may not be used for a trip on another transit agency's system. This separation precludes payments from being transferred from one system to another. Note that some regions currently are integrating fare payment systems across multiple agencies—the Orca Card and Transit Go Ticket smartphone applications can be used between several transit agencies in the Seattle area.⁽³⁹⁾ However, fare payment not integrated with a MMTP application requires the traveler to determine which fares must be purchased on which systems after planning a trip.

While there are no known smartphone applications that allow a traveler to pay a fare for more than one transit system, there are applications that provide a trip planning service for multiple transit systems. Based on the smartphone location, the application downloads real-time and scheduled transit data from transit agencies to provide a trip planning service to the user. The application may plan a trip using one or more of the available transit services. Other applications provide additional information about wait times, vehicle location, and routing.

Contactless Payment

Contactless payment smartphone applications provide an interface to allow the user to enable the device for NFC payment and to disable the payment system after the purchase is complete. This capability limits the device's ability to communicate with other potentially unauthorized devices. Contactless payment applications operate on the same basis. To initialize the contactless payments on the smartphone, the traveler enters payment information. This payment information can then be exchanged with a payment terminal via NFC. The payment terminal then authorizes a payment from the account associated with the payment to a merchant or service provider.

While these payments are predominately used at sales terminals in retail establishments, they are starting to become accepted as one-time fare payments when boarding a bus or passing through faregates. The benefit of such payment services is that they are relatively quick, and an Internet connection is not needed for the mobile device user to pay when the payment device has been set up. A handful of transit systems accept NFC contactless payments (in addition to other payment methods), including but not limited to Utah Transit Authority, Chicago Transit Authority Ventra, and Southeast Pennsylvania Transportation Authority Key.⁽⁴⁰⁾

Though not specific to the transportation space, contactless payment services could be integrated into more transportation-related applications to enhance the user experience.

Ride Sourcing and Ridesharing

The premise behind ride-sourcing services is that a traveler can input their current location and a desired destination and have that request serviced by a mobility provider (such as a taxi, bus, or car share) based on constraints provided by the traveler. As a part of the Sharing Data Between Mobile Devices, Connected Vehicles and Infrastructure project, a prototype system was developed to allow a DSRC-enabled mobile device to communicate with a driver who can service the travel request through various communications media.⁽⁴¹⁾ The mobile device attempts to communicate directly to nearby vehicles via DSRC, but if no vehicles are nearby to service the request, then the mobile device will attempt to communicate with vehicle through a trip planning service through cellular data.

A driver provides input to an in-vehicle device if he or she can service the traveler's trip request (provided the traveler's constraints), and a response is issued to the traveler's mobile device to indicate the trip has been accepted. Other types of messages are exchanged when the traveler decides to cancel the trip or when the vehicle arrives at the traveler's specified pickup location. When the vehicle arrives, the traveler enters the vehicle as a passenger and the driver of the vehicle then services the travel request by transporting the traveler to the specified destination. The prototype as developed did not allow for exchange of payment information.

Similar applications, such as Uber and Lyft, are mainstream applications that are available to smartphone users but require the smartphone user to have an Internet connection.

These ride-sourcing applications typically allow a traveler to use their smartphone to request a ride. The request is fielded to a pool of drivers (that interface with the system through a similar driver-focused application). When a driver accepts the ride request, a confirmation is provided to the traveler and the driver services the request. These services also enable payment from the traveler to the driver (the travel provider typically takes a portion of this payment to offset costs associated with business operation). After the ride is completed, a fare based on time and distance traveled is assessed to the traveler—a portion of this fare is provided to the driver as compensation.

More recently, taxi companies have been creating their own smartphone application to allow travelers to request a taxi. Traditionally, travelers had to rely on being in a location where there were empty taxis, or calling a taxi dispatch center, which would send a taxi to the traveler's location.

One of the newest features added to ridesharing applications is a ridesharing service for travelers. Travelers selecting this option will be matched with other travelers heading in the same direction and allows the travelers to share the ride. Multiple stop ridesharing allows travelers to pick up and drop off other passengers at various locations. While this may result in a longer trip for the traveler, the traveler will pay a lower fare, as fare for the portion(s) of the trip that are shared with other passenger(s) are split. Trip matching is likely performed at a processing center. When the new trip is added, the driver is rerouted accordingly.

Rules in place allow the driver to wait for no longer than 2 min for a passenger to minimize waiting time for passengers in the vehicle. Communication technologies on today's smartphones are the primary enabler of ride-sourcing applications. Smartphones must have a connection to the Internet to enable these services.

A smartphone typically accesses the Internet via short-range wireless communications or cellular data. Neither of these communications media are ubiquitous in coverage. However, in cities, where these applications are typically used, cellular coverage is generally expected, although the traveler must subscribe to a cellular data service, which is an expense to the traveler.

Alternatively, short-range wireless communications access can be used to access the Internet. While a short-range wireless communications connection does not necessarily require a subscription to a data plan, this type of connectivity is not guaranteed at the traveler's given location. Even when a short-range wireless communications connection is available, access to unknown or unsecure short-range wireless networks comes with the risk of compromising the traveler's privacy or the security of the traveler's device.

Route Information and Routing

Applications that provide information regarding route information and planning aim to improve traveler mobility by providing the most efficient route from an origin to a destination based on current traffic conditions. Travel applications require the traveler to enter an origin, destination, time of departure or arrival, and mode of transport to obtain directions from the origin to the destination. Additional options allow the user to avoid highways or tolls. The directions are tailored to each mode. For instance, bicycle trips can take bike paths and not freeways.

Rideshare applications may use community provided traffic and navigation information services. Some ridesharing applications require users to both contribute data and use the service to find the fastest route between the driver's current location and destination. When such an application is running, it collects location and speed data and sends the data to the provider. The service providers use these data, in combination with its mapping system, to determine roadway network speeds on a link-by-link basis. When a user specifies a destination, applications use the aggregated link speed data to determine the fastest route to complete a trip.

Due to the ever-changing nature of traffic conditions, applications may attempt to predict traffic conditions, to estimate travel times beyond a certain time horizon. As drivers moves throughout the roadway network and as traffic conditions change, the route is reassessed to determine if a better route is available for further minimizing travel time. Users also can manually input crashes they observe, or other events, so that information can be made known to other drivers.

Traveler Information

TMCs gather data from ITS devices, which is generally used to monitor traffic conditions on a roadway network. Traveler information applications (such as 511) make the data available to smartphone users through a smartphone application, and typically allow access to many different types of data, which may include but is not limited to current speeds/travel times, road weather conditions, view CCTV images (streaming or still shots), incidents, and road work. Each State or region is responsible for developing its own traveler information smartphone application. As

with many other smartphone applications, such applications require an Internet connection, typically Wi-Fi or cellular data.

Other applications make use of real-time data from management capabilities of other systems, such as transit and bikeshare systems. For instance, Transit App makes use of General Transit Feed Specification (GTFS) data, GTFS Realtime data (or other types of route and real-time transit information), real-time bikeshare information, and real-time carshare information to provide travelers the location and time of arrival for various bus lines that stop near the traveler's location and the location and availability of bikeshare and carshare services.^(42,43,44) There are many other applications that have been independently developed that make use of various forms of openly available data to support the traveler's information needs.

Integrated Dynamic Transit Operations (IDTO)

IDTO project set out to improve the mobility of the local traveling public (especially travelers needing to use multiple transit providers on a given trip) by integrating the capabilities and offerings of three public transit mobility applications within a single real-time system that can meet the public's expectations on trip performance and satisfaction. The three applications that were developed include Dynamic Transit Operations (T-DISP), Connection Protection (T-CONNECT), and Dynamic Ridesharing (D-RIDE).⁽⁴⁵⁾

T-DISP seeks to expand transportation options by leveraging available services from multiple modes of transportation. Travelers would be able to request a trip via a handheld mobile device (or phone or personal computer) and have itineraries containing multiple transportation services (public transportation modes, private transportation services, shared ride, walking and biking) sent to them via the same handheld device. A physical or virtual central system, such as a travel management coordination center would dynamically schedule, and dispatch trips based on aggregated input received from all travelers.

The goal of T-CONNECT is to improve rider satisfaction and reduce expected trip time for multimodal travelers by increasing the probability of automatic intermodal or intramodal connections. T-CONNECT protects transfers between both transit (e.g., bus, subway, and commuter rail) and nontransit (e.g., shared-ride modes) modes, and will facilitate coordination between multiple agencies to accomplish the tasks.

D-RIDE is an approach to carpooling in which drivers and riders arrange trips within a relatively short time in advance of departure. D-RIDE provides an alternative to transit when it is not a feasible mode of transport or unavailable within a certain geographic area. This application allows a traveler to input a desired origin and destination, which can be serviced by a vehicle.

These three applications were designed and developed to run on a mobile device-based application. The prototype system that was ultimately developed for the IDTO project demonstrated the functionality of each application.

Functionality of the T-DISP application is found on several MMTPs, such as Open Trip Planner, which provides an open-source interface that allows a traveler to search for itineraries that include pedestrian, bike, transit, and car components.⁽⁴⁶⁾ Open Trip Planner relies on open data standards: GTFS for transit schedule data, OpenStreetMap for street network information, and

GTFS Realtime for vehicle position, delay, and transit service alert data. Functionality of T-CONNECT outside of the prototype system is not known, and the functionality of D-RIDE is found in ride-sourcing applications, described previously in the section Ride Sourcing and Ridesharing.

Current Mobile Device Messaging Conventions

This section primarily focuses on messaging in the DSRC or C-V2X space (see sections DSRC and C-V2X), where message types and content is defined in standardized data dictionaries. It identifies the information or issues to consider that support development of messages and supporting components, why these components are needed, what may or may not exist for standards or evolving industry recommended practices, and how messages should be configured and used. The messages, strategies to reduce wireless message transmission, and issues to consider for sharing messages with mobile devices are used as a basis for determining potential additional data elements to be included in future messages.

Standardized Messages

The primary standards considered include SAE J2735, European Telecommunications Standards Institute (ETSI) TS 102 637, and GTFS Realtime.^(11,48,49) SAE J2735 defines a message set along with associated data frames and data elements that are used to build several different types of messages. Messages transmitted via DSRC are limited to those specified in this standard, although these messages also could be transmitted via other various communications media. There have been a number of projects that focus on the development of new messages to be included in the SAE J2735 standard. These messages, which have been developed and used in prototypes, have been used to demonstrate several use cases that intend to meet the needs of mobile device-carrying travelers:

- **Basic safety message (BSM) (SAE).** The BSM is used in a variety of applications to exchange safety data regarding vehicle location and motion. This message is broadcast frequently to surrounding vehicles with data content as required by safety and other applications. Transmission rates are beyond the scope of this standard, but a rate of 10 times per second is typical when congestion control algorithms do not prescribe a reduced rate.
- **Signal phase and timing (SPaT) (SAE).** As stated in the message name, the SPaT message provides signal phase and timing information for an intersection. It can be linked to movements defined in a MapData (MAP) message so that signal states can be applied to each movement.

- **MAP (SAE).** The MAP message contains intersection and roadway geometry data and are typically broadcast from roadside devices and received by vehicles and mobile devices so that these devices can determine their position with respect to the roadway. At an intersection, MAP messages can be paired with SPaT data so that an intersection's condition can be applied to each intersection movement.
- **Traveler information message (TIM) (SAE).** TIMs contain advisory information used by vehicle operators. TIMs are sent from the roadside to vehicles, which must subscribe to receive the TIM. The TIM protocol provides the location and situation (e.g., vehicle speed) parameters that must be met for the TIM to be delivered to the vehicle operator. For instance, a TIM that advises a vehicle operator of a speed limit in a designated area would only be displayed to the vehicle operator when approaching the area and if the vehicle operator is traveling above the speed limit within the area.
- **Signal request message (SRM) (SAE).** The SRM contains data that is used to request signal preemption or signal priority from a signalized intersection. These data include the desired movement, the priority type (priority or preempt), and the priority level. Additionally, The SRM includes estimated time of arrival (ETA) and duration of service data fields. These data items are essential to ensuring that all vehicles traveling in a platoon can be accommodated in the priority request and move through the intersection if the request can be granted. This message is sent from vehicles that require preemption or priority at an intersection and are received by roadside units. When SRMs are received from multiple vehicles, the traffic signal controller or other processing equipment must arbitrate the requests based on the priority level of the request.
- **Signal status message (SSM) (SAE).** The SSM contains data about the operational state of the intersection (e.g., normal, priority, preempt). This message is sent from an intersection to relay information to a vehicle regarding whether the signal priority request parameters were accepted by the intersection. Data contained in this message can be populated using the output from a National Transportation Communications for ITS Protocol (NTCIP) 1202-compliant traffic signal controller.
- **Personal safety message (PSM) (SAE).** The J2735-defined PSM transmits a mobile device's position, speed, and heading, among other information. For a general collision avoidance application, surrounding vehicles could receive the PSM, and along with its own telematics, determine if a collision is imminent. However, the device-to-everything (D2X) Hub broadcasts a version of this message that is slightly different, but contains the same core elements, because the PSM did not exist when the D2X Hub was developed. The PSM was first developed and defined as a part of the Sharing Data Between Mobile Devices, Connected Vehicles, and Infrastructure project.⁽⁵⁰⁾
- **Probe vehicle data (PVD) message (SAE).** The PVD message is designed to collect vehicle status data over a defined distance and/or time in a structured manner and to provide it to the infrastructure. The infrastructure can forward these data to a TMC, where it can be used for traffic management purposes. A vehicle is expected to provide probe vehicle data in accordance with parameters specified in the probe data management (PDM) message, described in the next paragraph.

- **PDM message (SAE).** The limited range or number of roadside equipment may influence the use of PVD messages to fill in the gaps in coverage in the case cellular technology is not available. The probe management process involves sending the PDM message from roadside equipment to the vehicles to specify how the vehicle gathers and reports data (i.e., at what frequency and including what detail). The messages have the potential to specify the data, the frequency of collection, and delivery from the connected and automated vehicle (CAV) or connected mobile device back to the roadside equipment.⁽⁵¹⁾

ETSI has developed the basic information message (BIM), decentralized environmental notification message (DENM), and the cooperative awareness message (CAM), which are exchanged between devices in a transportation environment to create and maintain awareness of each other and to support cooperative performance of the road network:

- **BIM (ETSI).** BIM is a proposed new message format that enables the transmission of all required data elements for V2I safety applications in a single message and is extensible to support future event-based applications. This concept of message structure uses existing SAE J2735 data elements.⁽¹¹⁾
- **DENM (ETSI).** Provides information about 13 use cases: emergency electronic brake light, wrong-way driving warning, stationary vehicle—accident, stationary vehicle—vehicle problem, traffic condition warning, signal violation warning, road work warning, collision risk warning, hazardous location, precipitation, road adhesion, visibility, and wind.
- **CAM (ETSI).** Information about presence, position, and basic status of an ITS station is communicated to neighboring ITS stations located within a single hop distance. Includes vehicle position and vehicle basic data (acceleration, path history, curvature, and vehicle size). CAM supports 32 use cases in four application classes, including active road safety (e.g., emergency vehicle warning), cooperative traffic efficiency (e.g., regulatory speed limit notification), cooperative location services (e.g., parking management), and global Internet services (e.g., insurance and financial services).

GTFS Realtime is a feed specification that allows public transportation agencies to provide real-time updates about their fleet to application developers.⁽⁴⁴⁾ When used in an application installed on a mobile device, travelers carrying mobile devices can access and use real-time transit data to improve mobility.

Prototype Messages

In some instances, standards do not exist to meet the data transmission requirements that support the needs of travelers. Consider modifying existing standards to meet these needs. The initial mobile devices research prototype project considered modifications to the set of DSRC messages to support coordination of multiple travelers and the safety needs of pedestrians in a vehicular environment. This section provides details about the messages developed for the Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure project and the data they

contain. The PSM uses the same core elements as the PSM that is standardized in SAE J2735 as follows.⁽⁵⁰⁾

- **Personal mobility message (PMM).** The PMM is intended to enable new applications benefitting a variety of users. Presently, the PMM is not standardized as part of J2735, however, the message and integration into the API, which was tested as a part of the prototype, was developed for use with the D2X Hub. The purpose of the PMM is to provide information about the traveler's next intended trip and associated movement (i.e., the next portion of a traveler's trip that is expected to take place on a single mode or within a single system where availability/capacity for transport could be limited, e.g., shared bicycle/car, transit/taxi) to get from departure location to destination location and their requirements for travel such as schedule constraints, mobility, and other issues. The PMM also contains information about the constraints on the traveler's trip such as requiring any special needs or issues which should be considered in support of the successful completion of the trip (e.g., a transit vehicle with a wheelchair lift). Request identification (ID), traveler location, number of travelers, pickup time, pickup location, destination, mode of transport, and mobility needs are captured in the prototype PMM. The ETA threshold was considered but not developed as part of the D2X Hub project.
- **Personal mobility message Response (PMM-RSP).** The PMM-RSP or PMM-Response is a message sent from a vehicle back to a travel group leader to acknowledge that the travel group can be accommodated. The PMM-RSP message contains Request ID (corresponding to the Request ID in the PMM), vehicle location, mode of transport, DSRC support indicator.
- **Personal mobility message cancel (PMM-CANCEL).** A PMM-CANCEL message is issued from a mobile device back to a vehicle if a travel group completely dissolves before the vehicle arrives, or if the travel group leader receives more than one PMM-RSP from a vehicle. The PMM-CANCEL only requires a Request ID (corresponding).
- **Personal mobility message arrival (PMM-ARRIVE).** The vehicle sends a PMM-ARRIVE message to let the group leader know that the vehicle is in the vicinity for the purposes of disbanding the group, and that they will soon enter the vehicle. PMM-ARRIVE works with PMM-RSP to coordinate travel of multiple, mobile-device-carrying travelers with a common current and next destination. PMM-ARRIVE includes Request ID, vehicle location, and visible vehicle identification information. ETA was considered but not incorporated into the PMM-ARRIVE message in the D2X Hub project.
- **Surrogate BSM.** The Surrogate BSM was intended to be broadcast from a mobile device in a vehicle that is not capable of broadcasting its own BSMs. It was considered but not developed in the D2X Hub project. Thus, no plugins generate or use data contained in this message.
- **Coordination message.** Coordination messages allow mobile devices to directly communicate with other mobile devices at a local level to reduce the number of messages needed to be sent or received. This overall reduction in the communication burden

directly benefits the communications system (e.g., cellular, DSRC, Wi-Fi) in terms of the throughput for specific devices (e.g., mobile devices, in-vehicle devices). Specifically, these coordination messages are used to temporarily link travelers together into ad-hoc travel groups so that only a single message representing the group needs to be transmitted to an infrastructure or vehicle component rather than individual messages from every member of the group as follows:

- **Coordination request:** Request ID, number of travelers in group, pickup time, pickup location, destination location, and mode of transport.
- **Coordination confirmation message:** Message ID, travel group ID.
- **Heartbeat message:** Message ID, group ID.
- **Coordination end message:** Message ID, travel group ID.
- **Alight vehicle message.** The Alight Vehicle Message contains a request ID, exit location, and arrival time estimation. It was considered but not developed in the D2X Hub project.
- **Request to cross street message.** The Request to Cross Street Message contained a request ID, intersection corner indicator, crosswalk indicator, number of pedestrians, and the minimum pedestrian crossing speed. This message was intended to support one or more pedestrians requesting to use a crosswalk at an intersection. However, it is expected that functions intended to be supported by this message can be supported by a signal priority request message, which is defined in SAE J2735.⁽¹¹⁾
- **Crossing street acknowledgment message.** The Crossing Street Acknowledgment Message contains a request ID that corresponds to a request ID in the request to cross street message. It is sent in response to a request to cross street message to indicate that the request was received. This message was intended to support one or more pedestrians requesting to use a crosswalk at an intersection. However, it is expected that functions intended to be supported by this message can be supported by an SSM, which is defined in SAE J2735.⁽¹¹⁾

Strategies to Reduce Wireless Message Transmission

One concern pertaining to wireless communication is the potential message congestion (or message interference) that is caused when too many wireless devices attempt to exchange data at the same time. As the number of wireless devices in a given area increases, the likelihood of message congestion increases.

SAE J2945/1 describes performance and functional requirements for transmitting V2V messages such as the BSM.⁽⁵³⁾ This standard specifies that the transmit power of the wireless communication decreases as a function of the density of vehicles increases in a given area or as the speed of the vehicle decreases. Under certain safety-critical situations, the vehicle would still broadcast safety messages at full transmit power. Under increased vehicle density and lower vehicle speed, a

reduced transmit power can still provide the needed safety benefits while reducing the burden on the wireless bandwidth.

For the prototype system developed as part of the Sharing Data Between Mobile Devices, Connected Vehicles and Infrastructure project, a number of functions were included to minimize the number of PSMs that were broadcast by mobile devices.⁽⁵⁰⁾ When held by a pedestrian, the mobile device would only broadcast a PSM when within a specified radius of the vehicle that is a function of the vehicle's speed. Furthermore, the system allowed multiple mobile device users to coordinate travel, and, in this situation, a "leader" and multiple "follower" mobile devices could be established. The leading device would continue to broadcast PSMs on behalf of the group, while other mobile devices would cease broadcast PSMs.

Finally, the prototype system design included a function so that a mobile device would only broadcast a PSM when positioned in an unsafe area, such as an active travel lane. One of the more important aspects of this project was to cease the transmission of PSMs when a mobile device was in a vehicle. When present in a vehicle, the mobile device no longer needs to broadcast PSMs because the traveler would be an occupant of the vehicle, and not a pedestrian (or another VRU), which is an inherent attribute of the PSM.

With regard to the transmission of PDMs, the traffic management system or TMC can use the roadside equipment to change the data collection from CAVs and connected mobile devices by modifying the PDM message. The message can be modified based on the data needs of the TMC at a given time. As probe data needs of a TMC decrease, it can specify that vehicles provide fewer data or stop providing data, to minimize the amount of information being sent wirelessly so that wireless bandwidth can be available to send other messages to ensure the system can continue to support other traveler's needs. This strategy also is used to minimize the amount of data that is consumed, processed, and archived by the TMC.

Issues to Consider

There may be issues that agencies need to consider about exchanging messages with mobile devices. Agencies may need to develop additional messages to meet the needs of travelers. If these messages are intended to be sent by a communications media such as DSRC or C-V2X, these messages will need to be prototyped and standardized so they are ready for use in an operational environment. Furthermore, message content and size should be thoughtfully considered to minimize the likelihood of wireless communications congestion.

CHAPTER 4. ENABLING TECHNOLOGIES, PROTOTYPES, AND PILOT DEPLOYMENTS

The objective of this chapter is to provide the reader with an understanding of how data are shared with travelers carrying mobile devices in practice. The sharing of electronic messages is a key component of any mobile device-based system. The ability to share electronic messages ultimately determines which traveler-based use cases can be supported and enables agencies and communities to improve safety and mobility and provide increased services to travelers that carry a mobile device. This chapter builds off the use cases and user needs in chapter 2 and the definition of mobile devices, communications, and applications in chapter 3 by considering the activities that have taken place that promote the development of mobile device communications and technology.

An agency can use the information in this chapter to understand intermediate devices that enable communications between existing infrastructure and mobile devices, and how mobile device communications have been used in prototype and deployments to provide safety and mobility benefits to travelers. These projects establish a foundation for agencies to build on when determining how electronic messages might be shared with mobile devices in practice to meet local user needs in the future.

Before determining how mobile devices can provide information to travelers to assist in decisionmaking, understanding the state of the practice of using mobile devices in a connected environment is essential. This chapter provides background on the following topics:

- **Interfacing Existing ITS Infrastructure with Mobile Devices.** Use of roadside equipment to exchange information between roadside ITS devices and mobile devices (via wireless V2I communications media, such as DSRC, C-V2X, cellular, and short-range wireless communications).
- **Mobile Device Prototypes and Deployments.** Use of mobile devices in CV pilot sites.
- **Integrating Emerging Data Sources into Operational Practice.** Integration of emerging data sources with traffic management systems (to help provide information to satisfy traveler needs).

Interfacing Existing ITS Infrastructure with Mobile Devices

The Integrated V2I Prototype, now known as the V2I Hub, is part of USDOT's V2I program and was developed to support jurisdictions in deploying V2I technology by reducing integration efforts and issues. The V2I Hub is a software platform that enables CVs to talk to existing traffic management hardware and systems, such as traffic signal controllers, TMCs, pedestrian and vehicle sensors, road weather sensors, and CMS. The V2I Hub simplifies integration by translating communication between different standards and protocols. The design of the V2I Hub allows for the use of software plugins that enable efficient connections to new hardware, custom connections to specialized systems, and CV safety apps to run on roadside equipment.

The V2I Hub, or its companion D2X Hub software can be located on the roadside, in a vehicle, or as part of a mobile device.

On the roadside, a computing device hosts the computing platform, and supports the exchange of electronic messages (such as SPaT, MAP, Radio Technical Commission for Maritime Services (RTCM), and BSM) between a number of devices on the roadside, including but not limited to a CV radio, traffic signal controller, CMS, and traffic management systems (via backhaul). The in-vehicle device provides an interface between a CV radio and a driver interface and could be used to receive vehicle telematics data from the vehicle's onboard diagnostics port. Finally, a mobile device composed of a smartphone with a DSRC or C-V2X (external or integrated) radio allows the device to use the combined functionality of both devices, including smartphone sensors, cellular connectivity, Wi-Fi, Bluetooth®, DSRC/C-V2X, and a visual, audio, and haptic interfaces with the user.

The key feature of the V2I Hub computing platform is its modular architecture and use of customizable plugins. This feature allows the solution to be tailored to suit the needs of agencies, drivers, and mobile device users, and allows an agency to easily expand or reconfigure the solution as needed. The plugins allow these devices to perform tasks such as obtain information from other local ITS devices, communicate information wirelessly with another wireless device, and process data to provide notification outputs to the user that improve safety and mobility when necessary. There are many plugins that have been developed that allow the Hub to interface with external hardware devices and to process data that is received from these external hardware devices. For a complete understanding of functions supported by the V2I Hub and D2X Hub, please refer to documentation available in the software download packages, available on the Open-Source Application Development Portal.^(54,55)

One aspect of the V2I Hub and D2X Hub is that it uses standardized inputs and outputs to improve its transferability and ease of integration with other existing transportation systems. For instance, the SPaT plugin uses the NTCIP 1202 protocol for communicating with traffic signal controllers. The CV message receiver and transmitter use the SAE J2735 standard for messages sent via CV. The system also uses standardized communications protocols, such as Ethernet (IEEE 802.3), DSRC (IEEE 802.11p), Wi-Fi (IEEE 802.11a,b,g,n,ac), Bluetooth (IEEE 802.15), 3G/4G LTE (CDMA and 3GPP), and 5G to allow wireless devices and external components to communicate with the V2I Hub or D2X Hub. (See references 56, 1, 57–58, 30, 2).

Mobile Device Prototypes and Deployments

Assessing mobile device-enabled applications that are being deployed may lead to a better understanding of the technology readiness and capabilities of mobile devices. To be deployed in a live operational environment, the behavior of functionalities in deployed devices must be well understood and trusted. The CV pilots in New York City, NY, and Tampa, FL, are both implementing mobile device-based applications as follows: Mobile Accessible Pedestrian Signal System and Pedestrian in Signalized Crosswalk Warning. Furthermore, PedSafe, one component of the Connecting the East Orlando Communities (Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) Grant Application) includes mobile devices in the CV environment.⁽⁵⁹⁾

Sharing Data Between Mobile Devices, Connected Vehicles, and Infrastructure (prototype)

The Sharing Data Between Mobile Devices, Connected Vehicles, and Infrastructure project demonstrated the ability of a mobile device to send and receive electronic messages (e.g., tethering smart phones with a DSRC radio in the 5.9 GHz spectrum).⁽⁵⁰⁾ The specific technology is not critical as long as it is interoperable with other mobile devices. Research has shown that this configuration of handheld mobile devices could further leverage electronic messages through direct device-to-device or device-to-infrastructure interfaces, which would increase the functionality available to both travelers and agencies.

As part of this project, a mobile device prototype was developed to demonstrate 15 mobile device functions, including but not limited to the following:

- Broadcasting PSMs.
- Detecting transitions from pedestrian to in vehicle.
- Ceasing broadcast of PSMs when in a vehicle.
- Broadcasting rate/range.
- Capturing and processing data from other devices to issue warnings to a traveler via the mobile device.
- Coordinating with other mobile device users for trip requests for transit service.

Mobile Accessible Pedestrian Signal System (Tampa, FL, CV Deployment, New York, NY, CV Deployment, Multimodal Intelligent Traffic Signal System)

The mobile accessible pedestrian signal system provides a generalized warning to vehicles of pedestrians in the roadway and support for visually impaired (blind) pedestrians. For the support for the blind, it is assumed that the application will be implemented using a portable personal device (e.g., smartphone) that supports both normal cellular operation and communications in the DSRC spectrum such that the pedestrian can monitor the messages associated with the CV applications and provide input to the traffic controller to request service where a pedestrian crossing request is activated. The general operation is to use the MAP and SPaT information received by the smart device to orient the pedestrian, assist the pedestrian in confirming the location (street and cross street), and provide verbal information regarding the signal state and, thus, improve the pedestrian's ability to safely cross the street. The pedestrian application also will allow the pedestrian to issue calls to the intersection using the DSRC and the J2735 messages that are normally used for the priority signal request management.^(60,61)

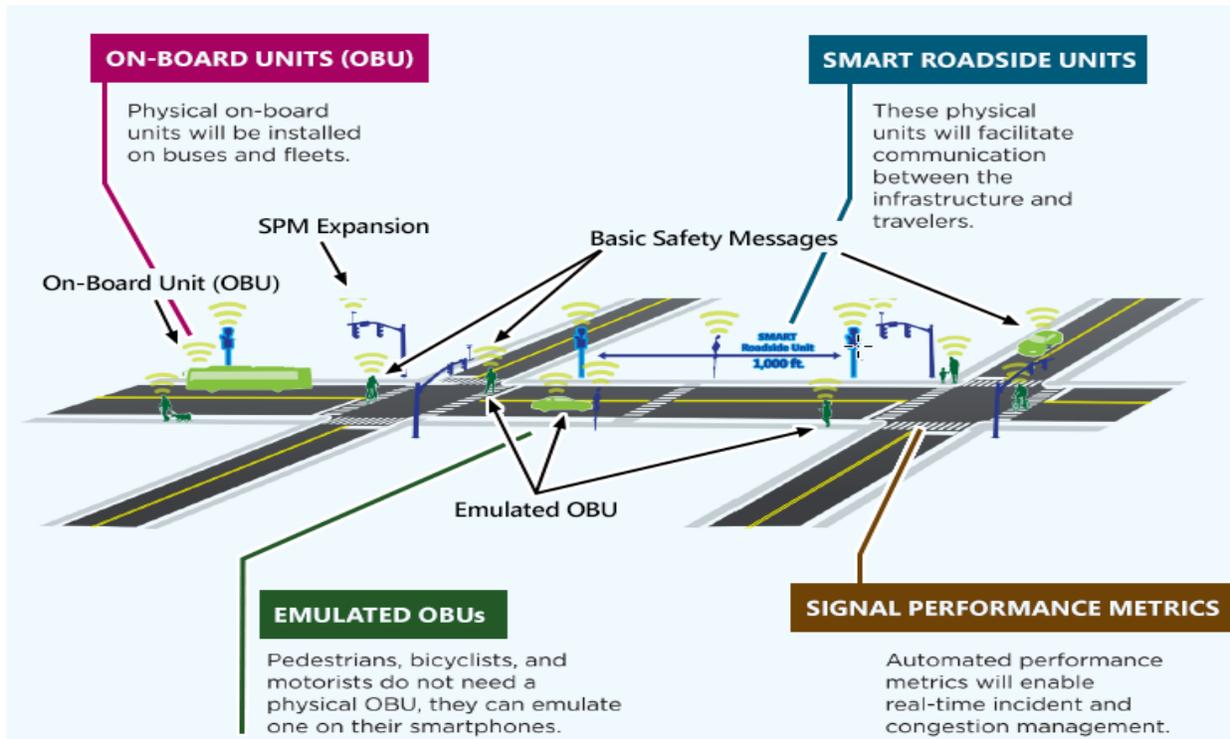
Pedestrian in Signalized Crosswalk Warning (Tampa CV Deployment, New York CV Deployment)

This application is enabled using pedestrian detection infrastructure and communication between a mobile device and the roadside infrastructure. As a pedestrian passes through a crosswalk at a signalized intersection with additional pedestrian detection equipment installed, the pedestrian's

presence will be detected by the traffic control system. The traffic control system will notify the vehicle of a pedestrian's presence in the crosswalk. At the same time, pedestrians who carry a mobile device will provide the pedestrians' locations to the roadside. The roadside equipment will, in turn, provide that information to in-vehicle devices. Drivers will become aware of pedestrians nearing their vehicle and will take action to avoid a conflict with the pedestrian. Pedestrians will become aware of a vehicle nearing them and will take action to avoid a conflict with the vehicle.

PedSafe

PedSafe will connect advanced traffic signal control through CVs to motorists, motorists' vehicles, bicycles, and pedestrians to reduce the occurrence of pedestrian and bicycle crashes. PedSafe is an innovative pedestrian and bicycle collision avoidance system currently being designed by the Florida Department of Transportation (FDOT).⁽⁶²⁾ PedSafe will connect advanced signal controller capability, use of CVs, and existing communication capabilities to reduce the occurrence of pedestrian and bicycle crashes. As a region and a State that annually tops the Dangerous by Design list of most dangerous areas for walking, development, and implementation of PedSafe is an immediate priority with multiple benefits.⁽⁶³⁾ The application will be easily transferable throughout the country.^(59,57) Figure 3 illustrates the PedSafe concept and defines high-level functions that are expected to be included in the final system.



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SPM = signal performance metrics.

Figure 3. Diagram. PedSafe concept.⁽⁵⁹⁾

Integrating Emerging Data Sources into Operational Practice

Data from ITS devices and emerging data from travelers, vehicles, infrastructure, and other sources is expected to transform how agencies manage their transportation systems. With the proper tools, agencies responsible for Transportation Systems Management and Operations (TSMO) can aggregate, store, and analyze new forms of traveler-related data that may be useful for operations. Primary sources of data today include traffic signals, ramp meters, CCTV, vehicle detection stations, incident data, and other sensors. The data from some of these sensors may be

appropriate to be shared with mobile device users. Thus, it will be important for any roadside device to be able to receive data feeds from mobile devices.

Many emerging transportation data sources use various communications media that could be accomplished with a mobile device. Connected traveler data are considered an emerging data source and is generally obtained through one of three methods: directly through an agency-branded application, indirectly through a third-party source, and indirectly through social media outlets. Many agencies make available 511 applications for smartphone users that typically push traveler information made available by a local or State TMC to travelers' smartphones.

Such applications can be leveraged, with appropriate privacy protocols, for collecting traveler data useful for TSMO activities. While most major regions only see a 2–3 percent adoption rate for 511 applications, it could be argued that adoption rates could be increased if new, location-based features and functionality were provided; in particular, features and functions that only TSMO agencies can provide. The value proposition would be to provide such functions in exchange for traveler behavior data, which could enhance TSMO activities.

The need for such data also is illustrated through partnerships that traffic management agencies make with third-party route planning services or third-party navigation software tools. In this case, the traveler installs an application on their smartphone to receive real-time traffic updates and route recommendations from a route planning service. In exchange, the application provides the location and speed of the smartphone inside of the vehicle back to the route planning service. This location and speed data are used to continuously update real-time traffic data, which can then be provided to the traffic management agency for use in various traffic management activities. Accessing data provided by such services generally requires payment.⁽⁶⁵⁾

The emerging data sources project also highlights the potential of capturing BSMs and probe data messages to improve traffic management capabilities. These messages, which would be broadcast by vehicles, would be received by roadside equipment when the vehicle and roadside equipment are within communications range of each other. Messages received at the roadside would then be forwarded to the TMC, where they would be parsed, processed, and used to support traffic management activities.

RFID is used in tolling, parking, weigh-in-motion checks, fuel dispensing, and fleet management applications. RFID tags contain a unique identifier that is separately linked to personal information, including but not limited to vehicle information, driver information, or account information. Infrastructure-based RFID radios detect the passage or presence of a vehicle with an RFID tag.

Furthermore, Wi-Fi and Bluetooth are used to perform probe travel time studies. To accomplish this, Wi-Fi and Bluetooth radios are placed at various locations of interest throughout the roadway network. These radios listen for the media access control (MAC) addresses of roaming Bluetooth- or Wi-Fi-enabled devices that are contained in vehicles on the roadway. MAC addresses obtained from a radio at one location can be matched against MAC addresses obtained from a radio at a second location to obtain a travel time. Because RFID information and MAC addresses are unique, there are generally issues associated with personal identifiable information

that must be overcome when public agencies are considering using such data for traffic management purposes.

These emerging data sources provide benefits to traffic management. Potential real-time and near-real-time benefits include the following:

- Realtime: Roadway hazard monitoring, speed warning, cooperative intersection collision systems, probe data collection, and electronic payment.
- Near realtime: Traffic incident management, signal control, metering, lane management, traffic information, weather monitoring, and parking management.⁽⁶⁶⁾

To take advantage of all the CV data that is expected to become increasingly available, edge processing will be necessary to significantly reduce demand for storage at the TMC and communication bandwidth between the roadside and the TMC. These data could even entail performing functions that are traditionally performed at the TMC at the roadside. Such functions are capable of being supported by the V2I Hub (see the section Interfacing Existing ITS Infrastructure with Mobile Devices) and customized plugins can be created to perform these required functions.⁽⁵⁴⁾

CHAPTER 5. IMPACTS DURING DEVELOPMENT

This chapter identifies known limitations of platforms developed as part of other related projects that may have an impact on the outcome of a mobile device deployment such as the V2I Hub and D2X Hub that have the potential to impact plans to develop a mobile device-based system. Data privacy aspects that a local agency may need to consider when developing a mobile device-based system also is provided.

Updates are continuously being made to the V2I Hub and D2X Hub.^(54,55) As these software platforms are used in prototype development for other projects (such as Transit Bus Stop Pedestrian Warning and Enhanced Transit Retrofit Package), additional plugins or fixes to the current ones are being incorporated to meet the requirements and design of those prototype systems. These plugin additions and modifications could potentially be useful for meeting the needs of travelers.

For instance, researchers that performed testing for the D2X Hub several years ago found that several issues were present during testing and recommended the following improvements:

- Addressing time synchronization issues. All devices must be time synchronized to the accuracy of milliseconds so that data being sent between devices can be related temporally or how messages can be used if no time is identified.
- Investigating the future communication methods and protocols (such as C-V2X, 5G, and Android Neighbor Aware Networking) and how they can be integrated into the new software platform to be developed.
- Integrating passenger drop-off location in the trip scheduling in the smartphone and in-vehicle device API.
- Incorporating more advanced media switching strategies into the platform to enable automated switching between different communication mediums (e.g., DSRC, Wi-Fi, Bluetooth, cellular, 5G) to support ensuring messages are sent and received as conditions warrant.
- Improving mobile devices sending PSMs and PMMs when in vehicle and on foot, which are appropriate based on the specific mode of travel.
- Ensuring the functionality and performance of the software APIs is maintained as the number of users increases substantially. The D2X Hub software was tested using only one vehicle and 12 mobile devices. More mobile devices also are needed to gain a better understanding of the benefits of informal travel groups and how this functionality can be used to coordinate and reduce the number of messages that are being sent.

- Adding the software or APIs needed for functionality to allow another group leader to be initiated in case the travel group leader’s mobile device crashes or if the leader leaves the group. Currently, the cloud service handles the grouping of travelers. If coordination is still desired, then that coordination also should allow peer-to-peer coordination to occur using Bluetooth, Wi-Fi, DSRC, or C–V2X.
- Changing the timeout period for a heartbeat response, as this change causes some groups to “hang,” resulting in problems with subsequent trip requests.
- Adjusting the algorithm to provide the notification on a more consistent basis because the arrival message did not initiate due to the bus stopping beyond the arrival zone.
- Using non-Android smartphone and mobile device operating systems (e.g., iOS and Windows® Phone would vastly improve the market for these applications for testing that is expected to occur in the future).
- Adding functionality to allow taxi, transit, or shared mobility drivers to manage trip requests on the devices they may be using.
- Experimenting with various virtual roadway buffers to account for inaccuracy in mobile device positioning capability. This buffer will ensure with high probability that a mobile device will broadcast safety messages when in the roadway.

The D2X Hub is expected to be a starting point from which future development pertaining to mobile devices will emanate. Thus, these recommended improvements should be strongly considered because they will impact any system conceptualized.

Furthermore, stakeholders must consider potential privacy implications of transmission, handling, and sharing of route planning data, fare payment, and ride-sourcing information. This consideration is especially true for agencies that deploy technologies to foster the sharing of this type of information. All agencies will need to develop an approved data privacy and security plan to ensure that potentially identifiable data they touch is handled in a manner that preserves the privacy of individuals and other stakeholders that leverage the mobile device-enabling technologies deployed by the agency.

REFERENCES

1. IEEE. 2024. “Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments” (web page). <https://standards.ieee.org/ieee/802.11p/3953/>, last accessed February 20, 2024.
2. Third Generation Partnership Project (3GPP). 2024. “Specifications and Technologies Release 14” (web page). <https://www.3gpp.org/specifications-technologies/releases/release-14>, last accessed February 20, 2024.
3. USDOT. 2020. “Architecture Reference for Cooperative and Intelligent Transportation” (web page). <https://www.arc-it.net/>, last accessed February 14, 2024.
4. FHWA. 2023. “MUTCDs & Traffic Control Devices Information by State” (web page). https://mutcd.fhwa.dot.gov/resources/state_info/index.htm, last accessed March 2, 2023.
5. USDOT. 2024. “Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) Version 9.2—TI07: In-Vehicle Signage” (web page). <https://www.arc-it.net/html/servicepackages/sp115.html>, last accessed February 20, 2024.
6. USDOT. 2024. “Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) Version 9.2—TM10: Electronic Toll Collection” (web page). <https://www.arc-it.net/html/servicepackages/sp109.html>, last accessed February 20, 2024.
7. USDOT. 2024. “Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) Version 9.2—PT15: Transit Stop Request” (web page). <https://www.arc-it.net/html/servicepackages/sp80.html>, last accessed February 20, 2024.
8. USDOT. 2024. “ARC-IT Version 9.2. PT04 Transit Fare Collection Management” (web page). <https://www.arc-it.net/html/servicepackages/sp154.html>, last accessed February 8, 2024.
9. Pierce, B., E. Plapper, J. Rizek, and Battelle Memorial Institute. 2016. *Accessible Transportation Technologies Research Initiative (ATTRI): User Needs Assessment: Stakeholder Engagement Report*. Report No. FHWA-JPO-16-354. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/31320>, last accessed February 26, 2024.
10. FHWA. 2012. *Manual on Uniform Traffic Control Devices for Streets and Highways—2009 Edition, including Revision 1 dated May 2012 and Revision 2 dated May 2012*. Washington, DC: Federal Highway Administration. <https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/mutcd2009r1r2edition.pdf>, last accessed February 26, 2024.

11. SAE International. 2023. *V2X Communications Message Set Dictionary*. SAE J2735_202309 Revised 2023-09-22. Warrendale, PA: SAE International. https://www.sae.org/standards/content/J2735_202309/, last accessed February 8, 2024.
12. Fitzpatrick, K., M. A. Brewer, S. Chrysler, N. Wood, B. Kuhn, G. Goodin, C. Fuhs, et al. 2016. *Guidelines for Implementing Managed Lanes*. NCHRP Research Report 835. Washington, DC: Transportation Research Board. <https://nap.nationalacademies.org/catalog/23660/guidelines-for-implementing-managed-lanes>, last accessed March 2, 2023.
13. Dudek, C. L. 2008. *Changeable Message Sign Displays During Non-Incident, Non-Roadwork Periods*. NCHRP Synthesis 383. Washington, DC: Transportation Research Board. <https://nap.nationalacademies.org/catalog/23070/changeable-message-sign-displays-during-non-incident-non-roadwork-periods>, last accessed March 1, 2023.
14. Kuhn, B., L. Higgins, A. Nelson, M. Finley, G. Ullman, S. Chrysler, K. Wunderlich, V. Shah, and C. Dudek. 2014. *Effectiveness of Different Approaches to Disseminating Traveler Information on Travel Time Reliability*. Strategic Highway Research Program 2 (SHRP 2) Report S2-L14-RW-1. Washington, DC: Transportation Research Board. https://transops.s3.amazonaws.com/uploaded_files/SHRP2%20S2-L14-RW-1.pdf, last accessed March 2, 2023.
15. Kuhn, B., L. Higgins, A. Nelson, M. Finley, G. Ullman, S. Chrysler, K. Wunderlich, V. Shah, and C. Dudek. 2014. *Lexicon for Conveying Travel Time Reliability Information*. SHRP 2 Report S2-L14-RW-2. Washington, DC: Transportation Research Board. <https://nap.nationalacademies.org/catalog/22604/lexicon-for-conveying-travel-time-reliability-information>, last accessed March 2, 2023.
16. Lunenfeld, H., and G. J. Alexander. 1990. *A User's Guide to Positive Guidance*. 3rd edition. Publication No. FHWA-SA-90-017. Washington, DC: Federal Highway Administration.
17. Schweiger, C. L. 2003. *Transit Cooperative Research Program (TCRP) Synthesis 48—Real-Time Bus Arrival Information Systems—A Synthesis of Transit Practice*. Washington, DC: Transportation Research Board. https://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_syn_48.pdf, last accessed March 2, 2023.
18. Office of the Federal Register, National Archives and Records Administration. 1990. *Americans With Disabilities Act of 1990*. Public Law 101-336. Washington, DC: U.S. Government Publishing Office. <https://www.govinfo.gov/content/pkg/STATUTE-104/pdf/STATUTE-104-Pg327.pdf>, last accessed January 22, 2024.
19. Federal Transit Administration. 2016. *The ADA and Fixed Route Service Requirements (FTA ADA Circular Webinar 3)*. (Webinar slides). <https://www.transit.dot.gov/regulations-and-guidance/civil-rights-ada/ada-and-fixed-route-service-requirements-fta-ada-circular>, last accessed March 2, 2023.

20. Sorensen, J., S. Murtha, M. Waisley. and C. Toth. 2016. *A Next Generation Advanced Traveler Information Precursor System (ATIS 2.0 Precursor System) Concept of Operations*. Report No. FHWA-JPO-17-481. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/32050>, last accessed March 2, 2023.
21. USDOT. n.d. “Office of the Assistant Secretary for Research and Technology Intelligent Transportation Systems Joint Program Office—Data Capture and Management (DCM)” (web page). https://www.its.dot.gov/research_archives/data_capture/index.htm, last accessed February 20, 2024.
22. StatCounter. 1999–2024. “Mobile Operating System Market Share United States of America” (web page). <https://gs.statcounter.com/os-market-share/mobile/united-states-of-america>, last accessed February 20, 2024.
23. SAE International. 2024. *On-Board System Requirements for V2V Safety Communications*. SAE J2945/1_202004, 2020-04-30 revision. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2945/1_202004/, last accessed February 10, 2024.
24. IEEE. 2024. *IEEE Standard for Wireless Access in Vehicular Environments—Security Services for Application and Management Messages*. IEEE 1609.2-2022, 2023-03-20 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/1609.2/10258/>, last accessed February 20, 2024.
25. IEEE. 2024. *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)—Networking Services*. IEEE 1609.3-2020, 2021-03-09 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/1609.3/10360/>, last accessed February 20, 2024.
26. IEEE. 2024. *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)—Multi-Channel Operation*. IEEE 1609.4-2016, 2016-03-21 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/1609.4/6183/>, last accessed February 20, 2024.
27. USDOT. n.d. “The Safety Band #SafetyBand” (web page). <https://www.transportation.gov/content/safety-band>, last accessed February 20, 2024.
28. FCC. 2019. *In the Matter of Use of the 5.850-5.925 GHz Band*. Docket No. 19-138. Washington, DC: Federal Communications Commission. <https://docs.fcc.gov/public/attachments/FCC-19-129A1.pdf>, last accessed February 20, 2024.
29. NIST. n.d. “Code Division Multiple Access (CDMA)” (web page). https://csrc.nist.gov/glossary/term/code_division_multiple_access, last accessed February 20, 2024.
30. 3GPP Global Initiative. 2024. “Specifications and Technologies—Release 16.” (web page). <https://www.3gpp.org/specifications-technologies/releases/release-16>, last accessed February 20, 2024.

31. U.S. Space Force. 2023. “GPS: The Global Positioning System” (web page). <https://www.gps.gov/>, last accessed February 20, 2024.
32. Russian Federation. n.d. “About GLONASS” (web page). <https://www.glonass-iac.ru/en/>, last accessed February 20, 2024.
33. European Union Agency for the Space Programme. 2024. “Galileo Is the European Global Satellite-Based Navigation System” (web page). <https://www.euspa.europa.eu/european-space/galileo/What-Galileo>, last accessed February 26, 2024.
34. China National Space Administration. n.d. “BeiDou Navigation Satellite System” (web page). <http://en.beidou.gov.cn>, last accessed February 10, 2024.
35. IEEE Standards Association. 2024. *IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks—Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN*. IEEE 1802.11ax-2021, 2021-05-019 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/802.11ax/7180/>, last accessed February 10, 2024.
36. ISO. n.d. *Cards and Security Devices for Personal Identification*. ISO/IEC 15693-3:2019, 2019-04 revision. Geneva, Switzerland: ISO. <https://www.iso.org/standard/73602.html>, last accessed February 10, 2024.
37. ISO. n.d. *Cards and Security Devices for Personal Identification*. ISO/IEC 14443-4:2018, 2018-06 revision. Geneva, Switzerland: ISO. <https://www.iso.org/standard/73599.html>, last accessed February 10, 2024.
38. Smart Card Alliance. 2024. “Transit Open Payments Resources” (web page). <http://www.smartcardalliance.org/smart-cards-applications-transit-open-payments-resources/>, last accessed February 27, 2024.
39. King County METRO. 2024. “Transit GO Ticket” (web page). <https://kingcounty.gov/depts/transportation/metro/fares-orca/transit-go-ticket.aspx>, last accessed February 27, 2024.
40. Pierce, B., R. Brooks, T. Timcho, R. Zimmer, C. Toth, S. Nallamotheu, and J. Rosenbohm. 2016. *Sharing Data Between Mobile Devices, Connected Vehicles and Infrastructure Task 3: Concept of Operations*. 2nd revision. Report No FHWA-JPO-16-422. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/31815>, last accessed February 27, 2024.
41. Transit. n.d. *Transit App* (software). <https://transitapp.com/>, last accessed, February 10, 2024.

42. Mobility Data. n.d. “GTFS: Making Public Transit Data Universally Accessible” (web page). <https://gtfs.org/>, last accessed February 10, 2024.
43. Mobility Data. n.d. “GTFS Realtime Reference” (web page). <https://gtfs.org/realtime/reference/>, last accessed February 10, 2024.
44. USDOT Intelligent Transportation Systems Joint Program Office. n.d. “Integrated Dynamic Transit Operations (IDTO)” (web page). https://www.its.dot.gov/research_archives/dma/bundle/idto_plan.htm, last accessed February 10, 2024.
45. Open Trip Planner. n.d. “Open Trip Planner” (web page). <http://www.opentripplanner.org/>, last accessed February 27, 2024.
46. SAE International. 2016. *Dedicated Short Range Communications (DSRC) Message Set Dictionary*. J2735_201603, 2016-03-30 revision. Warrendale, PA: SAE International. https://www.sae.org/standards/content/j2735_201603/, last accessed March 2, 2023.
47. ETSI. 2010. *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service*. ETSI TS 102 637-3 V1.1.1 (2010-09). Sophia Antipolis Cedex, France: ETSI. http://www.etsi.org/deliver/etsi_ts/102600_102699/10263703/01.01.01_60/ts_10263703v010101p.pdf, last accessed March 2, 2023.
48. Google[®] Transit. 2022. “GTFS Realtime Overview” (web page). <https://developers.google.com/transit/gtfs-realtime/>, last accessed March 2, 2023.
49. Timcho, T., D. Stephen, C. Toth, M. Burns, and J. Rosenbohm. 2016. *Sharing Data Between Mobile Devices, Connected Vehicles, and Infrastructure—Task 3: System Requirements Specifications (SyRS)*. Report No. FHWA-JPO-16-423. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/31816>, last accessed March 1, 2023.
50. Sumner, R., D. Gettman, A. Toppen, and J. Obenberger. 2018. *Integrating Emerging Data Sources Into Operational Practice—Capabilities and Limitations of Devices to Collect, Compile, Save, and Share Messages From Connected and Automated Vehicles and Connected Travelers*. Report No. FHWA-JPO-18-626. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/34985>, last accessed March 2, 2023.
51. FHWA. 2023. *V2I Hub* (software). Version 3.2.1. <https://github.com/OSADP/V2I-Hub>, last accessed January 24, 2024.
52. FHWA. 2017. *D2X Hub* (software). https://github.com/OSADP/Mobile_D2X_Framework, last accessed March 9, 2023.

53. IEEE. 2018. *IEEE Standard for Ethernet*. IEEE 802.3-2018. 2018-08-31 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/802.3/7071/>, last accessed February 10, 2024.
54. IEEE. 2023. "The Evolution of Wi-Fi Technology and Standards" (web page). <https://standards.ieee.org/beyond-standards/the-evolution-of-wi-fi-technology-and-standards/>, last accessed February 10, 2024.
55. IEEE. 2018. *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 15.1a: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Wireless Personal Area Networks (WPAN)*. IEEE 802.15.1-2005, 2005-06-14 revision. New York City, NY: IEEE. <https://standards.ieee.org/ieee/802.15.1/3513/>, last accessed February 10, 2024.
56. FDOT, MetroPlan Orlando, and the University of Central Florida. 2017. *Connecting the East Orlando Communities Volume 1—Technical Application*. Orlando, FL: FDOT. <https://www.cflsmarthighways.com/projects/design/future/FDOT-2017-ATCMTD-Vol-1.pdf>, last accessed March 1, 2023.
57. Galgano, S., M. Talas, D. Benevelli, R. Rausch, S. Sim, K. Opie, M. Jensen, and C. Stanley. 2021. *Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps)—New York City*. Report No. FHWA-JPO-16-299. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/30881>, last accessed March 2, 2023.
58. Waggoner, J., B. Frey, S. Novosad, S. Johnson, V. Blue, D. Miller, and S. Bahler. 2016. *Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps)—Tampa (THEA)*. Report No. FHWA-JPO-16-311. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/3588>, last accessed March 2, 2023.
59. FDOT. 1996–2022. "ATTAIN Central Florida" (web page). <https://www.fdot.gov/traffic/teo-divisions.shtm/cav-ml-stamp/cv/maplocations/attain-central-florida>, last accessed February 27, 2024.
60. Smart Growth America. 2022. "Dangerous by Design." (web page). <https://smartgrowthamerica.org/dangerous-by-design/>, last accessed February 10, 2024.
61. Dilmore, J. 2017. "FDOT & Orlando ATCMTD Grant." *TSM&O Disseminator* September–October 2017. Tallahassee, FL: FDOT. <http://www.fdot.gov/traffic/NewsLetters/2017/2017-Oct.pdf#page=6>, last accessed March 2, 2023.
62. Gettman, D., K. Hales, A. Voss, A. Toppen, and B. Tumati. 2016. *Integrating Emerging Data Sources into Operational Practice: State of the Practice Review*. Report No. FHWA-JPO-16-424. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/35143>, last accessed March 2, 2023.

63. Gettman, D., A. Toppen, K. Hales, A. Voss, S. Engel, and D. El Azhari. 2017. *Integrating Emerging Data Sources Into Operational Practice—Opportunities for Integration of Emerging Data for Traffic Management and TMCs*. Report No. FHWA-JPO-18-625. Washington, DC: Federal Highway Administration. <https://rosap.ntl.bts.gov/view/dot/34175>, last accessed March 2, 2023.



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