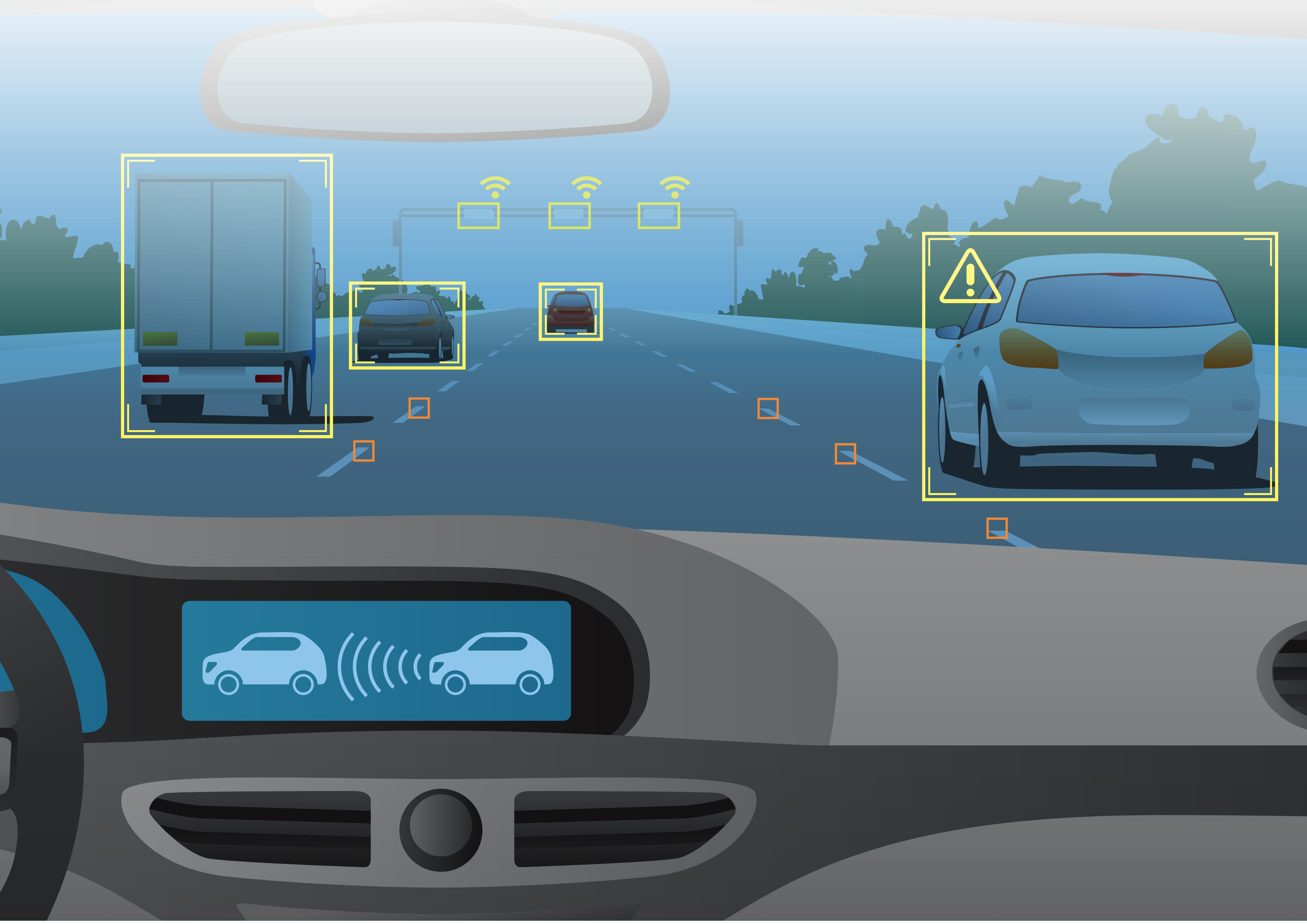
U.S. Department of Transportation
Federal Highway Administration

Leveraging the Promise of Connected and Autonomous Vehicles to Improve Integrated Corridor Management and Operations:

A PRIMER



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16. Abstract This primer examines connected and automated vehicles (CAV) and how the advent of this new technology can be incorporated into an integrated corridor management (ICM) approach. It also looks at ways ICM can address the challenges and opportunities of CAV. In addition, the document explores opportunities to effectively integrate CAV institutionally, operationally, and technically, both by leveraging existing platforms and considering options for coordination between ICM and CAV stakeholders. While integrating CAV and ICM holds great promise for more efficient operations on both ends, it is not without challenges. This document explores these challenges and how they can be overcome.		
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INTRODUCTION

The greatest concentration of a transportation system's typical operational challenges—congestion, accidents, lack of reliability, and pollution—have a propensity for occurring along critical corridors that link residential areas, business districts, and entertainment and shopping venues. Integrated corridor management (ICM), defined as a set of policies and procedures for coordinating transportation operations in order to improve travel management, is a key strategy for addressing these challenges. ICM enables infrastructure operators to optimize their available space by directing travelers to underused or more reliable capacity in a transportation corridor. These strategies may include encouraging shifts in users' trip departure times, routes, or modal choices. Other strategies may involve dynamically adjusting capacity by changing metering rates at entrance ramps or adjusting signal timings to accommodate fluctuating demand. In an ICM corridor, travelers can even shift their mode of travel during their trip in response to changing conditions.

The practice of ICM is about more than operations; it involves constant analysis, modeling, and even simulation and testing in an effort to stay abreast of the latest means and methods to improve performance. Today, this includes connected and automated vehicles (CAV). CAV promises exciting ways for the ICM community to improve the safety, mobility, environmental performance, and organizational efficiency on major travel corridors. This document provides a basic background on CAV to the ICM community and provides guidance about the institutional, operational, and technical integration of CAV into the ICM paradigm.

Who should read this primer?

The intended audience for this primer includes:

- Transportation operations professionals who manage components of a corridor and who find themselves under increasing pressure to do more with less in the face of static budgets, increased demand for transportation services and growing customer expectations.
- Facility operators who are aware that rapid advances in technology mean more opportunities to operate their facilities better – and those who see connected and autonomous vehicles (CAV) as a tremendous opportunity to enhance, if not completely reshape, current approaches to corridor management.
- Practitioners who agree that CAV-enabled integrated corridor management (ICM) strategies depend equally on building relationships and deploying technologies, and that new partners in the CAV community must be at the table to meet the challenges of integrating CAV into ICM.

The vision of ICM is that transportation networks will realize significant improvements in the efficient movement of people and goods through institutional collaboration and aggressive, proactive integration of existing infrastructure along major corridors. Through an ICM approach, transportation professionals manage the corridor as a multimodal system and make operational decisions for the benefit of the corridor as a whole.[1] Just as ICM represented an innovative approach to transportation when it began in 2006, CAV

1 USDOT, Intelligent Transportation Systems Joint Program Office, "Intermodal Research: Integrated Corridor Management" Web page. Available at: http://www.its.dot.gov/research_archives/icms/index.htm.

similarly offers unprecedented opportunities to integrate new thinking, new methods, and new technologies into ICM. This primer examines the impacts of CAV on the transportation system and suggests ways this technology can be incorporated into an ICM approach. It explores opportunities to effectively integrate CAV institutionally, operationally, and technically, both by leveraging existing platforms and considering options for coordination between ICM and CAV stakeholders. Lastly, although integrating CAV and ICM holds great promise for more efficient operations on both ends, it is not without challenges. This document explores these challenges and how they can be overcome.

BACKGROUND

The Integrated Corridor Management Research Initiative

The USDOT formally began its ICM research initiative in 2006 to explore and develop ICM concepts and approaches and to advance the deployment of ICM systems throughout the country. Initially, eight pioneer sites were selected to develop concepts of operations (ConOps) and system requirements for ICM on a congested corridor in their region. Three of these sites went on to conduct analysis, modeling, and simulation (AMS) for potential ICM response strategies on their corridor. In the final stage, two sites – the US-75 Corridor in Dallas, Texas, and the Interstate-15 (I-15) corridor in San Diego, California – were selected to design, deploy, and demonstrate their ICM systems.

> **FHWA ICM Program Information:**
>
> http://www.its.dot.gov/research_archives/icms/index.htm

The Dallas and San Diego demonstrations "went live" in the Spring of 2013. Each demonstration has two phases: 1) design and deployment, and 2) operations and maintenance. Both sites chose to develop a decision support system (DSS) as a technical tool to facilitate the application of institutional agreements and operational approaches that corridor stakeholders agreed to over a rigorous planning and design process.

In 2015, 13 other regional corridors were awarded grants to develop pre-implementation ICM foundations. Although the demonstration sites provide valuable insights into the necessary components of building an ICM system, they do not represent the only way to implement ICM. There is no "one-size-fits-all" approach to ICM, since the circumstances of a particular corridor will vary based on traffic patterns, agency dynamics, available assets, and a host of other factors. Thus, the Federal Highway Administration (FHWA) is committed to raising awareness for ICM through their knowledge and technology transfer program, which advances the implementation and integration of ICM with other concepts.

CONNECTED AND AUTOMATED VEHICLES

Forms of connected and automated vehicles are here now: automated driving features are seen in entry-level vehicles, and Google's Self Driving Car Project has logged 1.5 million miles. But to some degree, the CAV arrived when General Motors first offered OnStar in its 1997 Cadillac branded-vehicles. CAV was also evident in 2008, the first time drivers used smartphones to download Waze, a crowd-sourced smartphone traffic app that infers real-time travel conditions. While the pace of CAV advancement makes a static chart quickly outdated, there is general consensus on the four main stages of the concept that connects them all, called "connected mobility," and all of them overlap. The stages of connected mobility, or levels of autonomy, are explained below to illustrate, in a very simple way, a rough timeline of CAV and connected mobility:

1. **Connected Drivers** are defined as drivers who "carry in" their communications technology. This concept came to be when smartphones gained a significant market share (around 2008) and drivers began to use new crowd-sourced traffic applications, or "apps," such as Waze (www.waze.com) to help navigate.

2. **Connected Vehicles** technically arrived in 1997 with the advent of General Motor's embedded Global Positioning System (GPS) and cellular-based OnStar solution.[2] Next came satellite and internet connectivity, including embedded cellular, for the purposes of infotainment, streaming music and concierge services such as Ford Sync, as well as wirelessly transmitted updates for vehicle software. These are not considered to be true "connected vehicles" by those in the transportation operations community because of the inability of such vehicles to "cooperate" with others to provide applications in vehicle and pedestrian safety, emissions management, and traffic management.

Connected and Automated Vehicle Applications

1. **Traffic Safety** – In-vehicle traffic hazard warnings, intelligent speed adaption (automated cruise control and cooperative cruise control), lane departure warning, automatic braking, e-call services.
2. **Traffic Efficiency** – Travel planning, traffic management, event and incident notifications and re-routing, traffic alerts, eco-driving.
3. **Vehicle Interaction** – Remote diagnostics and software updates, service calls, charging support for electric/hydrogen vehicles.
4. **Fees & Charges** – Road usage charging, usage based auto insurance, congestion management fees and access control.
5. **Infotainment** – In-car entertainment, personal information management, location-based services (advertisements and points of interest).

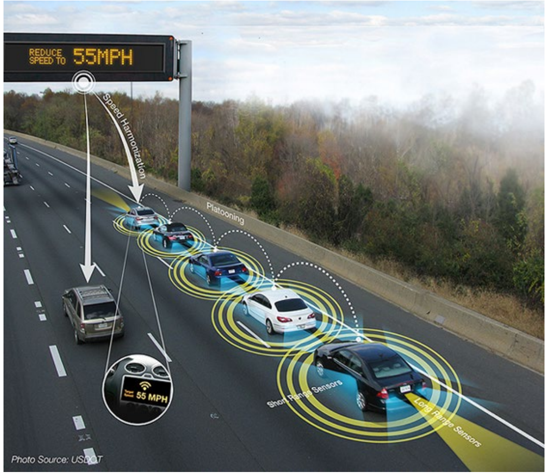
2 General Motors, "GM Heritage Center - OnStar" Web page. Available at: https://history.gmheritagecenter.com/wiki/index.php/OnStar.

3. **Automated Vehicles**, the penultimate step in connected mobility, are vehicles with computers that replace the human driver in some aspect of vehicle operation and control. In the context of this primer, the related application is autonomous (or adaptive) cruise control, where the vehicle automatically speeds up, slows down, or stops in response to other vehicle movements in the traffic stream. The first examples of this technology appeared in in luxury vehicle brands such as Jaguar and Mercedes Benz in the late 1990s; since then, automation has moved from luxury vehicles to entry level cars like the 2016 Honda Civic, which offers its Lane Keeping Assist System and adaptive cruise control.

Source: U.S. Department of Transportation

Figure 1. Illustration. Connected vehicles can help to prevent crashes at busy intersections.

4. **Autonomous Vehicles** are the final frontier of connected mobility and incorporate connectivity and/or automation to allow vehicles to operate anywhere with no human assistance whatsoever. Some manufacturers even envision vehicles without steering wheels or gas and brake pedals. There are three general autonomous vehicles types:
    1. Those that operate autonomously – meaning they do not have two-way communication with any other vehicle or road side equipment (RSE).
    2. Those that operate cooperatively and "talk" only with other similarly equipped vehicles.
    3. Those using a combination of 1 and 2, but which also communicate with RSE. Today, most advances are in categories 1 and 2 because the necessary RSE infrastructure is not built.



Source: U.S. Department of Transportation

Figure 2. Illustration. Platooning uses cooperative adaptive cruise control to improve traffic flow stability.

Regulatory and Government Enablers

The Federal government influences, directs, and in essence enables CAV primarily by its funding for research, development, and testing related to CAV standards, technologies, and applications; advancing key rulemakings; and providing guidance and architectures that inform and instruct deployment communities. New technologies to enable vehicle automation have largely been driven by the private sector, including both traditional auto manufacturers and the new "disrupter" businesses in the CAV market, which include companies such as Google, Apple, and Uber. In contrast, connected vehicle technologies have been driven largely by the regulatory and government efforts which are described in Table 1 below.

Table 1. Connected vehicle deployment driven by the regulatory and government efforts.

Project	Dates	Technology	More Information
Federal Communications Commission (FCC) Frequency Allocation	1999	Dedicated short-range communications (DSRC)	In 1999, the FCC allocated 75MHz of unlicensed radio spectrum in the 5.9GHz band to "intelligent transportation systems," or ITS, requiring these systems to share the spectrum on a co-primary basis subject to coordination.
Standards Development	2000-Present	Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I)	Standards development organizations such as International Organization for Standardization, Institute of Electrical and Electronics Engineers, and Society of Automotive Engineers developed the physical communication and application layer standards for DSRC-enabled V2V and V2I communication under the umbrella term "Vehicle Infrastructure Integration." The development programs were supported by the U.S. Department of Transportation (USDOT).
Connected Vehicle Test Beds	2007-Present	Connected vehicle test beds	The USDOT supported DSRC-based V2V and V2I connected vehicle test facilities, beginning with simple proof of concept testing, then expanding in 2010 to the "Michigan Test Bed," with 3000 vehicles and a suite of apps. This was followed by the Affiliated Test Bed Concept, which still receives Federal funding.

Table 1. Connected vehicle deployment driven by the regulatory and government efforts (continued).

Project	Dates	Technology	More Information
Deployment Guidelines	2014-Present	Connected and automated vehicle (CAV) deployment	The Federal Highway Administration is influencing CAV by incorporating results and lessons-learned from their various test experiences into a set of comprehensive deployment guidelines that advance an integrated approach to CAV deployment.
V2V Rulemakings	2014-2015	Requirement of V2V devices in new light vehicles	In August 2014, USDOT and National Highway Traffic Safety Administration (NHTSA) released an Advance Notice of Proposed Rulemaking (ANPRM) and research report regarding V2V communications. The ANPRM seeks public input to support the agency's regulatory work to eventually require V2V devices in new light vehicles. USDOT Secretary Anthony Foxx announced in May 2015 that he is accelerating the NHTSA schedule to require V2V devices on new vehicles.
Connected Vehicle Reference Implementation Architecture (CVRIA)	2013-Present	Unifying framework and common language for connected vehicle applications	The USDOT supported the creation of this architecture, the CVRIA, to provide a unifying framework and common language for the development and deployment of a wide variety of connected vehicle applications.
Connected Vehicle Pilots	2015-Present	Connected vehicle pilot deployments in Tampa, FL, Wyoming, and New York City to demonstrate various CAV technologies	USDOT ITS Joint Program Office awarded three 12-month connected vehicle pilot deployments to teams representing Tampa, FL, Wyoming, and New York City. These pilot deployments will demonstrate various CAV technologies and application in conformance to the Deployment Guidelines and CVRIA; USDOT has also put out an opportunity to evaluate these and other deployment sites (as of May 2016).

Connected Vehicle Deployment Status

From facility- and corridor-specific tests conducted by one primary organization, to city-wide integrated mobility concepts deployed cooperatively by diverse teams with USDOT technical and financial support, the scope and breadth of connected vehicle pilots shows that CAV can be a natural extension – the next step, if you will – in integrated corridor management. Below are a handful of CAV pilot initiatives and brief descriptions.

> **FHWA Connected Vehicle Resources:**
>
> http://www.its.dot.gov/landing/cv.htm

- USDOT ITS Joint Program Office (JPO) Connected Vehicle (CV) Pilot Deployment Program:
  - The Tampa Hillsborough Expressway Authority will use CAV to solve peak rush hour congestion in downtown Tampa and to protect the city's pedestrians by equipping their smartphones with the same connected technology being put into the vehicles. Tampa also committed to measuring the environmental benefits of using this technology.[3]
  - The New York City Metropolitan Transportation Commission will install vehicle-to-vehicle (V2V) technology in 10,000 city-owned vehicles, cars, buses, and limousines that frequently travel in Midtown Manhattan, and it will install vehicle-to-infrastructure (V2I) technology throughout Midtown. This includes upgrading traffic signals with V2I technology between 14th Street and 66th Street in Manhattan and Brooklyn. Additionally, roadside units will be equipped with connected vehicle technology along FDR Drive between 50th Street and 90th Street.[4]
  - The Wyoming Department of Transportation (WYDOT) pilot focuses on the efficient and safe movement of freight through the I-80 east-west corridor, which is critical to commercial heavy-duty vehicles moving across that part of the country. Approximately 11,000 – 16,000 vehicles travel the corridor daily. Using V2V and V2I applications, WYDOT will collect information and disseminate it to vehicles not equipped with the new technologies.[5]
- A Colorado Department of Transportation (CDOT) CV test on I-70 will equip more than 700 CDOT, first responder, ski shuttle, and commercial vehicles with dedicated short-range communications (DSRC) devices to transmit information on road conditions, traffic and closures. The devices will also be installed on roadside infrastructure to collect data on vehicle speed and incidents. The goal is to make trips across the corridor more efficient and improve traffic by informing drivers and vehicles about upcoming hazards. CDOT will invest $10 million over the next several years.

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3 USDOT, Intelligent Transportation Systems Joint Program Office, "U.S. Department of Transportation Announces up to $42 Million in Next Generation Connected Vehicle Technologies," press release issued September 14th, 2015. Available at: http://www.its.dot.gov/press/2015/ngv_tech_announcement.htm.

4 Ibid.

5 Ibid.

- The Google Self-Driving Car Project may be the most famous private sector CAV effort today.[6] Google designed, built, and is testing fully autonomous vehicles (intended to operate with no human intervention). Google is also testing a Level 4 autonomous vehicle with no steering wheel, brake or gas pedals. By October 31, 2016, the Google car had logged more than 2 million autonomous miles.[7] Other private companies competing in this market include Tesla, Apple, Verizon, BMW, Audi, Ford, and essentially every auto original equipment manufacturer (OEM) and Tier-1 electronics supplier.[8]

- Public/private CAV efforts that bring private sector funds to a private sector research entity include:

  - o Uber's partnership with Carnegie Mellon University (although Uber also opened its own CAV research center).
  - o Google and Mountain View, California, a jurisdiction that permits Level 4 autonomous vehicles to operate on its city streets.
  - o Toyota and the University of Michigan Transportation Research Institute (UMTRI), which together announced in April 2016 a partnership that aims to help the newly launched Ann Arbor Connected Vehicle Test Environment (AACVTE) deploy 5,000 vehicles equipped with a vehicle awareness device to transmit speed and positioning data to other equipped vehicles as well as to the surrounding roadside and intersections.[9]

6 Google, "Google Self-Driving Car Project" web page. Available at: https://www.google.com/selfdrivingcar/.

7 Google, "Google Self-Driving Car Project, Monthly Report, October 2016." Available at: https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports/report-1016.pdf.

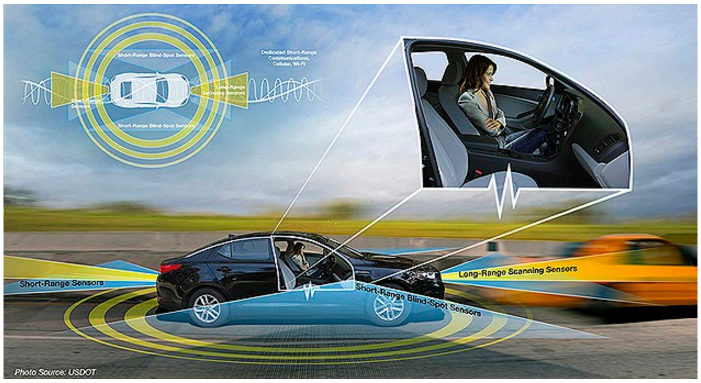
8 OEM or Original Equipment Manufacturer, is a common name in the auto industry for the "traditional" car manufacturers. This differentiates them from the new disrupter community. Tier 1 providers are the primary major parts manufacturers that supply many of the OEMs.

9 Nicole Casal Moore, University of Michigan College of Engineering, "New Toyota autonomous vehicle hub boosts region's leadership in transforming mobility," April 7, 2016. Available at: http://www.engin.umich.edu/college/about/news/stories/2016/april/new-toyota-autonomous-vehicle-hub

INCORPORATING CONNECTED AND AUTONOMOUS VEHICLES INTO THE INTEGRATED CORRIDOR MANAGEMENT APPROACH

The integrated corridor management (ICM) approach is based on three fundamental concepts: a corridor-level “nexus” to operations; agency integration through institutional, operational, and technical means; and active management of all available, and hopefully participating, corridor assets and facilities. Each of these concepts is described below.

A corridor-level focus on operations is a fundamental element of ICM. The United States Department of Transportation (USDOT) defines a corridor as a travel shed that serves a particular travel market or markets that are characterized by similar transportation needs and mobility issues. A combination of networks comprising facility types and modes provide complementary functions to meet those mobility needs. These networks may include freeways, limited access facilities, surface arterials, public transit, and bicycle and pedestrian facilities, among others. Cross-network connections permit travelers to seamlessly transfer between networks for a truly multimodal transportation experience.



Source: U.S.Department of Transportation

Figure 3. Illustration. Automated vehicles use a variety of technologies to help perform safety-critical driving functions.

Integration requires actively managing assets in a unified manner so that actions can be taken to benefit the corridor as a whole, not just a particular piece of it. Integration occurs along three dimensions:

- **Institutional** – Coordination and collaboration between various agencies and jurisdictions (i.e., transportation network owners) in support of ICM, including distributing specific operational responsibilities and sharing control functions in a manner that transcends institutional boundaries.
- **Operational** – Implementation of multi-agency transportation management strategies, often in real-time, that promote information sharing and coordinated operations across the various transportation networks in the corridor and facilitate management of the total capacity and demand on the corridor.

- **Technical** – The means by which information, system operations, and control functions can be effectively shared and distributed among networks and their respective transportation management systems, and by which the impacts of operational decisions can be immediately viewed and evaluated by the affected agencies. Examples include communication links between agencies, system interfaces, and the associated standards. This cannot be accomplished without institutional and operational integration.

Active management is the fundamental concept of taking a dynamic approach to a performance-based process. Integrated corridor management requires that the notion of managed corridors, and the active management of the individual facilities within the corridor, be considered. It is expected that a managed corridor will have basic ITS capabilities for most if not all of the associated networks within the corridor. While not always synonymous with improved management and operations, ITS has proven to be a significant enabler of management and operations. ITS allows for the rapid identification of situations with a potential to cause congestion, unsafe conditions, reduced mobility, etc.; and then allows for the implementation of appropriate strategies and plans for mitigating these problems and minimizing their duration and impact on travel. Such "management" may take the form of improved traffic controls, priorities for transit vehicles, improved response to incidents, and improved traveler information.

THE RELATIONSHIP BETWEEN CONNECTED AND AUTONOMOUS VEHICLES AND INTEGRATED CORRIDOR MANAGEMENT

ICM improves safety, mobility, and reliability and reduces emissions and fuel consumption by optimizing existing transportation infrastructure along a corridor, enabling travelers to make informed travel decisions. ICM involves a number of strategies to do this, including active traffic management, adaptive ramp metering, traveler information, incident response policies, transit-only lanes, transit signal priority, pricing and integrated payments, real-time signal coordination, and inter-agency information sharing, coordination, and collaboration. Many ICM strategies, e.g., active travel management and speed harmonization, employ advanced roadside technologies. The "hi-tech" nature of these strategies forms the basis of the relationship between ICM and connected and autonomous vehicles (CAV), and defines how the platforms integrate institutionally, operationally and technologically. A relationship is informed by the context in which the two entities interact. CAV has three factors that intersect and simultaneously form the basis for new mobility concepts available to the ICM community: the "car," the "industry," and the "driver."

1. **The Car** – Cars are growing smarter and more efficient, connected, automated, and eventually autonomous. A key trend pushing CAV is the Internet of Things, which is the network of physical objects—devices, vehicles, buildings, etc.—embedded with electronics, software, and sensors that have network connectivity, which enables the collection and exchange of data. Next, the ways people and vehicles communicate are proliferating and getting less expensive, which means that connectivity is at a personal level at all times.

2. **The Industry** – Vehicle manufacturers are responding to technology companies offering "carry-in" connected vehicle devices and apps. Their goals are to provide value-added services and collect data to improve existing services and offers. ICM operators are also witnessing a paradigm shift in terms of how data is collected and applied to management. Roadside data collection devices (loop detectors, pneumatic tubes, etc.) provided by

intelligent transportation systems (ITS) manufacturers are now supplemented by smartphone and vehicle-sourced data collected and integrated by auto and tech-focused Silicon Valley companies. The latter data is more precise, personal, and can be turned in into actionable information quickly.

3. **The Driver** – When force is applied to an object, it changes its attributes or direction. This applies to drivers, too. In the near future, CAV will make people to look at cars differently. Rather than buying and owning vehicles outright, people may tire of paying for and maintaining an asset that sits still 96 percent of the time and buy mobility services instead via a mobility-on-demand model. Even for those who drive their own cars, they will view them as spaces to consume media, make calls, and do other things made possible by CAV.

The first two factors are inputs that shape and enable CAV ecosystems. The third is an outcome – something to expect from CAV. The three factors encompass the key touchpoint between CAV and ICM, which is that CAV aids ICM goals. How well it does that depends on how well CAV is integrated into ICM from the institutional, operational, and technological perspectives.

BEST PRACTICES FOR INCLUDING CONNECTED AND AUTONOMOUS VEHICLES STAKEHOLDERS INTO THE INTEGRATED CORRIDOR MANAGEMENT APPROACH

As a technology-driven practice, ICM is well-positioned to include the CAV community among its stakeholders. Advances in technology already drive changes in ICM, and ICM operators constantly scan the technology environment to stay on top of advancements that improve corridor performance. ICM operators also incorporate strategies that include acquiring new technologies guided by best practices that take into account the impact that new technology has on the organization, customers, employees, suppliers, and other stakeholders. Including CAV stakeholders is an extension of those practices and therefore requires steps that overlap with how ICM supports the inclusion of new stakeholders, which is described below.

Building Interest

The ICM community must first care about the CAV community before including it among other stakeholders. There are several arguments for why the ICM community should be interested in the CAV community as a stakeholder:

- **Innovation in Continuing to Contribute towards Enhanced Mobility** – If ICM stakeholders are committed to providing safe, efficient, and healthy transportation services, they must be open to the idea of CAV proliferation, which is the next stage in mobility technology.

- **Gaining First-mover Advantage** – If ICM stakeholders that are currently ready to accommodate CAV do not make the voluntary move to advance the technology, then outside actors will fill that role and dictate how CAV contributes to ICM.

- **Organizational Evolution to Accommodate the Future of Mobility Technology –** If ICM stakeholders can manage the CAV revolution internally, they will more likely be able to control their role and destiny in the CAV ecosystem.

Building Champions and Stakeholders

Even when rationale is understood, the integration of CAV into the ICM community requires support from internal and external champions and stakeholders – people and groups with a stake in the corridor and who are affected by its operations. Table 2 below defines the two groups.

Table 2. Definition of champions and stakeholders.

Internal Champions & Stakeholders	External Champions & Stakeholders
✓ Within the primary organization that is developing or operates a system. ✓ Play a significant role in system function. ✓ Are significantly affected by changes in system design and function.	✓ Interact with organization and/or system but are outside the scope of both. ✓ Play a secondary role in organization and/or system function and are only affected by system function.

Internal champions and stakeholders count both the organization's employees and its management. External champions and stakeholders include both public and private groups. It is important to distinguish between them all because each has different motives and objectives.

Building Organizational Support

Corridors are comprised of discrete organizations that, while sharing the same high-level goal (improve mobility), have separate, individual challenges that they must overcome. However, by its very nature, CAV offers solutions for meeting many ICM stakeholders' business goals, such as increasing capacity, reducing accidents, or increasing revenue. In short, internal stakeholders must see that integrating the CAV community stakeholders supports their goals too. For stakeholder agency employees, incorporating the CAV community and technologies into operations and management activities can be presented as a way to develop new technical skills or as a form of professional development with promotional opportunities. To management, incorporating CAV into existing strategies or approaches can be presented as a means to demonstrate to external stakeholders an agency management's vision about the future of transportation and their willingness to innovate to improve it. It can be presented as evidence to the community that ICM leaders are open-minded. By integrating CAV institutionally, management is at the forefront of mobility technology and applications.

While the input, involvement, and support of external stakeholders are critical, ICM champions must emphasize that employees and other internal stakeholders hold the key to successful ICM. Therefore, each organization's credibility in the eyes of external stakeholders is proportionate to the extent that its mission, goals, and values are embedded throughout the organization. If internal stakeholders believe in the agency's policies and practices and support the organization in its strategic plan to integrate CAV, the more likely external stakeholders will be to support and assist with the process.

Aligning Resources

To influence internal and external stakeholders toward integrating CAV stakeholders into ICM approaches, involve them early in the process and present the positive (i.e., professional development, improved operations, better customer service, increased regional relevance) and cautionary (customers demand it; CAV is the next way to maintain service; if you don't do it, someone else will) arguments.

Next, demonstrate that the corridor is the ideal candidate for integrating CAV because it has the assets in hand to do so; namely, the technology resources, personnel resources, and Federal Highway Administration (FHWA) resources:

- *Technology resources* are the hardware, software, peripherals, wired/wireless communications services, power and data networks, etc. that corridors have deployed and that support the facility and the organizations from an information technology perspective.
- *Personnel resources* include the technical, administrative, policy, and managerial expertise needed to support the integration of CAV both internally (on the facilities themselves and their staff) and externally—i.e., the public (the public relations aspect of CAV).
- *FHWA Resources* like this document and other guides and educational materials are available to assist organizations with every step in the process.

THE TWO-WAY BENEFITS OF INCORPORATING CONNECTED AND AUTONOMOUS VEHICLES INTO INTEGRATED CORRIDOR MANAGEMENT

The integration of CAV into ICM offers a number of potential cross benefits to ICM operators, suppliers and users of CAV technologies:

- **More Comprehensive Knowledge of Corridor Operations:** A critical element in the management of transportation corridors is obtaining real-time information regarding current conditions and operations. To this end, monitoring capabilities are a vital component of ICM projects. ICM-CAV integration can lead to the greatly enhanced real-time data from CAVs and better information sharing between agencies that can yield a more complete picture of conditions. That data in turn informs traveler information, which can be sent directly, and in real-time, to vehicles and travelers who are using the corridor currently or who are planning their trips.
- **More Efficient Operations:** More knowledge of vehicle (single-occupancy vehicle and transit) and roadway conditions can improve ICM resource management. This can include short-term adjustments in response to incidents or longer-term adjustments designed to minimize the impacts of recurring conditions like congestion. Whether through enhanced knowledge about current conditions from direct CAV data or the implementation of various priority treatments – such as for transit and emergency vehicles – ICM-CAV integration can result in more efficient resource allocation and lead to a more reliable and safe corridor for all users, CAV-equipped or not.

- **Better Informed Travelers:** By collecting more comprehensive data on current conditions directly from vehicles and disseminating this information back to travelers in a coordinated manner, the traveling public can make more informed decisions about when and how they travel. This can lead to more efficient use of all parts of a travel corridor.

- **Increased Transit Ridership:** More efficient service, reduced delays, better incident response, and more information about travel options can make the corridor's transit components more attractive to potential users. Increased ridership also has secondary benefits, such as increased transit service revenue, reduced congestion, lower fuel consumption, and reduced emissions.

- **More Efficient Implementation of Infrastructure and Improvements:** Coordinated planning between agencies helps the ICM community identify opportunities where many improvements can be incorporated into the same design and construction efforts, and where key infrastructure may be installed to serve multiple goals. CAV data can help inform these decisions and help eliminate the redundancies that reduce disruptions due to construction (e.g., individual agencies making improvements separately on the same facility) and provide cost savings.

- **Funding for ICM Improvements:** A number of treatments that provide direct travel time benefits can be implemented as part of an ICM project. By participating in a coordinated initiative that integrates CAV into ICM planning and operations, the ICM community may be able to make stronger arguments for itself. For example, corridor stakeholders may be able to justify deploying Connected Transit Vehicle technologies for buses in order to feed real-time data into an ICM system. Additionally, they could work with local signal operators to request CAV-enabled advanced detection and signal systems on arterials.

OPPORTUNITIES AND CHALLENGES TO INTEGRATION

There are numerous opportunities for integrating connected and autonomous vehicles (CAV) into an integrated corridor management (ICM) process. ICM project teams can leverage existing platforms and initiatives to engage CAV stakeholders and incorporate CAV technologies and strategies into their ICM concepts. However, there are also challenges associated with connecting ICM and CAV. The following sections will explore institutional, operational, and technical opportunities and challenges in more detail.

INSTITUTIONAL INTEGRATION

Institutional integration involves coordination and collaboration between various agencies and stakeholder groups in support of ICM, including the distribution of specific operational responsibilities and the sharing of control functions in a manner that transcends institutional boundaries. Understanding who the CAV stakeholders are – and their goals – is the first step in identifying the right individuals to engage in ICM.

Shared goals should generate benefits to mutual stakeholders. Ideally, this is a two-way street. Figure 3 shows the sets of benefits from both ICM and CAV and where they may overlap. The following describes some of the benefits that are typically associated with ICM deployments, but which also may be accrued by CAV deployments:

Table 3. Bringing together integrated corridor management and connected and autonomous vehicle stakeholders.

Entity	Description	Role	Benefit of CAV Integration
Public Agency	• Federal, State and regional public agencies • Departments of transportation and motor vehicles, metropolitan planning organizations, port authorities, the U.S. Departments of Defense and Homeland Security • Public safety agencies • Transportation operators	•Responsibility for emergency transportation operations •Implement and execute response strategies as conditions change	•Provide real-time data on conditions to inform evacuation decisions and routes, the response to be implemented, the equipment and personnel needed •Enable communication about ICM conditions, closures, priority •Real-time information to provide visibility on facility conditions and inform decision making and agency coordination

Table 3. Bringing together integrated corridor management and connected and autonomous vehicle stakeholders (continued).

Entity	Description	Role	Benefit of CAV Integration
Private industry	•Any company who interacts with traveler (driver or rider) via devices •Vehicle manufacturers and their suppliers •Cellular carriers •Phone manufacturers •Application makers •Systems and technology vendors (e.g., IBM, Cisco, Siemens, Hitachi) •Privacy stakeholders (e.g., Electronic Frontier Association, American Civil Liberties Union, Federal Communications Commission) •Insurance industry	•Communication with travelers •Enabling communication •Development, sales and marketing for devices, software and applications •Integrating systems •Data aggregation and protection	•Reduction of aggregate premiums (as fewer cars are driven by individuals – thus reducing collisions and claims •Determination of insurance rates at a granular level (as enabled by the concept of “usage-based insurance” and aftermarket devices such as the OBD-II port-plug-in “fobs” from insurance providers
Research Community	• Universities and university transportation centers (MIT, Stanford) • Non-Profits • Privately funded research initiatives (e.g., Google, Apple, Uber)	•Experimentation •Simulation and testing •Commercialization	•Neutrality – The unique capacity for interdisciplinary research and impartiality, this community allows private sector and public sector CAV stakeholders—engineers, computer scientists, policy makers—to collaborate and innovate in a neutral setting •Capacity building – working on complex real-world problems, universities provide students with meaningful CAV-related educational and research experiences needed by both public and private stakeholders

CAV = connected and autonomous vehicle, ICM = integrated corridor management, MIT = Massachusetts Institute of Technology, OBD-II = on-board diagnostic system

The long list of stakeholders implies a broad range of goals and objectives among them, some of which are complementary and some not. Whether goals and objectives are complementary or at odds depends on the purposes behind an important feature of CAV—the collection of rich, deep, real-time data. For ICM, CAV is about improving the performance of the corridor. For many CAV stakeholders, it is often about creating additional touchpoints with travelers and designing, marketing, and offering location-based or subscription commercial services. This is where the data privacy issue appears: where does the ICM operator sit in the debate? Who is responsible for CAV data if the "app" that collected it "occurs" on, or is provided by, an ICM facility.

Opportunities for Institutional Integration

CAV stakeholders include those who provide CAV technology and services to the traveling public, and the traveling public who use them. When these stakeholders interact with an ICM corridor, their respective goals and objectives can intersect. In order to gain buy-in and support from CAV stakeholders, ICM project leaders should be prepared to effectively articulate how ICM could help achieve CAV-specific goals and objectives. The goal is to go from information sharing to coordination and then to collaboration between stakeholders, agencies, and jurisdictions to produce results that surpass institutional boundaries. Logical institutional areas where ICM and CAV overlap and can be integrated include:

- **Standards:** CAV technologies and communications systems are emerging, and data and message standards are developing. Now is the time to develop standards for ICM applications such as traveler information and dynamic route guidance that are both informed by CAV (and connected devices) and delivered back to the traveling public by ICM operators.

- **Security:** Connectivity, from concept and design to manufacturing and the driving experience, is pervasive in the CAV community, and the next few years are poised to see even more rapid change. As CAV becomes integrated into our society in terms of travel experience, customer safety, privacy, and reliability, quality will become ever more important an engineering challenge. Quality encapsulates understanding and acting to mitigate evolving threats, secure increasingly complex systems, and adapt to creative, persistent data security threats. As a result, cyber security is a key business driver to CAV and will, by association, become one for ICM. The opportunity exists for ICM and CAV communities to collaborate on the security of data that is collected from vehicles and connected services without hindering the customer experience, which is improved by returning that data as value-added traveler information.

- **Licensing and Regulation:** As CAV becomes more commonplace over time, a potentially sweeping impact on mobility will be that unlicensed travelers (senior citizens, children and others unable to drive) will be riding in CAVs. This is not science fiction. Recent steps toward this day include Volvo, which recently announced it will provide semi-autonomous vehicles in London in 2017, plus Tesla, and a Chinese company called Le Holdings Co., which will market semi-autonomous cars now. These developments show the CAV community is not waiting: major automotive and technology companies in April 2016 announced the creation of a self-driving car lobby that includes Ford, Google, Uber, Lyft, and Volvo. Therefore, as CAV evolves from a "hip" development to the point where CAV companies are seriously creating an environment that advances their vision, ICM stakeholders have the opportunity to integrate with CAV at the institutional level so that the benefits of CAV are broadly distributed.

- **Exploiting Existing Forums for Collaboration:** The Fixing America's Surface Transportation Act (FAST Act) delivered more than 20 provisions that encourage innovation and accelerate researching and deploying intelligent transportation systems (ITS), including funding for the Smart City Challenge and the Connected Vehicle Pilot Deployment Program. In addition to advancing CAV technologies for the U.S. Department of Transportation's Smart City Challenge these programs encourage a cross-section of public- and private-sector stakeholders to collaborate on these test deployments, making this a logical venue for ICM to engage the CAV community on ICM and market its benefits to CAV.

Challenges to Institutional Integration

While there are benefits to both ICM and CAV stakeholders from engaging in institutional integration, there are also challenges. First, the private sector is generally reluctant to actively engage in public sector-led activities without a well-defined return on investment (ROI). It may be difficult to convince CAV stakeholders of their role in a public project if they do not know how they benefit (or may be financially hurt). Quantifying ROI is difficult when the parties define it differently, but it is also hindered by the different time horizons each sector operates under, with the public sector evaluating project success on continuums spanning 5-10 years, while a long-term outlook for CAV stakeholders is achieving positive ROI in 6-12 months.

It can also be challenging for CAV stakeholders to engage in public-sector initiatives because their planning windows are shorter and more elastic than those of the public sector. Decisions are oftentimes made at the corporate level, which requires input and approval from fewer stakeholder groups than typical for the public sector. If engaged, it can be hard to sustain CAV stakeholder commitment through the long project lifecycles characteristic of public projects. A particularly stubborn challenge with the private sector is the “time is money” argument; the amount of time CAV stakeholders have to participate in ICM research-oriented efforts is limited. This is particularly true where there is uncertainty about the schedule and the benefits that can be achieved. CAV stakeholders will not wait.

The two stakeholder groups also face challenges pertaining to the rules and regulations that are present in one community but which can unintentionally conflict with or prohibit the other community’s ability to do something. The ICM community tends to prioritize “safety and reliability” whereas the CAV community’s focus is on “monetization.” In addition, due to the public nature of most ICM stakeholders, their tendency is to be “reactive,” whereas the private nature of the CAV community makes these stakeholders more "proactive” in their approach. Finally, in terms of financing, the CAV community often perceives the ICM budgets to be comparatively unlimited compared with the more constrained budgets of the private manufacturing community.

The last challenge to ICM and CAV integration at the institutional level relates to CAV’s most promising attribute: data. A key challenge to including CAV stakeholders in an ICM project is securing institutional agreements on data sharing and operations—especially among private sector CAV stakeholders, whose data are highly sensitive and proprietary. A closely related challenge is that it may be difficult to bring CAV stakeholders together due to the fact they compete with each other. The fact is that CAV stakeholders are running businesses. They may not care to share with each other, much less the ICM community.

OPERATIONAL INTEGRATION

Operational integration involves implementing multi-agency transportation management strategies, often in real-time, that promote both information sharing and coordinated operations across the various transportation networks in the corridor while also facilitating management of the total capacity and demand of the corridor by multiple classes of users (e.g., single-occupancy vehicles, transit, freight). Operational integration of CAV into ICM occurs via a logical process:

1. ICM stakeholders should **identify and develop operational strategies** by which individual CAV technologies and apps can be operationally integrated in their corridors. This requires analysis and evaluation tools that, if not in hand, should be created to support development of strategies and selection of those aspects of CAV to be integrated.
2. ICM practitioners would **perform a corridor resource and component inventory** and use this information to identify the capabilities they have in their corridors and determine what capabilities are needed.
3. ICM practitioners would then **map the identified capabilities to the various corridor operations strategies** that utilize and leverage CAV.

Opportunities and challenges are inherent in this process.

Opportunities for Operational Integration

CAV initiatives associated with ICM do exist. One such initiative at the Federal level is the USDOT Dynamic Mobility Applications (DMA) Program, initiated in 2011 to expedite the development, testing, commercialization, and deployment of innovative mobility applications to maximize system productivity and enhance the mobility of individuals within the system. Notably, the DMA Program has realized broad internal and external participation, including Intelligent Transportation Systems Joint Program Office; Federal Transit Administration; the Federal Highway Administration Offices of Research and Development, Operations, and Safety; Federal Motor Carrier Safety Administration, and the National Highway Transportation Safety Administration.

In the last 5 years, the DMA program has advanced numerous connected vehicle applications from the conceptual stage to prototype testbed deployments. Several of these tested applications are highly relevant to ICM and offer the potential to extend and enhance the ICM capabilities. Specifically, the following “bundles” (collections of functionally related connected vehicle applications) provide the best opportunities for ICM-CAV operational integration, as they employ connected vehicle-enabled active transportation and demand management approaches, which underlie the key operations of ICM:

- **Enable ATIS:** Enable Advanced Traveler Information Systems. ICM-relevant application:
    - o Advanced Traveler Information Systems – This applications represents a future operational environment that will support and enable an advanced, transformational traveler information services framework. This future framework will be enabled with a robust pool of real-time data through connected vehicles, public and private systems, and user-generated content.
- **R.E.S.C.U.M.E.:** Response, Emergency Staging and Communications, Uniform Management, and Evacuation. ICM-relevant applications:
    - o Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG) – This application provides situational awareness information to public safety responders while traveling to an incident.
    - o Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) – This application warns drivers that are approaching temporary work zones at unsafe speeds, and warns public safety personnel and other officials working in the zone through an audible warning system.
    - o Emergency Communications and Evacuation (EVAC) – This application provides drivers with dynamic route guidance information, current traffic and road conditions, and the location of available lodging, fuel, food, water, cash machines, and other necessities. The application also provides users needing assistance with information to identify and locate people who are more likely to require guidance and assistance, and information to identify existing service providers and other available resources.
- **INFLO:** Intelligent Network Flow Optimization. ICM-relevant applications:
    - o Dynamic Speed Harmonization (SPD-HARM) – This application works to dynamically adjust and coordinate maximum appropriate vehicle speeds in response to downstream congestion, incidents, and weather or road conditions in order to maximize traffic throughput and reduce crashes.
    - o Queue Warning (Q-WARN) – This application provides drivers with sufficient warning of an impending queue backup in order to brake safely, change lanes, or modify the route such that secondary collisions can be minimized or even eliminated.
    - o Cooperative Adaptive Cruise Control (CACC) – The objective of CACC is to dynamically and automatically coordinate cruise control speeds among platooning vehicles in order to significantly increase traffic throughput.
- **IDTO:** Integrated Dynamic Transit Operations. ICM-relevant applications:
    - o Connection Protection (T-CONNECT) – This application is used to improve rider satisfaction and reduce expected trip time for multimodal travelers by increasing the probability of automatic intermodal or intra-modal connections.
    - o Dynamic Transit Operations (T-DISP) – This application is used to expand transportation options by leveraging available services from multiple modes of transportation.

- Dynamic Ridesharing (D-RIDE) – This application offers a different approach to carpooling in which drivers and riders arrange trips within a relatively short time in advance of departure.

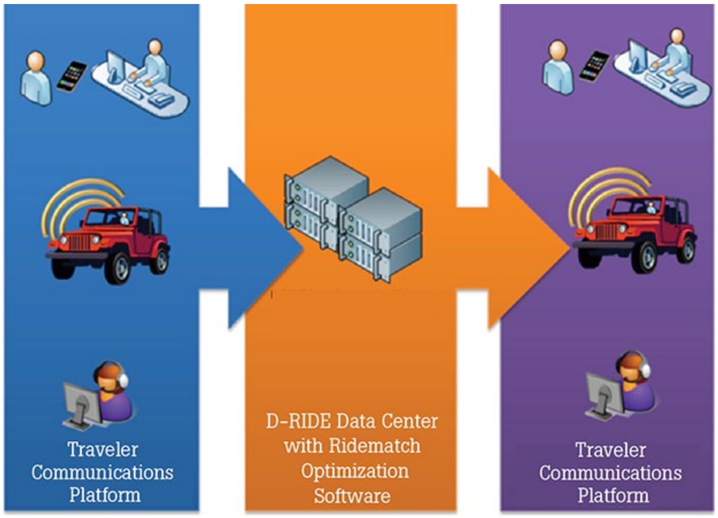


Figure 4. Illustration. Dynamic Ridesharing (D-RIDE) communication flow.

- **FRATIS:** Freight Advanced Traveler Information Systems. ICM-relevant application:
    - Freight-Specific Dynamic Travel Planning and Performance – This application will include all of the traveler information, dynamic routing, and performance monitoring elements that users need.
- **MMITSS:** Multimodal Intelligent Traffic Signal System. ICM-relevant applications:
    - Intelligent Traffic Signal System (I-SIG) – This application uses high-fidelity data collected from vehicles through V2V and V2I wireless communications as well as pedestrian and non-motorized travelers, in order to control signals and maximize flows in real time.
    - Transit and Freight Signal Priority (TSP and FSP) – The TSP application allows transit agencies to manage bus service by adding the capability to grant buses priority based on a number of factors. The FSP application provides signal priority near freight facilities based on current and projected freight movements.

It is well understood that ICM approaches are most valuable during non-recurring congestion conditions. Results from the DMA testbeds have shown that the connected vehicle applications likewise generate greatest benefit under non-recurring congestion conditions, indicating that their value in an ICM context is significant.[10]

Table 4. Relevant impact assessment results.

Program	Application	Relevant Impact Assessment Results
Enable ATIS	Advanced Traveler Information Systems	EnableATIS seeks to transform how traveler information is collected and shared, as well as how agencies use this information to better manage and balance the transportation networks. It would also transform how travelers using the app would obtain information about their trip.

10 J. Colyar, "DMA-ATDM Analysis, Modeling, and Simulation (AMS) Testbed Project," presentation dated February 26, 2015. Available at: http://www.its.dot.gov/research_archives/dma/pdf/DMA_webinarAMS_Testbed.pdf.

Table 4. Relevant impact assessment results (continued).

Program	Application	Relevant Impact Assessment Results
R.E.S.C.U.M.E	RESP-STG INC-ZONE EVAC	R.E.S.C.U.M.E. seeks to provide government officials conducting evacuations with greater communication with vehicles and roadside equipment, public safety personnel in the field, as well as the public itself. Public safety personnel in the field using portable communications devices will be able to provide real-time information to operations and traffic management centers, which will improve traffic and route guidance during incidents and evacuations.
INFLO	SPD-HARM Q-WARN CACC	INFLO will be a connected vehicle system that is both vehicle- and infrastructure-based. SPD-HARM and Q-WARN benefits are optimized when implemented as infrastructure-based applications that reside at a central entity such as a traffic management center (TMC) as the TMC system has broader visibility into the traffic state, allowing operators to implement a more proactive approach for predicting queues and congestion. The apps would also provide road users with enhanced information about the state of the transportation system, pre-trip planning, route-making, and incident avoidance.
IDTO	T-CONNECT T-DISP D-RIDE	IDTO applications will alter existing transit services in order to enhance mobility. The current transit services and communications can be fragmented, leading to insufficient protections, untimely information, and inconvenience for travelers. The IDTO apps seek to resolve these gaps and evolve the current state to offer transformative impacts while minimizing risks.
FRATIS	Freight-Specific Dynamic Travel Planning and Performance	FRATIS will leverage connected vehicle data and integrate existing data sources in a way that is specific to freight's unique operational characteristics, which require different data and methods/time frames for information delivery.

Table 4. Relevant impact assessment results (continued).

Program	Application	Relevant Impact Assessment Results
MMITSS	I-SIG TSP and FSP	MMITSS will use DSRC to provide real-time knowledge of vehicle class (passenger, transit, emergency, commercial), position, speed, and acceleration on each approach. The widespread availability of wireless communications media (e.g., WiFi, 3G/4G, and Bluetooth) provide coverage for pedestrians and cyclists as well as coverage for long-range messages from vehicles that can support traffic signal system management in areas with sparse deployments of DSRC roadside equipment.

ATIS = Advanced Traveler Information Systems. DSRC = Dedicated short-range communication.
FRATIS = Freight Advanced Traveler Information Systems.IDTO = Integrated Dynamic Transit Operations.
INFLO = Intelligent Network Flow Optimization.MMITSS = Multimodal Intelligent Traffic Signal System
Q-WARN = Queue Warning. R.E.S.C.U.M.E. = Response, Emergency Staging and Communications, Uniform Management, and Evacuation. SPD-HARM = Dynamic Speed Harmonization

Other Federal programs that can be counted as CAV/ICM integration include the Connected Vehicle Pilot Deployment Program[11] and the Smart City Challenge.[12]

Challenges to Operational Integration

The key underlying challenge to CAV/ICM integration is the lack of specific knowledge and familiarity between the two stakeholder groups. For the CAV community, there is often a lack of understanding and appreciation for how technology and operational strategies in general are being used to support effective integrated corridor operations. Operational scenarios in use today in ICM—such as signal timing, ramp metering, and other approaches that require coordinating freeway, intersection, transit, and freight operations—are not known (or therefore valued) by CAV stakeholders, but must be understood and embraced before ICM strategies can be combined effectively with CAV. At the same time, the ICM community may not appreciate the specific incentives, timelines, or market pressures the CAV community operates under. Some of the complex challenges to coordinating and integrating CAV into ICM at the operational level include:

- **Prioritizing Value** – as referred to above, CAV and ICM stakeholder groups often do not appreciate the value of each other's initiatives, strategies, operating environments or limits. Therefore, to effectively integrate CAV into ICM, harmonization of the two communities' goals and objectives is an early priority. Achieving this will aid both stakeholder groups in securing private sector participation in public sector-led initiatives and vice versa.

11 USDOT, Intelligent Transportation Systems Joint Program Office, "Connected Vehicles:CV Pilot Deployment Program" Web page. Available at: http://www.its.dot.gov/pilots/.

12 U.S. Department of Transportation, "Smart City Challenge" Web page. Available at: https://www.transportation.gov/smartcity.

- **Lack of Integration** – Discrete modal and facility operations are not uncommon in corridors. This implies limited integrated network-wide operational strategies. In such a physically and operationally disaggregated corridor, the potential of CAV to contribute to seamless multi-modal mobility is limited if not impossible.
- **Differences in Analysis Capabilities** – Because ICM and CAV communities have different goals and objectives (i.e., ICM stakeholders' focus on priority on aggregate congestion mitigation vs. the CAV community's focus on a particular vehicle owner's mobility needs), the competencies and resultant tools each stakeholder employs can differ significantly and thus be difficult to integrate into a seamless, synergistic set of analytical capabilities.
- **Legal and Regulatory Barriers** – The potential applications of CAV are advancing more quickly than the regulatory and legal structures that bound transportation operations. The potential of autonomous vehicles will, for example, reveal shortcomings and/or necessitate changes in the issuance of driver's licenses, insurance requirements and liability, and traffic enforcement procedures.

TECHNICAL INTEGRATION

Once stakeholders are committed at the institutional level, and operational integration opportunities are identified, prioritized, and perhaps even underway, the last step in CAV/ICM integration is technical integration. Technical integration in this context means the seamless combination of the technical elements of CAV and ICM—e.g., communications systems including data and information links and systems interfaces—and perhaps even the system operations and control functions that should be effectively shared and distributed among the various components of the new, integrated CAV/ICM network.

Opportunities for Technical Integration

The technical architecture for ICM is readily adaptable to incorporating CAV elements. Common ICM technology resources that can be extended to support a CAV environment include the ICM facility hardware, software, peripherals, wired and wireless communications, and power/data networks. ICM facility personnel resources charged with maintaining the ICM system likewise can leverage their technical, administrative, and managerial expertise to support the design, implementation, and management of new CAV technologies.

Specific areas of technical integration opportunity include the following:

- **Data Collection, Storage Support, and Analysis** – Real-time data from CAV about corridor travel patterns can be incorporated into existing data inventories to supplement current information gaps and enhance the overall picture of conditions into the transportation network. One key area where new sources of mobile user data could provide the traditional ICM system valuable insight is in road weather information. Current road-weather information systems (RWIS) gather general temperature, precipitation, and road surface conditions information from fixed position roadside monitor stations. However, weather conditions can change quickly and are often variable across a transportation corridor, to an extent that cannot be captured by fixed RWIS stations. Mobile, weather-capable CAV can supplement traditional ICM detection, providing an enhanced and significantly more granular real-time awareness of the road weather conditions on the facility. This can enable more accurate, better targeted, and more effective corridor management response plans.

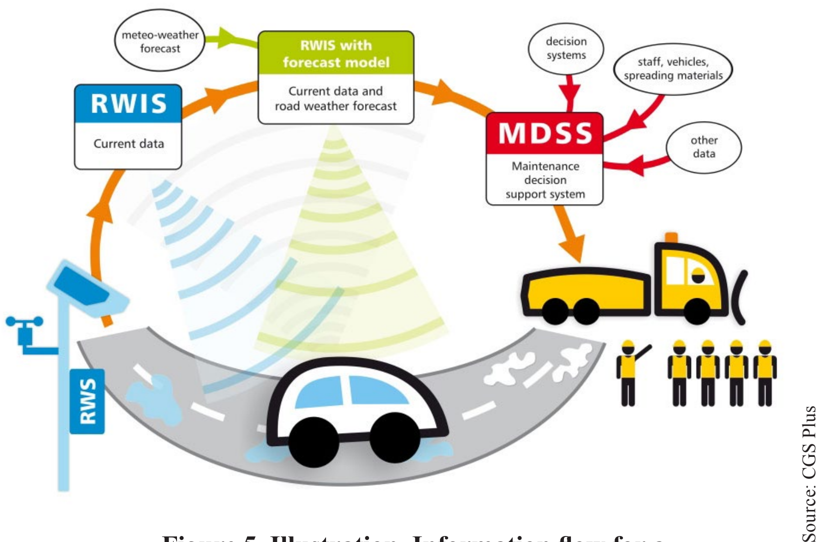


Figure 5. Illustration. Information flow for a road weather information system.

- **Traveler Information Dissemination** – Utilizing its in-vehicle interface capability (to the driver or directly to the driving system), CAV can extend the en-route traveler information capabilities of ICM beyond the traditional infrastructure-based message signs. In-vehicle signing, following the standard ITS message protocols, can be used to communicate ICM messages more precisely and across a greater segment of the corridor.

- **Transportation Facility Operations** – From a program example standpoint, the $50 million USDOT Smart City Challenge has seen proposals in which CAV data would be used to inform transportation facility and traffic management operations. This begs the question, how would a typical traffic management center be impacted by CAV in terms of both data coming in and information going out?

- **System and Performance Reporting** – CAV has the potential to vastly improve the practice of system and performance reporting in terms of data richness and efficiency.

Challenges to Technical Integration

Challenges to technical integration include incompatible data standards, conflicting and/or incongruent data security and credentialing requirements, and a lack of cross-network device-to-device data, communication, and procedure integration. A non-technical challenge to technical integration could be data ownership (an unresolved issue) and thus data-set cost as well as privacy policies or requirements that could complicate or limit the ability to capture and use CAV-derived data.

SUMMARY AND CONCLUSIONS

This primer documents numerous opportunities for transportation operators to incorporate connected and autonomous vehicles (CAV) into their integrated corridor management (ICM) programs and processes. ICM project teams can leverage their existing platforms and initiatives and invite and engage CAV stakeholders to enhance and add new capabilities to them. ICM project teams can also encourage CAV stakeholders to integrate ICM concepts into their CAV solutions. As presented in prior sections, both approaches have institutional, operational, and technical challenges to overcome. Regardless, CAV technologies and capabilities are advancing rapidly, as are the traveling public's expectations of the technology and their regional transportation operators plans to deploy it. Therefore it is appropriate for ICM stakeholders to get ready for CAV now.

GETTING READY FOR CONNECTED AND AUTONOMOUS VEHICLES

Integrated corridor management stakeholders, especially transportation agencies, should begin to plan where they need infrastructure to support the needs of CAV. An asset mapping exercise can provide information to individual organizations as well as CAV stakeholders about the strengths and resources of the organization and the corridor as well as:

- Uncovering best-case deployment scenarios for CAV partners.
- Allowing all partners to think about how to build on their own assets and link them more efficiently and effectively.
- Promoting buy-in, organizational involvement, ownership, and eagerness to begin working together.

A key component of CAV is communication systems. Therefore, it is important to understand and prepare the corridor's data and power networks, as well as its back office systems, to support the large amounts of data that CAVs generate and CAV mobility applications demand.

Corridors encompass multiple jurisdictions, operating agencies, and modes and therefore the ICM community has unique and practical experience in promulgating standards, whether for performance metrics or communications protocols, that enhance operations. Stakeholders should bring this experience to the CAV table and work with the CAV community to shape, adapt, or develop the policies and standards that CAV technologies and services require to operate on a corridor-wide scale.

Finally, an excellent means to get ready for CAV is simply to follow, observe, and even participate in CAV technology initiatives, programs, and pilots to learn how CAV might best apply to your ICM program.

THE BENEFITS OF INCORPORATING CONNECTED AND AUTONOMOUS VEHICLES INTO INTEGRATED CORRIDOR MANAGEMENT

In summary, integrating CAV into ICM promises to greatly enhance the capability of ICM to provide its core function of optimizing transportation corridor capacity by coordinating transportation operations in response to fluctuations in network supply and demand. The benefits of this integration to CAV stakeholders are less clear cut, however. Nevertheless, such benefits must be clearly articulated in order to achieve the support and buy-in of CAV partners.

The following are the key benefits of ICM-CAV integration to ICM stakeholders:

- A new source of highly-detailed real-time information that can improve the ICM stakeholders' understanding of the real-time and historical picture of the corridor.
- A means to supplement or potentially obviate expensive fixed traveler information dissemination infrastructure (e.g., gantries, dynamic message signs, lane use signs).
- A means to improve the ubiquity, precision, and individualization of traveler information dissemination to the driver or driving system by leveraging the in-vehicle interface. This allows for a more effective and dynamic ICM response generation capability. For example:
    - A greater portion of the vehicle stream can be targeted by ICM congestion management approaches.
    - Recommendations can be better tailored to specific vehicles based on their precise locations, known destinations, or other relevant characteristics.
    - Connected or automated vehicles can accommodate and enact more granular or complex congestion management response actions (e.g., precise vehicle speed changes, complex diversion routing) than could be expected from an unequipped human driver.

The following are the key benefits of ICM-CAV integration to CAV stakeholders:

- CAV vehicle system and operators will received detailed information on the state of corridor transportation conditions (e.g., congestion, road weather conditions, incidents, incident clearing status) that would otherwise not be available. CAV systems are free to use these data to integrate into and enhance first-party services and offerings.
- CAV vehicle systems and operators will have ccess to individualized operational guidance and recommendations that may improve safety, comfort, travel time and trip reliability for the CAV user.

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