UNITED STATES
DEPARTMENT OF TRANSPORTATION

ITS ePrimer
Module 13: Connected Vehicles

ITS Professional Capacity Building Program
ITS Joint Program Office
U.S. Department of Transportation

ite Learning HUB

United States Department of Transportation
Office of the Assistant Secretary for Research and Technology
Intelligent Transportation Systems Joint Program Office

INTELLIGENT TRANSPORTATION SYSTEMS
PROFESSIONAL CAPACITY BUILDING

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Learning Objectives

- Understand the connected ecosystem, including CVs, the connected infrastructure, and communications
- Understand the technological evolution and programmatic history of CVs as they have begun to be deployed within the transportation system, including the roles of government and industry stakeholders
- Understand the benefits and challenges of CV application development and deployment

INTRODUCTION

Connecting Vehicles and Infrastructure

- Vehicles have always been connected—only the means of communications have changed
- Traditional traffic communications have been visual
  - Hand signals from driver to driver
  - Traffic signals
  - Pavement markings
  - Signs
- Digital wireless communications vastly increase the flow of information
  - Vehicle-to-vehicle (V2V)
  - Vehicle-to-infrastructure (V2I)
  - Vehicle-to-everything (V2X)

The Connected Vehicle Ecosystem

- A connected vehicle ecosystem enables cooperation among multiple modes and vehicle types as they interact across the road network
- CV ecosystem includes
  - Vehicles and travelers
    - Passenger
    - Commercial
    - Transit
    - Bicycles and scooters
    - Pedestrians
  - Infrastructure
    - Traffic controls
    - Traveler information
  - Communications
    - Onboard and roadside units
    - Message

Source: U.S. DOT ITS JPO

Benefits of Connectivity

- Crash reductions from increased awareness of events and hazards
- Mobility improvements from travelers having more information on conditions and travel options
- Mobility improvements from operators enabled to act in real time
- Maintenance and operation improvements from improved monitoring and asset allocation
- Environmental impact reductions from better routing and vehicle response to controls

CV Benefits

Impact Area	Estimated Impacts	Relevant Applications*	Program
Safety	Crash population targeted by V2I safety applications at intersections includes up to 575,000 crashes (involving more than 5,100 fatalities) annually**	PCW, RLVW, SSGA, SSVW	V2I Safety
Safety	Crash population targeted by V2I safety applications at curves includes up to 169,000 crashes (including 5,000 fatal crashes) annually**	CSW	V2I Safety
Safety	Reduction of crashes by up to 25% during winter weather due to weather traffic management applications on freeways***	WRTM-VSL	RWM
Safety	Reduction in speed variations between freeway segments by 18%-58% and within freeway segments by 10%-47%, resulting in fewer rear-end crashes****	SPD-HARM	DMA
Safety	Fewer instances of hard braking and up to 89% reduction in maximum deceleration in incident zones***	INC-ZONE	DMA
Mobility	Reduction in travel time on arterial corridors by 6% to 27% when combined multimodal traffic signal system is implemented***	I-SIG, FSP, TSP	DMA
Mobility	Reduction in travel time for transit vehicles by up to 10% with priority***	TSP	DMA
Mobility	Reduction in travel time by up to 23% and number of stops by up to 15% for emergency vehicles***	INC-ZONE	DMA
Mobility	Reduction in average network-wide delay of up to 14% due to alerts to incident zone workers***	INC-ZONE	DMA
Mobility	Annual travel time reductions of 246,000-740,000 hours when an integrated corridor management decision support system with eco-capabilities is implemented****	Eco-ICM	AERIS
Mobility	Reduction in travel time on freeways by 33% to 42% when cooperative adaptive cruise control, and speed harmonization are optimized for the environment****	Eco-Lanes	AERIS
Environmental	Fuel savings of 2%-22% when signal operations and freeway lane management are optimized for the environment****	Eco-Lanes, Eco-Signal Operations	AERIS
Environmental	Annual fuel savings of 323,000-981,000 gallons when an integrated corridor management decision support system with eco-capabilities is implemented****	Eco-ICM	AERIS
Environmental	Annual mobile emissions savings of 3,100-9,400 tons when an integrated corridor management decision support system with eco-capabilities is implemented****	Eco-ICM	AERIS

Historical Context

- 1992 – FHWA Automated Highway System
- 1999 – FCC allocates 75 MHz of spectrum in the 5.9 GHz band for ITS applications
- 2003 – Vehicle Infrastructure Integration (VII) program formed by USDOT, AASHTO, and automakers
- 2006 – VII Concept of Operations published by USDOT
- 2006-09 – VII Proof-of-Concept testing with CAMP in Michigan
- 2011 – VII renamed to Connected Vehicle program; first demonstration of applications at ITS World Congress
- 2011-13 – Testing to determine future of NHTSA Rulemaking
- 2015 – USDOT announces Connected Vehicle Pilot Deployment awards to New York City DOT, the Tampa Hillsborough Expressway Authority, and Wyoming DOT
- 2019-20 – FCC issues notices of proposed rulemaking on allocation of the 5.9 GHz band and use of specific communications technology in that band

CV APPLICATIONS

CV Application Concepts

- V2I safety applications use infrastructure information to warn drivers of unsafe conditions
- V2V safety applications exchange information among vehicles to warn of potential vehicular conflicts
- Agency applications are focused on system monitoring, planning, and maintenance
- Mobility applications aggregate data from vehicles to facilitate moving around events and enhance movement through the network
- Environmental applications build on the mobility apps to reduce environmental impacts
- Road weather applications use data from vehicles to warn other vehicles of unsafe road conditions
- Smart Roadside applications assist freight operations with infrastructure

Source: USDOT

Connected Vehicle Applications

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

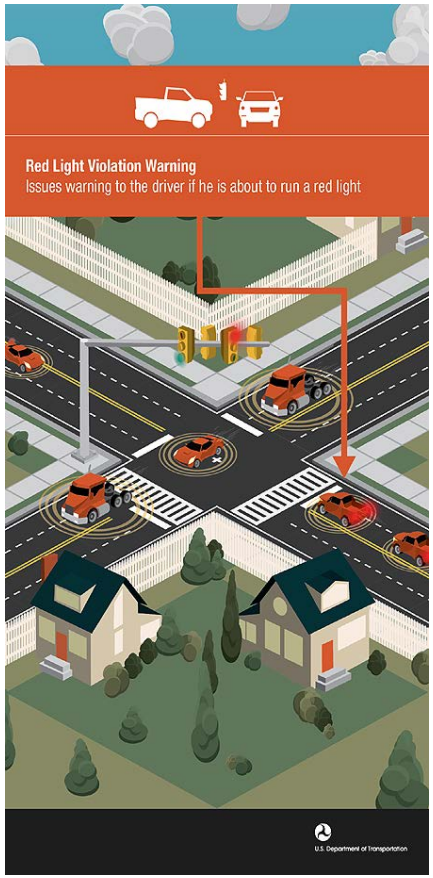
Smart Roadside

- Wireless Inspection
- Smart Truck Parking

Source: USDOT

Example Application – Red Light Violation Warning

- RLVW is a priority V2I application
  - A CV approaching an intersection gets information about the intersection geometry and signal phase and timing (SPaT)
  - An on-board app determines from its position and speed whether the vehicle can make it through the intersection without violation
  - A warning is issued to the driver if a violation is likely



Source: USDOT ITS JPO

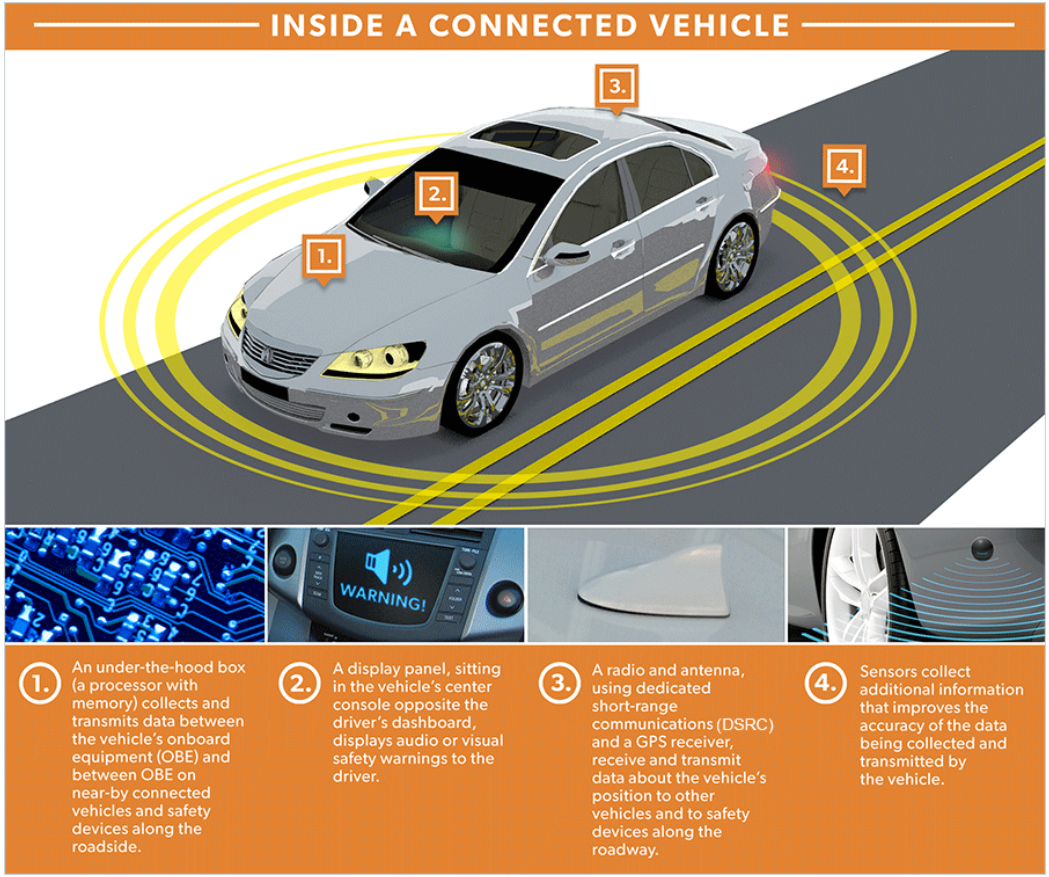
CV Application Architecture Reference

- National ITS Reference Architecture (now ARC-IT) incorporates connected vehicle applications with the infrastructural ITS architecture
- Four architectural views
  - Enterprise
  - Functional
  - Physical
  - Communications
- Architecture components modeled as 48 physical and 372 functional objects
  - Back office centers and services such as TMCs and security certificate systems
  - Field objects such as traffic signals and CV roadside equipment
  - Vehicles and their CV apps
  - Personal objects such as user devices (cell phones)
  - Communications objects such as vehicle on-board equipment

CONNECTED ECOSYSTEM TECHNOLOGIES

Connected Vehicle Technologies

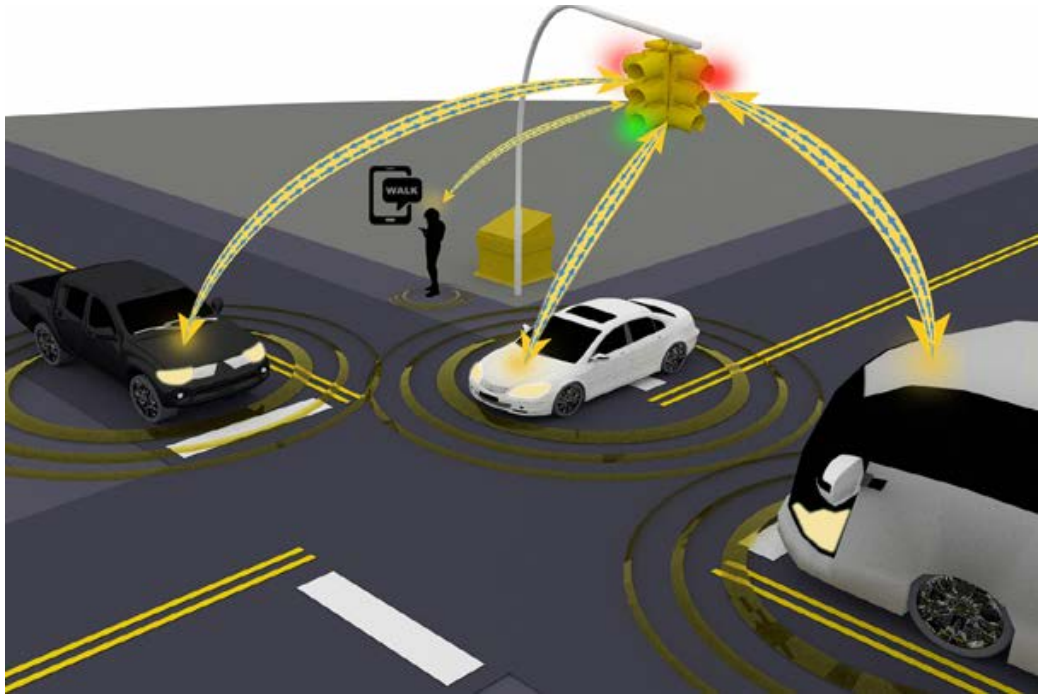
- Location technology
  - GNSS/GPS
  - Differential GPS
- Vehicle sensors, e.g.,
  - Accelerometers
  - Steering angle
  - Wheel speed
  - Braking
  - Headlights
- On-board communications
  - Radio
  - Message processing
- Driver-vehicle interface
  - Displays/alerting
  - Tablet/phone



Source: USDOT ITS JPO

Connected Infrastructure Technologies

- Roadside ITS technology
  - Traffic signal controllers
    - Broadcast signal phase and timing
    - Map messages
    - Support violation and signal priority applications
  - Dynamic message signs
  - Ramp meters
  - Environmental sensor stations
    - Support motorist advisories and warnings



Source: USDOT ITS JPO

More Connected Infrastructure Technologies

- Roadside equipment for communications
  - RSEs provide the infrastructure interface for V2I messaging
  - Radio and antenna
  - Processor
  - Local and area network interfaces
  - Standardized for spectrum and media protocol, supported by a Qualified Product List
- V2X Hub
  - Network edge process for data translation between message standards
  - Supports, for example, SPaT translation from NTCIP 1202 into SAE J2735
- Center systems and backhaul
  - Not required for all CV apps
  - Can enable apps to access cloud computing resources and data
  - Example ATMS interactions:
    - CV probe data in
    - Traveler information out

Communications and Messaging Standards

- Connected vehicle communications technologies are in transition in 2021
  - The FCC in 1999 allocated spectrum in the 5.9 GHz band to be reserved for Dedicated Short-range Communications in support of vehicular safety applications
  - The FCC in 2020 issued Notices of Proposed Rule Making (NPRMs) to amend that allocation and indicated intent to:
    - Reduce the bandwidth from 75 to 30 MHz
    - Replace DSRC with Cellular V2X (C-V2X) technology
  - The FCC docket has collected substantial comments on the NPRMs; the matter is in review as of March 2021
- Updated information on 5.9 GHz communications is available on the USDOT Safety Band website and on the FCC online docket resources
- Other wireless communications technologies have and may in the future play roles in CV applications
- More information at the USDOT Safety Band website: https://www.transportation.gov/content/safety-band

Dedicated Short Range Communications (DSRC)

- A set of standards and technologies
- A variant of Wi-Fi for wireless access in vehicular environments
  - Derived from the IEEE 802.11 standard
  - Includes WAVE Short Message protocol defined in IEEE 1609 standard
- Proven technology for low-latency applications
- Data transmitted as often as 10 times per second
- Nominal range of 300 meters
  - Actual range may vary
- Privacy built into protocols and standards

3G/4G/LTE Cellular Communications

- 3G/4G/LTE cellular communications have been used for applications tolerant of some latency (on the order of seconds)
- Can provide high data rates to a large number of users simultaneously
- Widely available in personal devices and vehicles
- Good coverage – all urban areas and most major highways
- Have proven utility in routing and mobility applications

Cellular V2X (C-V2X)

- C-V2X is an extension to existing cellular technologies (LTE Direct)
- Can add V2X technology to existing cellular devices
- Operates in two modes
  - Direct communications for V2X in the 5.9 GHz band
  - Cellular connections for V2N over carrier network
- FCC approved for demonstration operations in the 5.9 GHz band
- Provides eventual path for transition to 5G cellular communications

Messaging Standards

- Messaging standards are critical for ensuring interoperability of applications across technologies and vendors
- Data representations are defined in SAE J2735 message sets, including the following:
  - Basic Safety Message (BSM)
  - Emergency Vehicle Alert (EVA)
  - Map Data (MAP)
  - Signal Phase and Timing (SPAT)
  - Real-time position correction in a standard Radio Technical Commission for Maritime Services (RCTM) format
  - Traveler Information (TIM)
- Performance requirements for specific applications are developed under the SAE J2945 family of standards
- Messaging standards are intended to apply to all technologies used for V2X applications

Cyber Security

- Cyber security is a major concern for CV applications and technology
- Must address vehicles, infrastructure, and communications
  - Vehicle cyber security focuses on preventing access to vehicle systems and components
  - Infrastructure cyber security focuses on protecting against threats to roadside equipment and systems
  - V2X communications cyber security focuses on ensuring trust in communications among vehicles and with infrastructure
- Vehicles and infrastructure have security threats and countermeasures independent of CV applications, addressed in other contexts
- V2X communications security is founded on a Security Credential Management System (SCMS)
  - Uses a public key infrastructure of encryption and certificate management
  - Used digital certificates issued by the SCMS
  - Contains no personal or equipment identification

CV INITIATIVES AND PROGRAMS

USDOT Safety Pilot

- Deployed CV safety technologies, applications, and systems using everyday drivers in the real world from 2011-13 in two components
  - Driver Clinics
  - Model Deployment
- Driver Clinics
  - Safety applications in controlled roadway situations
  - Explored everyday driver reactions
  - Six sites across the U.S.
- Model Deployment
  - Tested concentrated deployment of 2800 vehicles for data interfaces and vehicle interactions
  - Test site in Ann Arbor, MI, with mix of cars, trucks, and transit vehicles

Source: USDOT

USDOT Connected Vehicle Pilot Program

- USDOT initiative to spur deployment and begin to address ongoing deployment and operational issues
- Proposed projects identified local needs, set performance goals and selected CV applications to meet those goals

Source: USDOT

USDOT CV Pilot Deployment Program Sites

- Three sites selected for Pilot Deployment in 2015
  - New York City – vehicle and pedestrian safety
  - Wyoming I-80 Corridor – freight vehicles and weather applications
  - Tampa-Hillsborough Expressway – congestion relief and safety
- Three-phase deployment
  - 12-month concept development
  - 24-month development and site deployment
  - Ongoing operations to monitor impacts
- More information at http://www.its.dot.gov/pilots/index.htm

Smart Cities - Columbus

- USDOT launched Smart City Challenge in 2015
  - 78 applicant mid-sized cities applied
  - 7 finalist cities
  - Columbus, Ohio selected
- CV technologies and applications key to Columbus solutions, within larger perspectives and vision for an integrated, first-of-its-kind smart transportation system
- More information at https://www.transportation.gov/smartcity

CV Pooled Fund Study

- CV Pooled Fund Study (PFS) formed in 2009
  - Federal, state, local agencies
  - Chartered to aid IOOs and OEMs in justifying and promoting large-scale CV deployments
  - Projects in modeling, planning, engineering, and development
- 13 completed projects and four projects underway as of 2020
  - V2I Queue Advisory/Warning
  - Using Third-Party Data to Deliver V2I
  - Multi-modal Intelligent Traffic Signal System – Phase III: Deployment Readiness Enhancements
  - Creation of a Guidance Document for MAP Preparation
- More information at http://www.cts.virginia.edu/cvpfs/

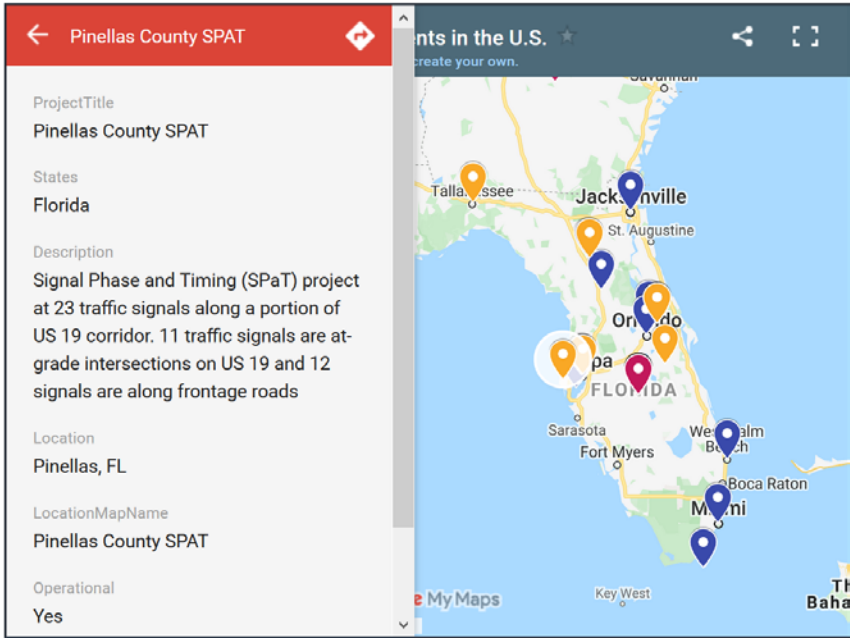
Cooperative Automated Transportation (CAT) Coalition

- Collaborative focal point for connected and automated vehicle deployment
- Sponsored by AASHTO, ITS America, and ITE
- Members from among IOOs, OEMs, technology and service providers, and Internet of things (IoT) suppliers
- Seven working groups covering
  - Programmatic and strategic activities
  - Planning, scenarios, and resources
  - Infrastructure and industry
- Numerous studies, initiatives, ad technical resources
- More information at https://transportationops.org/CATCoalition/resources
- SPaT Challenge
  - Issued in 2015 to stimulate US IOO V2I infrastructure deployment for SPaT and MAP message broadcasts
  - 26 states, 216 intersections operating, 2121 intersections planned as of 2020
  - https://transportationops.org/spatchallenge

CV Deployments in the U.S.

Source: USDOT

Source: USDOT



https://www.transportation.gov/research-and-technology/interactive-connected-vehicle-deployment-map

NCHRP 20-102

- *Impacts of Connected and Automated Vehicles on State and Local Transportation Agencies*
- Extensive body of research on CAVs and IOOs
  - Business models
  - Data management
  - Planning guidance
  - Laws and regulations
- More information at https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3824

http://bit.ly/2y8gEm4 January 2021

Impacts of Connected Vehicles and Automated Vehicles
TRB's Cooperative Research Program Efforts

The **Transportation Research Board** (TRB) manages four cooperative research programs [NCHRP, TCRP, ACRP, BTSCRP] that all have projects related to connected vehicles, automated vehicles, shared mobility, and other disruptive technologies. Contact Ray Derr (rderr@nas.edu) for more information.

Reports Available

Low-Speed Automated Vehicles (LSAVs) in Public Transportation [TCRP Report 220] and Redesigning Transit Networks for the New Mobility Future [TCRP Report 221] present options.

Advanced Ground Vehicle Technologies for Airside Operations [ACRP Report 219] identifies potential applications.

NCHRP Project 20-113F produced nine topical white papers for the TRB Forum on Preparing for Automated Vehicles and Shared Mobility.

Business Models to Facilitate Deployment of Connected Vehicle Infrastructure to Support Automated Vehicle Operations [NCHRP Web-Only Document 289] helps identify infrastructure investments and applicable business models.

Guidebook for Managing Data from Emerging Technologies for Transportation [NCHRP Report 952] and Development of Transactional Data Specification for Demand-Responsive Transportation [TCRP Report 210] address vital data issues.

Connected Road Classification System (CRCS) Development [NCHRP Project 20-24(112)] has produced a final report and summary presentation.

Cybersecurity of Traffic Management Systems [NCHRP Project 03-127] has produced an evaluation tool hosted by the National Operations Center of Excellence.

Foreseeing the Impact of Transformational Technologies on Land Use and Transportation [NCHRP Report 924] helps agencies prepare for a broad range of disruptive technologies.

Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles [NCHRP Report 896] includes an Executive Summary.

Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles [NCHRP Report 891] evaluates opportunities, constraints and guiding principles.

Implications of Connected and Automated Driving Systems [NCHRP Web-Only Document 253] helps states review their laws and regulations through six volumes and is supported by A Look at the Legal Environment for Driverless Vehicles [NCHRP Legal Research Digest 69].

Advancing Automated and Connected Vehicles: Policy and Planning Actions for State and Local Transportation Agencies [NCHRP Report 845] presents potential societal effects and strategies to advance public interests, including a briefing document.

Impacts of Regulations and Policies on CV and AV Technology Introduction in Transit Operations [NCHRP Web-Only Document 239] and Challenges to CV and AV Application in Truck Freight Operations [NCHRP Web-Only Document 231] identify next steps for deployment.

Broadening Understanding of the Interplay Between Public Transit, Shared Mobility, and Personal Automobiles [TCRP Report 195]. Private Transit: Existing Services and Emerging Directions [TCRP Report 196], and Partnerships Between Transit Agencies and Transportation Network Companies [TCRP Report 204] explore how transit agencies are adapting while airports are covered by Transportation Network Companies (TNCs): Impacts to Airport Revenues and Operations [ACRP Report 215].

Airports and Unmanned Aircraft Systems [ACRP Report 212] has three volumes and expands upon Unmanned Aerial Systems (UAS) at Airports: A Primer [ACRP Report 144].

TRB TRANSPORTATION RESEARCH BOARD

The National Academies of SCIENCES · ENGINEERING · MEDICINE

Connected Intersections

- CV technology interoperability largely achieved through standards for equipment and software
- Consistent deployment practices will also be needed
  - OEM and vehicle owner expect CV applications to be available and operate consistently across the U.S.
- ITE, USDOT, AASHTO, IEEE, SAE, and NEMA are working together on connected intersection standard practices
- Includes stakeholders from
  - IOOs
  - OEMs
  - Fleet operators
  - Safety advocacy groups
  - Multimodal partners
- More information at https://www.ite.org/technical-resources/standards/connected-intersections/

International Harmonization

- USDOT collaborates internationally with other governments, industry associations, and standards development organizations (SDOs) on deployment of CV applications
  - Shared research
  - Common hardware and software
  - Improved interoperability across borders
  - Facilitation of a global marketplace
- Other governments including EU, Australia, Japan, Korea, and Canada
- SDOs
  - International Organisation for Standardization (ISO)
  - European Telecommunications Standards Institute (ETSI)
  - European Committee for Standardization (CEN)
  - Domestic SDOs, including IEEE, SAE, AASHTO, and NEMA

Summary

- The connected ecosystem uses wireless connectivity among vehicles, the infrastructure, and mobile devices to bring about transformative changes in highway safety, mobility, and the environmental impacts of the transportation system
- Requires participation of a broad community of stakeholders: transportation agencies, vehicle manufacturers, telecommunications providers and manufacturers, information service providers, and researchers
- Benefits from the connected ecosystem come from the following:
  - Combined use of V2V and V2I communications to address crashes
  - Reductions in urban traffic congestion, travel delays, vehicle emissions and fuel consumption
- Seven categories of CV applications
  - V2V safety
  - V2I safety
  - Mobility
  - Environmental
  - Road Weather
  - Agency Data
  - Smart Roadside

Summary

- Deployment of technologies will include the following:
  - Connected vehicles, their sensors, and on-board equipment
  - Connected infrastructure
  - Communications
  - Standards for message exchange and content
- Successful CV application deployment requires collaboration
  - Federal, state, and local transportation agencies
  - Vehicle manufacturers and technology industries
  - Researchers in academia and industry
  - Standards development organizations
  - Professional and industry associations
- Challenges remain
  - Consistent application of cybersecurity practices across the connected ecosystem
  - Demonstration of CV application benefits in real-world deployments
  - Programmatic planning and investment for CV infrastructure

References

- USDOT Safety Band website: https://www.transportation.gov/content/safety-band
- CV Pilot Deployments: http://www.its.dot.gov/pilots/index.htm
- Smart Cities: https://www.transportation.gov/smartcity
- CAT Coalition: https://transportationops.org/CATCoalition/resources
- SPaT Challenge: https://transportationops.org/spatchallenge
- NCHRP 20-102: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3824
- Connected Intersections: https://www.ite.org/technical-resources/standards/connected-intersections/

Questions?