Connected Vehicle Pilot Deployment Program Independent Evaluation:

National-Level Evaluation Plan

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16. Abstract

This report describes the approach and procedures that the Texas A&M Transportation Institute (TTI) Evaluation Team plans to use in performing a national assessment of the potential benefits associated with extrapolating the safety, mobility, environment, and public agency (SMEP) results from the three connected vehicle (CV) pilot deployments—Wyoming, Tampa, and New York City—to the national level. This report describes the TTI Evaluation Team's planned approach for determining the types and proportion of nationwide travel that may benefit from CV technologies and applications as deployed at the three CV pilot sites. This plan also describes the team's approach for assessing, both quantitatively and qualitatively, the extensibility of the SMEP benefits accrued at the site level to the national level. This report contains the hypotheses and research questions to be tested by the evaluation, critical assumptions impacting the evaluation, limitations, and risks associated with the planned evaluation approach, the performance measures, data needs, and processes that the team intends to use in the analysis. This report also contains the approach the team plans to use to extend the SMEP benefits to similar regions and transportation networks nationwide. The report describes the approach the team plans to use to infer practical financial and institutional frameworks and models for short-, medium-, and long-term deployments.

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Chapter 1. Introduction

The US Department of Transportation (USDOT) connected vehicle (CV) research program is a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and travelers' personal communications devices. USDOT and others are sponsoring CV research to leverage the potentially transformative capabilities of wireless technology to make surface transportation safer, smarter, and greener. Concurrent Federal research efforts have developed critical crosscutting technologies and other enabling capabilities required to integrate and deploy applications. Descriptions of the relevant research products, developed by component CV research programs, are at www.its.dot.gov/pilots. These programs seek to identify, develop, and deploy applications that leverage the full potential of trusted communications among CVs, travelers, and infrastructure to better inform travelers, enhance current operational practices, and transform surface transportation systems management.

Scope

The scope of this document is limited to the planning of the national-level evaluation. The Texas A&M Transportation Institute (TTI) Evaluation Team will use the results of the mobility, environmental, and public agency (MEP) benefits analysis measured in the independent evaluation, and the safety benefits as determined by the Volpe National Transportation Systems Center, to complete this analysis. In addition, each site is responsible for assessing its deployments. The TTI Evaluation Team is responsible for projecting the benefits from these assessments to estimate the potential benefits of a national-level implementation of CV technologies.

Furthermore, the scope of this evaluation is limited to the applications and technologies deployed through each pilot deployment. This evaluation does not include additional CV technologies and applications deployed through projects other than USDOT's Connected Vehicle Pilot Deployment Program.

Purpose of Report

The objectives of the National-Level Evaluation of the Connected Vehicle Pilot Deployments are as follows:

- Determine the type and proportion of nationwide travel that may benefit from CV technology and applications as deployed at the three pilot deployment sites.
- Quantitatively and qualitatively assess the extensibility of the safety, mobility, environmental, and public agency (SMEP) benefits accrued at the site level to the national level.
- Recommend technical approaches, financial and institutional frameworks, and integrated deployment models derived from the site experience to accelerate CV deployment nationwide.

The purpose of this report is to describe the approaches and methodologies that the TTI Evaluation Team plans to use to:

- Conduct qualitative and quantitative assessments of national-level CV deployments against a no-CV technology baseline for the current time as well as projected over time by extrapolating findings from the three connected vehicle pilot deployments (CVPDs) to regions and transportation networks that have similar attributes and operational conditions.
- Determine the nature and proportion of national travel activity that may potentially benefit from CV technology as deployed at the pilot sites and assess the extent of potential SMEP benefits accrued.
- Infer practical financial and institutional frameworks and models for short-, medium-, and long-term deployment of CV-enabled applications across the Nation.
- Synthesize findings, challenges and solutions, best practices, and lessons learned across all sites to describe the potential of the CV technologies and applications in the short, medium, and long term, and recommend technical approaches and financial and institutional frameworks and models for accelerating CV deployment nationwide.

Connected Vehicle Pilot Deployments

On September 14, 2015, the Connected Vehicle Pilot Deployment Program initiated the pilot deployments of CV applications. The purpose of the pilot deployment was to demonstrate the applicability of new forms of CV mobile devices and infrastructure data to improve multimodal surface transportation system performance and to enable enhanced performance-based systems management. The pilot deployments intended to not only show improvement in safety, but also demonstrate that technology could produce MEP efficiency benefits. USDOT selected three locations—Wyoming, Tampa, and New York City—as pilot deployment sites. Each site designed, developed, and deployed CV-based applications designed to address specific SMEP efficiency issues related to its individual location. The following sections provide a brief overview of the applications and CV technologies deployed at each pilot deployment.

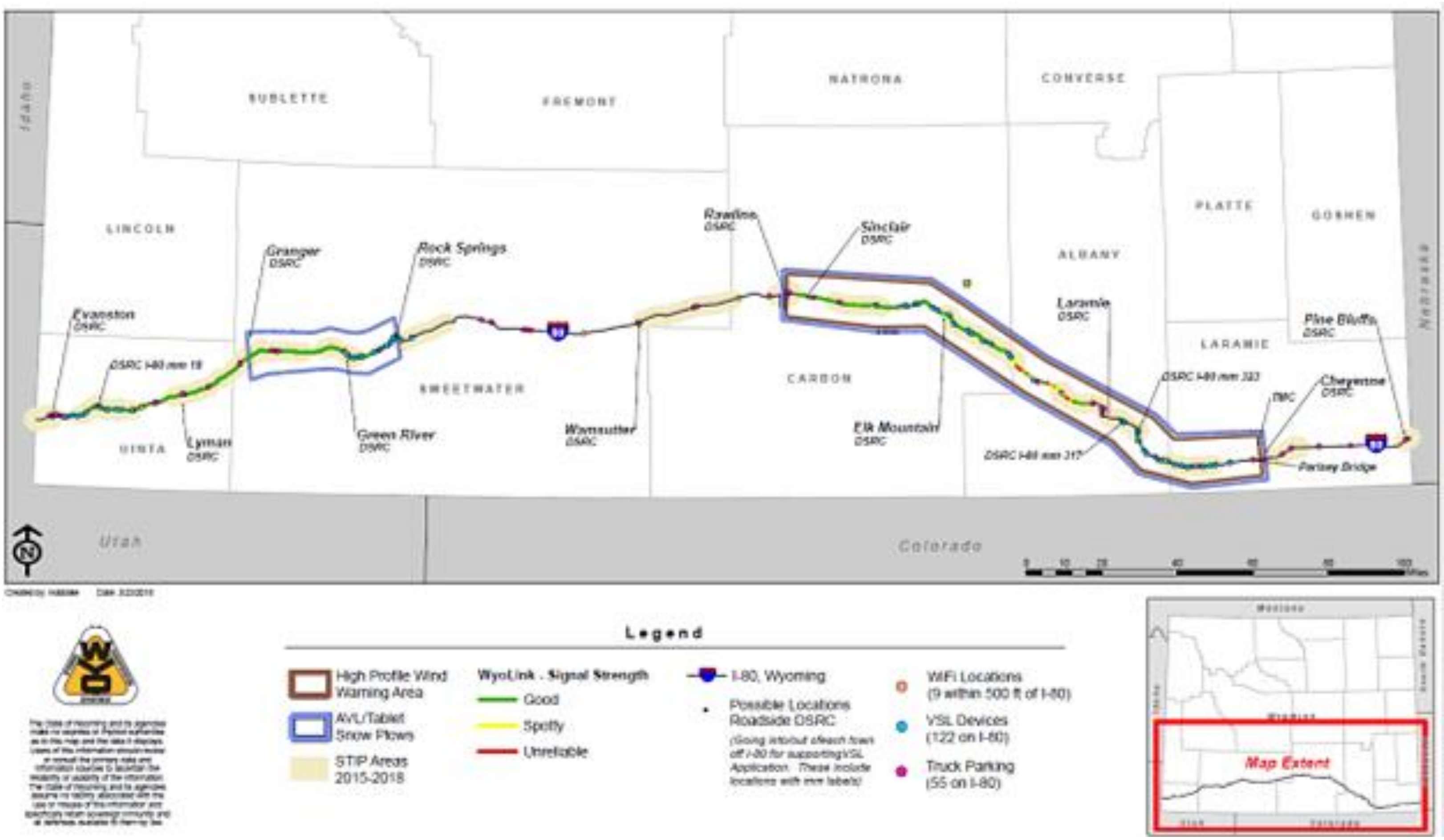
Wyoming

The goal of the Wyoming CVPD is to improve driver safety, particularly for commercial vehicle operators, on I-80 (*1*). I-80, which runs the entire length of the southern edge of the State, is susceptible to multivehicle collisions and roadway closures during winter weather due to icy roads and low visibility from blizzard conditions. The corridor also experiences extreme wind gusts that can cause trucks and other high-profile vehicles to blow over. These events can result in fatalities, extended closures, and significant economic loss. The Wyoming CVPD includes various applications to support a range of existing and new services, including traveler information, roadside alerts, and dynamic travel guidance for freight and passenger travel. These applications include the following (*1*):

- Forward Collision Warning—This application alerts drivers if a rear-end crash is imminent with a CV ahead using vehicle-to-vehicle (V2V) communications.
- Infrastructure-to-Vehicle (I2V) Situational Awareness—This application allows CVs to receive information about downstream conditions that may impact their travel. This application would provide drivers with information about downstream road conditions, weather alerts, speed restrictions, vehicle restrictions, incidents, parking, and road closures.

- Work Zone Warning—This application extends the I2V Situational Awareness application to provide information to vehicles approaching work zones. The approaching CV will receive information about work zone conditions, including obstructions in the travel lane, lane closures, lane shifts, speed reductions, and vehicles entering and exiting work zones.
- Spot Weather Impact Warning—This application broadcasts localized road condition information to drivers. The purpose of this application is to alert drivers of fog and icy roads that may exist only at isolated locations on I-80.
- Distress Notification—This application enables CVs to communicate a distress message if the vehicle's sensors detect an event that might require assistance from others or if the driver initiates a distress request.

To support this pilot, the Wyoming Department of Transportation (WYDOT) is deploying 75 roadside units (RSUs) in various sections of I-80 that can receive and broadcast messages using dedicated short-range communications. WYDOT will install these RSUs at locations upstream of identified hotspot areas. Through its collaboration partners, WYDOT will also equip 400 vehicles that regularly use I-80 with onboard equipment designed to provide CV information and to receive alerts and advisories issued by WYDOT. A portion of the equipped vehicles will have additional capabilities to collect and transmit environmental and road weather condition information through mobile weather sensors (*1*). Figure 1 shows the deployment corridor.



Source: US Department of Transportation, ITS Joint Program Office (*2*)

Figure 1. Wyoming CVPD Deployment Area.

The overall vision of the Wyoming CVPD is to address the safety needs of commercial vehicle operators in Wyoming, as summarized as follows from the Wyoming CVPD Concept of Operations document (*3*):

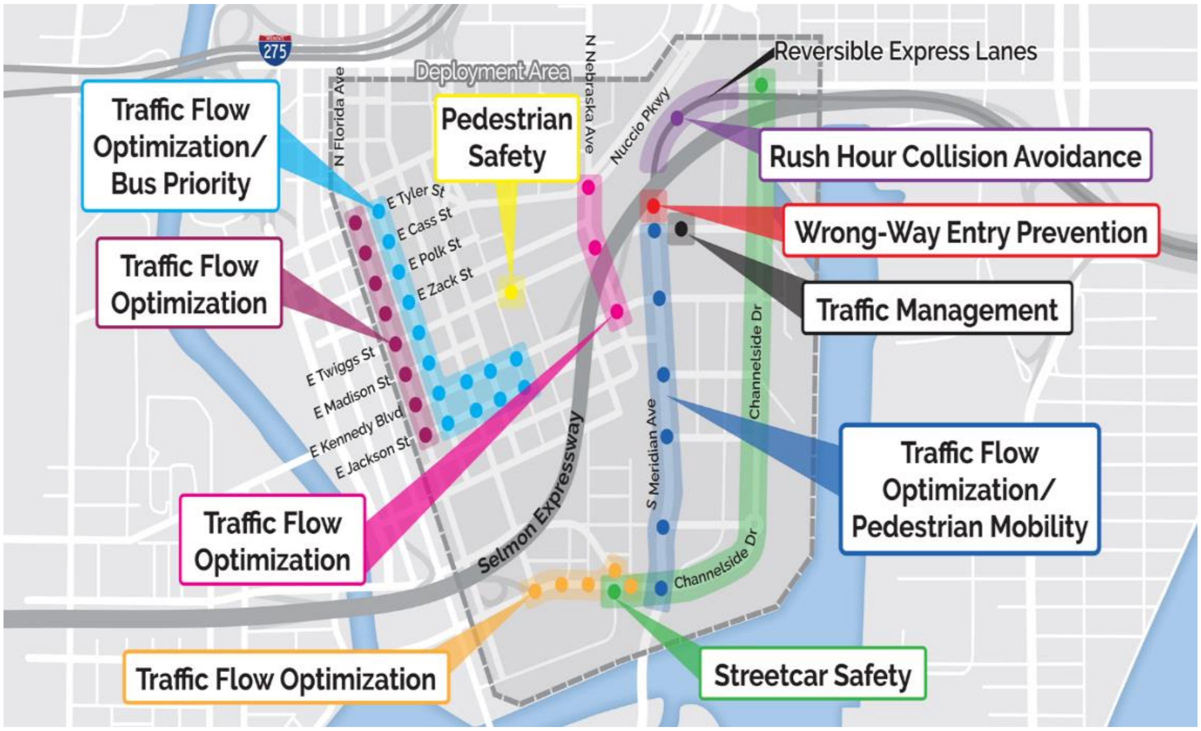
- Reduce the number of truck blow-over incidents and adverse weather-related incidents (including secondary incidents) on the I-80 corridor to improve safety and reduce incident-related delays.
- Improve emergency management on the I-80 corridor through early identification of conditions and improved messaging and communication.
- Improve freight drivers' ability to locate truck parking along the corridor. This objective is safety related since it allows drivers to find safer parking locations in designated areas and to meet hours-of-service regulatory requirements.
- Improve freight traveler information on construction activities in the corridor. This objective is related to both the safety of the construction zones and the increased efficiency of freight logistics through improved information for the scheduling of freight movements through the corridor.

Tampa

The goal of the Tampa CVPD is to transform the experience of automobile travelers, transit riders, and pedestrians by preventing crashes, enhancing traffic flow, improving transit trip times, and reducing emissions of greenhouse gases in the downtown Tampa area (*4*). The Tampa Hillsborough Expressway Authority (THEA) and its partner entities will be equipping buses, streetcars, and privately owned vehicles with CV technologies that will allow them to exchange safety and travel condition information with each other and with the infrastructure. Pedestrians will also be equipped with mobile devices to receive alerts and warnings to improve their safety and mobility. The objectives of the Tampa CVPD are as follows:

- Reduce morning peak-hour delays and rear-end crashes on the Lee Roy Selmon Expressway's Reversible Express Lane (REL) exit to downtown Tampa.
- Reduce vehicle-pedestrian conflicts at a busy mid-block crosswalk near the Hillsborough County Courthouse.
- Improve traffic flow by supporting traffic signal optimization on commuting corridors in downtown Tampa.
- Improve transit trip times by enhancing transit signal priority in the Marion Street Transitway.
- Reduce vehicle and pedestrian conflicts with the TECO Streetcar Line in downtown Tampa.

Figure 2 shows the corridors where THEA plans to deploy CV technologies in the downtown areas.



Source: Tampa Hillsborough Expressway Authority (*5*)

Figure 2. The Tampa (THEA) CVPD Deployment Corridors.

To support these objectives, THEA will be deploying the following applications as part of its CVPD (*4*):

- Emergency Electronic Brake Light Warning—This application alerts drivers when CVs ahead are braking hard.
- End of Ramp Deceleration Warning—This application warns drivers to slow down to a recommended speed as the vehicle approaches the end of a queue.
- Forward Collision Warning—This application warns drivers if a rear-end crash is imminent with a CV ahead using V2V communications.
- Intelligent Signal System—This application optimizes traffic signal timing based on real-time CV data.
- Intersection Movement Assist—This V2V application warns drivers when it is not safe to enter an intersection.
- Pedestrian Collision Warning—This application warns drivers when a pedestrian is using a crosswalk in the vehicle's projected path.
- Transit Signal Priority—This application gives buses priority at traffic signals to keep them running on schedule.
- Vehicle Turing Right in Front of Transit Vehicle—This application alerts a streetcar operator when a vehicle is turning right at an intersection as the streetcar is approaching.
- Wrong-Way Entry—This application warns drivers that enter the REL in the wrong direction. The application will also broadcast a warning to other equipped vehicles on the REL to be alert for wrong-way vehicles.

In the Tampa CVPD, THEA plans to deploy CV technologies on up to 1100 privately owned vehicles, 10 buses, and eight streetcars. THEA also plans to install 44 RSUs at strategic locations in the downtown area to support the CV applications (*4*).

New York City

The focus of the New York City (NYC) CVPD is to improve the safety of travelers and pedestrians in support of NYC's Vision Zero Initiative (*6*). Led by the New York City Department of Transportation (NYC DOT), the goal of the pilot is to reduce crash frequency and severity, manage vehicle speeds, and assess the potential for deploying CV technologies in a dense urban environment. As shown in Figure 3, the deployment area encompasses three distinct areas in the boroughs of Manhattan and Brooklyn:

- Four one-way corridors (1st, 2nd, 5th, and 6th Avenues from 14th to 57th Streets) and major east-west cross streets (14th, 23rd, 34th, 42nd, and 57th Streets).
- A 1.6-mile segment of Flatbush Avenue in Brooklyn.
- A 4-mile segment of Franklin D. Roosevelt (FDR) Drive in the Upper East Side and East Harlem neighborhoods of Manhattan.

The NYC CVPD will support the following specific V2V and V2I applications (*7,8*):

- Forward Collision Warning—This application alerts drivers in the event of an imminent rear-end crash with a CV ahead.
- Emergency Electronic Brake Lights—This application alerts drivers of stopped or hard-braking vehicles ahead in time to safely avoid a crash.
- Blind Spot Warning—This application alerts drivers when a remote vehicle is traveling in the adjacent lane near the CV and issues an alert to avoid side-swipe crashes.[1]
- Lane Changing Warning—Similar to the blind spot warning application, this application alerts a driver who is making a lane change when another vehicle is in the adjacent lane in the same direction of travel.
- Intersection Movement Assist—This application alerts the driver attempting to cross or turn when it is not safe to enter the intersection.
- Vehicle Turning Right in Front of Bus Warning—This application alerts a bus operator if a vehicle attempts to pull in front of the bus to make a right turn.
- Speed Compliance—This application alerts drivers when they exceed the posted regulatory speed limit.
- Curve Speed Compliance—This application alerts drivers approaching a curve that they are exceeding the recommended advisory speed.
- Speed Compliance in Work Zones—This application alerts drivers that they are exceeding the regulatory speed limit of a designated work zone.
- Red-Light Violation Warning—This application provides an alert to the driver of impending red-light-running violations.

[1] While the devices can perform this functionality, NYC DOT has decided to deactivate this application for the pilot deployment period due to the potential number of nuisance alerts because of the driving conditions in New York City.

- Oversize Vehicle Compliance—This application alerts commercial vehicle operators when their vehicle exceeds the height restriction of roadway infrastructures, such as bridge or tunnel clearances.
- Emergency Communications and Evacuation Information—This application provides alerts to drivers on travel and evacuation information during emergency events.
- Pedestrian in Signalized Crosswalk—This application alerts drivers to the presence of pedestrians crossing at a signalized intersection.
- Mobile Accessible Pedestrian Signal System—This application informs a visually impaired pedestrian of the signal status and provides orientation to the crosswalk to assist in crossing the street.

Source: New York City Department of Transportation (*6*)

Figure 3. NYC CVPD Deployment Corridors.

In addition to providing these applications, equipped vehicles will integrate with existing infrastructure detection to provide information to NYC's Midtown-in-Motion adaptive traffic signal system.

The NYC CVPD will be deploying CV technologies in up to 8,000 vehicles, including 3,200 taxis, 700 Metropolitan Transit Authority/New York City Transit Authority buses, and up to 3,200 Department of Civil Administrative Services (DCAS) vehicles, including 700 NYC DOT fleet vehicles and 170 Department of Sanitation fleet vehicles. NYC DOT plans to equip 100 pedestrians with devices. NYC DOT also intends to install approximately 400 RSUs at various locations (approximately 350 at signalized intersections in Manhattan, 35 at signalized intersections on Flat Bush Avenue, 12 on FDR Drive, and approximately 103 at support locations [e.g., river crossings, airports, and vehicle garages] throughout the city) (*6,7*).[2]

Report Structure

The structure of this report is as follows:

- Chapter 2 describes the overall hypotheses and research questions, assumptions, limitations, and risks associated with the national-level evaluation.
- Chapter 3 describes the performance measures the TTI Evaluation Team plans to use in conducting the analyses and answering the research questions.
- Chapter 4 provides a high-level overview of the analysis approach that the team will use to extend the SMEP benefits from the three deployment sites to the national level.
- Chapter 5 describes the approach that the team plans to use to infer practical financial and institutional frameworks and models for short-, medium-, and long-term deployment of CV-enabled applications across the Nation.
- Chapter 6 describes the approach that the team will use for synthesizing findings, challenges and solutions, best practices, and lessons learned across all the sites to describe the potential of the CV technologies and applications in the short, medium, and long term.

[2] Based on the Intelligent Transportation Systems Joint Program Office's CV Device Deployment Status (as of October 2019).

Chapter 2. Research Questions to Be Addressed

This chapter describes the overall hypotheses and research questions that the TTI Evaluation Team will examine as part of the national-level evaluation. The chapter not only describes the high-level research questions that the team will examine, but also summarize the key assumptions, limitations, and risks that may impact the extension of the site-measured SMEP benefits to the national level.

Research Questions and Hypotheses

This section describes the research questions to be addressed by the TTI Evaluation Team as part of the national evaluation. The specific research questions include the following:

- What are the potential SMEP benefits of deploying the same CV technologies as deployed in the three CVPDs (Wyoming, Tampa, and New York City) to other areas nationwide with similar characteristics as the deployment sites?
- What is the nature and proportion of national travel activity that may benefit from deploying similar CV technologies as deployed at the pilot sites?
- What are the practical financial and institutional frameworks and models for short-, medium-, and long-term deployment of CV-enabled applications across the Nation?
- What are the findings, challenges and solutions, best practices, and lesson learned across all the sites that can inform the potential of the CV technologies used in the CVPD?

The evaluation hypotheses that the TTI Evaluation Team will examine as part of the national-level evaluation include the following:

- Each of the CVPD sites possesses attributes that can be used to identify similar locations throughout the United States, which can potentially benefit from the deployment of CV technologies.
- Deployed nationwide, CV technologies will result in favorable SMEP benefits.
- The financial and institutional frameworks implemented by the three CVPD sites, if applied to similar locations throughout the United States, could accelerate the implementation of CV technologies nationwide.

Assumptions

This section describes the assumptions that the TTI Evaluation Team has made in developing this evaluation plan. Key assumptions include the following:

- The three CVPDs will generate SMEP benefits that can be quantified under readily identifiable operating conditions.
    - Each site is responsible for assessing the SMEP benefits produced by its deployment. The TTI Evaluation Team, as the independent evaluator, is also responsible for evaluating the MEP benefits produced by the deployments, while Volpe is responsible for conducting the safety analyses of each deployment.
    - The team assumes a successful deployment of CV technologies will occur at each site that addresses the identified issues and operational conditions specific to that site, and that enough vehicles are being equipped at each site to make enough of a measurable change in the performance measures along the deployment corridors.
- The benefits generated by each CVPD will be readily transferrable to other locations with similar attributes as CVPD sites.
    - Each deployment is designed to address specific situations and operational conditions at each site.
    - The team assumes that the technology deployed at each site is transferable to locations of similar characteristics and, once implemented, produces similar results in a new location.
- Future deployments will implement the same applications and in a similar manner as the three pilot deployments. The pilot sites are deploying technologies and applications that are still in the early stages of their development life cycle. It is logical to expect that CV technologies and applications are maturing as more locations implement them. However, the team cannot estimate how these changes are likely to impact the measured benefits.
    - For this analysis, the team assumes that all locations in the United States are adopting CV technologies at a similar rate.
    - Based on the penetration rates observed at each of the CVPD sites during the site-specific evaluation scenarios, the team will determine penetration rates that represent reasonable market penetration growth over seven years. The exact adoption rate of the CV technology is not known, so the team will assume rates that represent slow, moderate, and aggressive adoption scenarios. Until the team observes the penetration rates within the site-specific evaluation scenarios, it is too soon to estimate what rates will represent the three adoption scenarios.
    - The team plans to work with USDOT to identify appropriate levels of adoption based on the current market and industry projections.
- Compliance and driver responses to the alerts and warnings produced by the applications at other locations will be similar to those experienced at the CVPDs.

Limitations and Risks

This section identifies significant limitations and risks associated with the approach the TTI Evaluation Team plans to use for conducting this analysis. Critical limitations and risks include the following:

- The team must be able to identify other locations in the United States with similar attributes as the CVPD sites and to develop methodologies to extend the benefits to these similar sites. The team must achieve these tasks to conduct the national-level evaluation.
- The environmental benefits are predicated on mobility benefits. The team is basing its projection of air quality and fuel consumption benefits on the estimated impacts from the CVPDs. The actual impacts of air quality and fuel consumption benefits are highly dependent on fleet mix characteristics and environmental factors. The air quality and fuel consumption benefits will only be estimates.
- Limited data sets exist for conducting the evaluation. The basis of the evaluation from these three CVPD sites is a limited number of equipped vehicles at each site. Additionally, each pilot deployment is implementing only a limited set of safety applications. Also, there may not be measurable/significant impacts at the deployment sites for specific CV applications.
- Benefits will increase as more vehicles deploy CV technologies. Safety and mobility benefits could change substantially as more vehicles become equipped and these vehicles interact more frequently with one another.
- There have been no long-term measures of benefits. MEP benefits are being estimated based on one year of post-deployment data (and in some cases less than a year). Driver behavior is likely to change over the long term as drivers become more familiar with the technology, particularly with safety applications. Some drivers may increase their risk-taking behavior and drive more aggressively with CV technology, while other drivers may become more conservative. The level of trust that some drivers have in the applications may increase (or erode) over time based on both positive and negative experiences with the technology.

Chapter 3. Performance Measures

Table 1 lists the potential performance measures that the TTI Evaluation Team plans to use to estimate the SMEP benefits of the CVPDs. These performance measures are the same performance measures the team is using to assess the benefits of each CVPD.

Table 1. Potential Performance Measures.

Performance Category	Key Performance Measures
Safety	• Changes in crashes rates ○ Single-vehicle crashes ○ Multivehicle crashes ○ Vehicle-pedestrian crashes ○ Vehicle-transit vehicle crashes • Changes in surrogate safety measures ○ Driving speed/speed compliance ○ Changes in speed differentials • Characterization of driver response to application warnings ○ Response time ○ Response action ○ Response intensity
Mobility	• Changes in travel time and travel time reliability ○ Total peak-period travel times ○ Annual person delay ○ Travel time index[1] ○ Commuter stress index[2] ○ Planning time index[3] ○ Percent of daily travel in congested[4] conditions ○ Percent of peak travel in congested conditions
Environmental	• Changes in overall vehicle emissions • Fuel savings
Public agency efficiency	• Changes in on-time performance (transit) • Increased agency situational awareness (weather events, incidents, bridge strikes, etc.)

[1] Travel time index is the ratio of travel time in the peak period to the travel time at free-flow conditions.
[2] Commuter stress index is the travel time index based on the peak direction of travel only.
[3] Planning time index is the ratio of the 95th percentile travel time over the free-flow travel time.
[4] The *Urban Mobility Report* methodology defines a roadway segment to be *congested* when the 15-minute average speed is less than 80 percent of the uncongested speed on a freeway or less than 75 percent of the uncongested speed on an arterial.

Chapter 4. Analysis Approach

This chapter provides a high-level overview of the analysis approach that the TTI Evaluation Team will use to extend the SMEP benefits from the three deployment sites to the national level. This chapter describes the approach that the team will use to characterize the attributes of the pilot sites using both qualitative and quantitative measures. This chapter also describes the approach the team plans to use to identify other regions and locations in the Nation that are like the three pilot sites.

Figure 4 is a flowchart that highlights the steps in the analysis approach that the TTI Evaluation Team will follow in extending the results of the CVPD deployment to the national-level analysis.

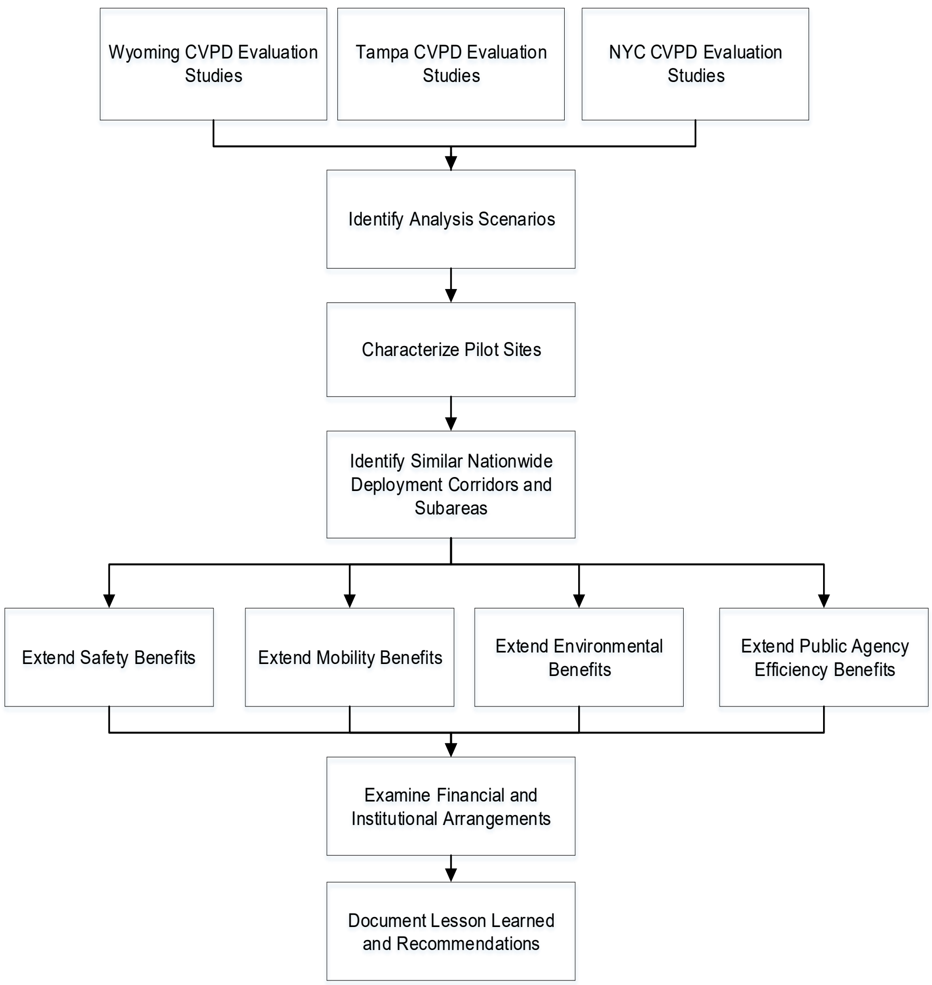


Figure 4. Analysis Approach for Conducting National Evaluation.

Analysis Scenarios

The TTI Evaluation Team will use the results of the independent evaluation to identify analysis scenarios. Each deployment is designed to address certain issues and situations specific to the site. As part of the site-specific independent analyses, the team will use clustering analysis and other techniques to identify particular analysis scenarios and operating conditions under which the CV applications operate. The team expects that different operational benefits will occur during these operational scenarios, and the team will seek to understand the variety of conditions in which the deployments produced benefits.

In extending the results of the CVPD deployments, it will be essential to quantify how frequently these operational scenarios occur at these potential deployment sites. To the extent possible, the research team will examine the factors that affect the performance of the deployment to develop a range of conditions that might benefit from deploying similar systems and technologies as the CVPDs. The team will then use these analysis benefits to extend the SMEP benefits to other potential sites nationwide.

Characterization of Pilot Sites

The three current pilot program locations for the study are I-80 in Wyoming, portions of downtown NYC, and a segment of downtown Tampa, Florida. This recommendation looks at identifying locations that contain the same attributes within similar geographic extents as those in the original study areas. The three sites differ significantly in various factors, including climate, population, infrastructure, and goals. Therefore, while the methods for determining each site will be mostly similar, the criteria will be vastly different. Overall, this problem is spatial and will require the use of geographic information systems (GIS) and spatial analysis knowledge to complete.

The first order of business is to define the criteria that make each of the sites unique. The team will glean this information from the Connected Vehicle Pilot Deployment Program technical documents. Next, the methodology recommended for use in analyzing those criteria will be outlined. These recommendations will mostly outline geospatial analysis fundamentals and non-software-specific tools.

USDOT did not specify the criteria it used to select the agencies that received the funding for this project. The choice was left to each agency to select a set of criteria and a geographic location that presented issues that wireless devices could potentially solve. Therefore, each of the sites differs significantly in the types of issues the deployment is addressing and the regional qualities. Each factor for a specific site can be used to identify new locations. Table 2 shows the criteria for each location. The research team built this table based on information contained in each agency's documentation submitted to USDOT.

While the issues outlined by Wyoming and NYC are spatial features in nature, some of the criteria for Tampa are qualitative categories. These can still be translated into spatial criteria by simply finding areas where those events might be an issue.

Table 2. Potential Attributes for Characterizing CVPD Sites.

Characterization Category	Wyoming	Tampa	NYC
Driving population (target audience)	• Freight operators: ○ Long-distance trips ○ Familiar with advanced technology in the cab	• Daily commuters • Transit operators • Pedestrian	• Operators of passenger car fleet vehicles (professional) • Transit operators • Commercial truck operators • DCAS fleet operators (snowplows, sanitation vehicles, etc.)
Vehicle population	• Long-distance interstate trucks (data consumer) • A high percentage of trucks and recreational vehicles	• Personal vehicles • Transit buses (express) • Fixed route transit: ○ Express buses ○ Trolley	• Auto-oriented fleet vehicles with high fleet turnover • Buses • Trucks • Maintenance fleet vehicles (sanitation trucks, snowplows, etc.)
Road geometry and network characteristics	• Rural interstate • Linear corridor • High operating speeds (during ideal conditions)	• Urban grid • Moderate population core • Moderate driveway density • Moderate operating speeds (≤35 mph) • Exclusive transitways • Moderate intersection spacing	• Urban grid • Corridor oriented • Dense population core • Low operating speeds (<25 mph) • Tight intersection spacing
Operational conditions—weather	• Snow and rain events • High wind events • Frequent closures due to hazardous travel conditions	• No CV apps were designed to operate only under specific weather conditions	• No CV apps were designed to operate only under specific weather conditions
Operational conditions—demand	• Relatively low average annual daily traffic (AADT) • A high percentage of truck traffic (≥50 percent) • Consistent demand levels (limited peaking)	• Moderate AADT • Peak period (particularly AM peak) • Pass-through to a major trip generator (e.g., Airforce base)	• High AADT • High pedestrian traffic • Non-peak period (midday/shoulder of peaks)

Characterization Category	Wyoming	Tampa	NYC
Issues to be addressed	• Collisions during severe weather events: ○ Multivehicle collisions ○ Single-vehicle rollover (wind)	• Point-specific safety issues: ○ Intersection oriented • Congestion-oriented issues: ○ Queuing ○ Improved signal progression • Conflicts between user populations: ○ Vehicle-pedestrian ○ Vehicle-trolley	• Individual driver safety/performance • V2V conflicts • Corridor-level performance (secondary)

Identification of Similar Nationwide Deployment Corridors and Subareas

After determining the critical attributes associated with each CVPD site, the TTI Evaluation Team will identify other locations in the United States that experience similar attributes. The team plans to use national and statewide data sets to identify other potential sites that might experience similar benefits if similar technologies and applications were deployed to address similar problems as those defined by the CVPD teams. The TTI Evaluation Team will attempt to quantify the extent to which a candidate site matches the attributes of each CVPD site. The team will use this approach to proportion the benefits measured at the CVPD site to the candidate locations. For example, the team will allocate a greater proportion of the benefits to sites that more closely match the conditions to one of the CVPD sites, compared to those where the match is less strong. Using the Wyoming site as an example, sites that more closely matched the critical attributes of the Wyoming site (a high percentage of truck volumes, rural interstate travel, and heavily impacted by winter-type weather) would receive more benefits than a site that does not closely match the attributes of the Wyoming deployment corridor (e.g., urban interstates with a low percentage of trucks and moderate weather conditions). One approach for determining how to proportion the benefits might be to use a weighting factor reflecting how well the site matches the pilot site (using some attribute such as the sum of squares value from the cluster analysis). The team plans to determine the details of how to proportion the benefits as part of the analysis.

The Federal Reserve Bank of Chicago has developed the Peer City Identification Tool (PCIT). The tool is intended to help individuals identify cities that are experiencing similar trends and challenges. Drawing on city-level indicators from the American Community Survey and historical Decennial Census records, the PCIT performs a cluster analysis to identify groups of similar cities along economic, demographic, social, and housing dimensions (*9).* The analysis tool used Ward's method for clustering peer cities. Ward's method minimizes the sum of squares errors across all variables in a given population to identify similar conditions.

The TTI Evaluation Team will consider applying a similar clustering technique to finding candidate locations that closely match the characteristics of the three CVPD sites. The team will develop a data table that includes potential classification variables from other candidate roadways. Examples of potential classification variables include the following:

- AADT.
- Vehicle miles traveled (VMT)—total.
- VMT—trucks.
- VMT—transit.
- Average daily speed.
- Average peak-period speed.
- Vehicle fleet composition (percentage of trucks and percentage of transit vehicles).
- Population density.
- Number of lane miles.
- Roadway classification.
- Type, frequency, and duration of weather events, by storm intensity.

The TTI Evaluation Team will use nationally available databases to quantify the characteristics at each site. The team will consult different databases to secure the information. For example, the team will use the National Highway Performance Monitoring System (HPMS) to gather data on the extent, condition, performance, use, and operating characteristics of the national highways. The National Performance Measure Research Data Set can be used to obtain information about average travel speeds and traffic volumes (AADT). Census data can be used to obtain information about population and driving characteristics. The team will obtain weather data from the National Oceanic and Atmospheric Administration's National Climatic Data Center.

Extending Safety Benefits

Each CVPD is deploying applications intended to address specific safety issues associated with the site. For example, in Wyoming, the focus of the CVPD is to improve safety and traveler information during winter and high-wind weather events (*3*). In Tampa, the focus of the deployment is to reduce the number and frequency of wrong-way-driving events, vehicles turning in front of transit vehicles, vehicles colliding with the back of standing queues, and vehicle-pedestrian collisions at a mid-block crosswalk (*5*). The NYC CVPD is attempting to reduce the number of collisions involving fleet vehicles and the frequency of vehicle-pedestrian collisions (*8*).

Volpe is responsible for analyzing the safety benefits associated with the CVPDs. Its analysis is attempting to determine the extent to which the CVPD achieved its safety performance goals. Volpe will analyze vehicle logs to try to estimate how the various alert messages and interactions between vehicles changed as a result of equipping a portion of the traffic stream with CV applications. Volpe plans to produce estimates of the potential crash avoidance measure for specific types of collisions addressable by specific applications (e.g., the effects of the electronic brake light system on rear-end collisions). The TTI Evaluation Team will explore the feasibility of using these crash avoidance factors associated with each CVPD application.

The application of this approach is highly dependent on the outcomes of the Volpe safety analysis. For this analysis, the TTI Evaluation Team will assume that the crash avoidance factor is a surrogate for the Federal Highway Administration's (FHWA's) crash reduction factor (CRF). According to FHWA's Office of Safety, a CRF is the percentage of crash reduction that one might expect after implementing a given countermeasure at a specific site *(10*). CRFs are *generic estimates* of the effectiveness of a countermeasure and, when used with appropriate engineering judgment, can be extended to estimate safety benefits at comparable locations. To apply the CRFs, the TTI Evaluation Team will consider the site-specific environmental, traffic volume, traffic mix, geometries, and operational conditions of each pilot site. The team will then follow the methodology described in the *Highway Safety Manual (HSM)* (*11*) to extend the safety benefits of the CVPDs to the other sites. Part C of the *HSM* provides a methodology for estimating the expected average crash frequency at a potential site. The method uses three components to predict the average expected crash frequency of a site:

1. The base model, called a safety performance function (SPF).
2. The crash modification factor (CMF) to adjust the estimate for additional site-specific conditions that may be different from the base condition.
3. A calibration factor to adjust the crash frequency estimates to account for State or local area differences.

The following equation can be used to predict average crash frequency at a site:

$$N_{Predicted} = N_{SPF} * (CMF_1 * CMF_2 * \ldots * CMF_{yz}) * C_x$$

Where:

$N_{Predicted}$	=	predicted average crash frequency for a specific year for site type x.
N_{SPF}	=	predicted average crash frequency determined for the base conditions for the SPF developed for site type x.
CMF_x	=	CMFs specific to the SPF for site type x.
C_x	=	calibration factors to adjust the SPF for local conditions for site type x.

This methodology uses SPFs to estimate predicted crash frequency as the function of exposure and roadway (or intersection) characteristics. The general form of an SPF is as follows:

$$Predicted\ Average\ Crash\ Frequency\ (N_{SPF}) = \exp[\alpha + \beta * \ln(AADT) + \ln(L)]$$

Where:

AADT	=	average annual daily traffic.
L	=	segment length.
α and β	=	calibration parameters developed in the regression analysis to produce the SPF.

An analyst can also include other factors (e.g., geometric conditions, weather, and other operational parameters) in the model. The calibration parameters represent factors from the regression analysis techniques that relate crash frequencies and severity to the operational conditions.

Ideally, the TTI Evaluation Team will use this methodology to estimate the safety benefits of the CVPDs to other locations nationwide. The team will use the following process to extend the safety benefits:

1. Identify potential sites that have similar exposure and operating conditions for each pilot site.
2. Using crash frequency and severity data from these sites, use SPFs relating crash experience to exposure and operating condition data for each deployment site and each application.
3. Using the SPF from each CVPD site, estimate the number of crashes that would occur without the benefit of the CVPD technologies at the identified nationwide sites.
4. Applying the results from the Volpe safety analysis, estimate the number of crashes that might occur if agencies were to deploy similar CV technologies as the CVPD site to the nationwide sites.
5. Compute the change in crash frequencies and severity by comparing the with- and without-crash frequency from each grouping and application.

This approach depends heavily on two assumptions:

- The TTI Evaluation Team can develop meaningful SPFs that can relate crash frequencies to the exposure and operating conditions for the sites that are similar to the CVPD sites.
- Volpe can measure reductions in crashes due to the CVPD improvements.

If these two assumptions cannot be met, the TTI Evaluation Team, at a minimum, will examine summary crash histories from the new study areas to determine the extent to which the safety benefits measured from the CVPD applies to each of the new study areas. The team will examine at least two years of crash summaries from the new study areas for the assessment

Extending Mobility Benefits

The TTI Evaluation Team will use a similar approach to extend the changes in mobility from the CVPD to the national level. The team will examine the congestion and mobility issues reported for each of the sites to examine the types of mobility issues and trends exhibited by these sites. The team will look at observed impacts of the deployed applications on mobility performance measures such as travel times, delays, travel time reliability, speed, and spatial extent of congestion at each of the CVPD sites. At a minimum, the team will use a case study approach to extend the mobility benefits to the identified sites qualitatively, in which the team will conduct an intensive analysis of one or two sites to examine the extent to which deploying a system similar to those used by the CVPD might benefit a specific location or instance. Often case studies are descriptive and explanatory and use both quantitative and qualitative data to extend results to a site. For example, only a limited number of sites may be similar to the Wyoming deployment. The team may examine one or two of those sites in detail to see how to extend the mobility benefits from the Wyoming site to those locations.

The TTI Evaluation Team may contact some sites to discuss the applicability and the extensibility of the CVPD deployments to their location. As in the safety analysis, the team will apply market penetration rates like those from the CVPD sites in estimating potential mobility benefits at each location. The team fully expects this approach will yield a range of mobility benefits to each site.

Another approach that the TTI Evaluation Team may use to estimate the mobility benefits is to apply the same methodology used in the *Urban Mobility Report (UMR) (12).* The *UMR* procedures estimate mobility at an area level. The approach describes congestion in a way consistent with allowing comparison across urban areas or groups of urban areas. The methodology computes the following performance measures:

- Travel delay.
- Person delay.
- Delay per auto commuter.
- Total peak-period travel times.
- Travel time index.
- Commuter stress index.
- Planning time index.
- Percentage of daily and peak travel in congested conditions.

The following steps are used to calculate the congestion performance measures for each urban roadway section under the *UMR* methodology:

1. Obtain HPMS traffic volume data by road section.
2. Match the HPMS road network sections with the INRIX traffic speed data set by road section.
3. Estimate traffic volumes for each hour time interval from the daily volume data.
4. Calculate average travel speed and total delay for each hour interval.
5. Establish free-flow (i.e., low-volume) travel speed.
6. Calculate congestion performance measures.

7. Perform additional steps when volume data have no speed data match.

The appendix describes the methodology that the team plans to use to compute the *UMR* performance measures.

The TTI Evaluation Team plans to use the case study approach if the site identification process identifies only one or two sites that are similar to the CVPD sites. Otherwise, the team plans to use the *UMR* approach. The team will use the cluster analysis from the site selection process to provide insight into which approach is appropriate. If only one or two other sites cluster with a CVPD site, then the team will use the case study approach. However, if multiple sites cluster with a CVPD site, then the team will use the *UMR* approach. The research team may develop case studies for one or two sites, even if the *UMR* approach is applied, to illustrate how other sites may generate benefits from deploying the CVPD site applications.

The process that the TTI Evaluation Team plans to use to extend the mobility benefits to other locations is as follows:

1. Compute the performance measures for each candidate location using the *UMR* methodology. The team plans to use this to represent an estimate of current mobility conditions at each site.
2. Apportion the CVPD mobility benefits based on the extent to which each identified site matches the characteristics of the CVPD site.

The team will explore several possibilities for determining how to apportion the CVPD mobility benefits to the candidate sites. One approach is to quantify the extent to which each site experiences the same operational scenarios as the CVPD sites. The team will then look at the frequency and duration of these operational scenarios that occur at each of the identified candidate sites. The team will apply the mobility benefits to those times only where the same conditions as the CVPD sites exist.

Another strategy is to develop a regression analysis or other similar statistical modeling techniques to proportion mobility benefits. In this approach, the team will examine and develop a statistical model on how the mobility benefits vary in response to changes in critical factors (e.g., weather, traffic volumes, and operational conditions) at each of the CVPD sites. The team will then extend the results of the regression analysis to the other sites to estimate the relative change in mobility benefits associated with the new candidate sites.

Extending Environmental Benefits

Extending the environmental benefits derived from the CVPD to other locations is more complicated. The current air quality measures influence the potential environmental benefits of CV technology. For example, the ratio of nitrogen oxides, carbon monoxide, volatile organic compounds, and sunlight determines ground-level ozone formation.

Air quality benefits will be estimated using a similar methodology developed for the *UMR (12)*. The methodology uses data from three primary data sources:

- FHWA's HPMS.
- INRIX traffic speed data.

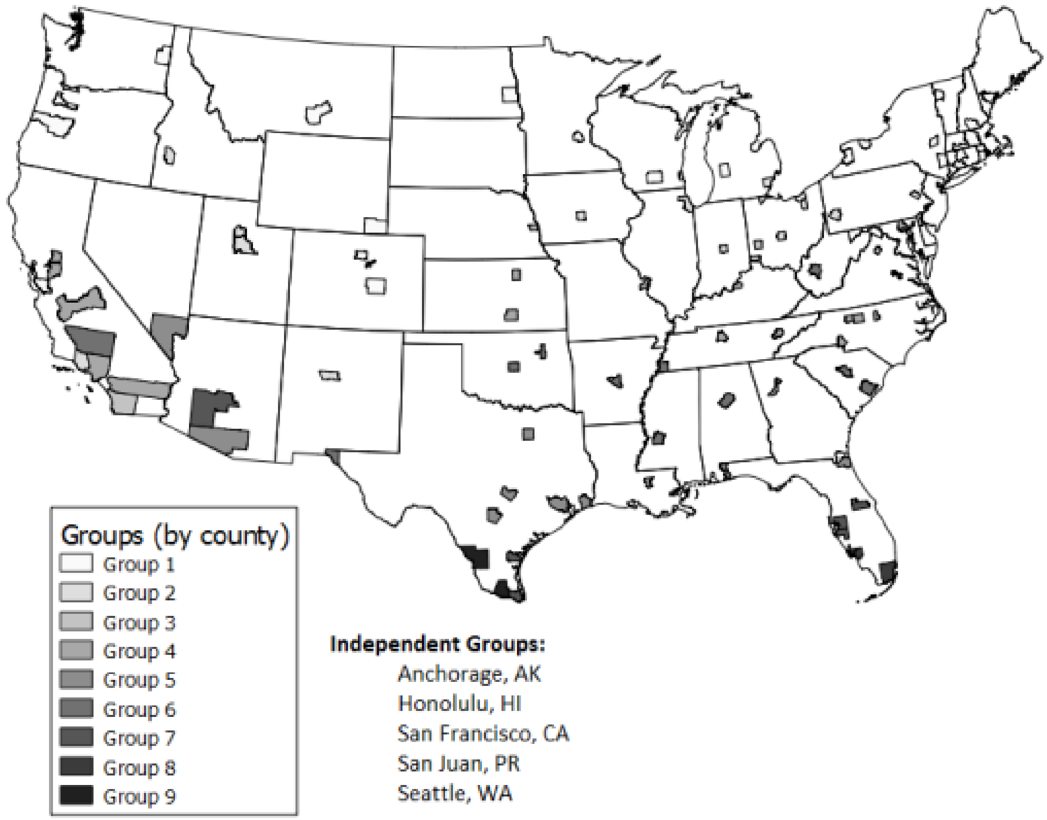
- The Environmental Protection Agency's MOVES model.

The TTI Evaluation Team will implement six steps in this analysis:

1. Group similar urban areas based on climatic conditions and background air quality levels. As shown in Figure 5, TTI maintains regional groupings as part of its *UMR*. The team will evaluate the value of using these pre-established groupings versus creating a new set of groupings. The team plans to use the same cluster analysis approach to create a regional grouping for the three candidate sites. These regional groupings will include an appropriate number of counties that look similar to each of the pilot sites. The team will determine the appropriate number of sites at the time of the analysis.
2. Obtain emission rates (grams per hour) for the selected pollutants of interest for each urban grouping using the MOVES model.
3. Develop curves that link emission rates with speed of travel using MOVES.
4. Combine real-world speed and volume data for congested conditions from HPMS and INRIX to estimate fuel consumption and total region-wide emissions without applying the environmental benefits from the CVPD sites
5. Estimate the fuel consumption and emission benefits for the three groupings using the speed changes measured in the CVPD sites.
6. Compute the change in fuel consumption and emissions with and without the benefits of having CV deployments in each of the three regions. This value will provide a maximum potential benefit of CV technologies deployed at scale at the national level.

The team will use a similar approach as that used to proportion mobility benefits to proportion the environmental benefits of deploying the CVPD technologies at the identified candidate site. This approach may include proportioning environmental benefits based on the percentage of time that conditions at the site match those of the CVPD site. The team may also apply a similar regression analysis approach used with the mobility benefits to environmental data. The exact method of proportioning the benefits will be determined once data from each CVPD site have become available.

Because the *UMR* analysis approach examines environmental impacts at the county level, the team will need to convert mobility benefits to the facility level. One approach for doing this might be to proportion the environmental benefits based on VMT. The team will determine the methodology for this conversion as part of the analysis.



Source: Texas A&M Transportation Institute (*12*)

Figure 5. Grouping of Counties with Similar Environmental Operating Conditions.

Extending Public Agency Efficiency Benefits

To the extent that the CVPDs' evaluation data will support this analysis, the TTI Evaluation Team will examine extending public agency efficiency benefits to the national level. Examples of improved public agency efficiency benefits include the following:

- Enhanced situational awareness.
- Reduced incident response and clearance times.
- Faster notification of equipment malfunctions.
- Improved coordination between agencies.

Because State and local departments of transportation have different levels of maturity in terms of their infrastructure, resource, and traffic management capabilities, it is challenging to apply measures of public agency efficiency benefits for the CVPD sites to other locations directly. As a result, the analysis of extending public agency benefits to the national level will consist of summarizing the findings of the public agency benefits analyses from the CVPD deployments and showcasing how other sites might achieve similar benefits. This analysis will be purely qualitative.

Data Needs

The national evaluation requires that the TTI Evaluation Team identify sites comparable to the current CVPDs. The methods for finding the comparable study areas require spatial analysis fundamentals and a GIS. The GIS data are needed from various sources to conduct the analysis. To use the criteria defined previously to determine new study areas, the spatial analysis techniques of proximity and overlay would be beneficial. The data should have spatial attributes and preferably be in shapefile or geodatabase format for inclusion in the GIS. Table 3 outlines some of the data sources that could potentially offer GIS data that would provide some of the needed information. The majority of these sources are open GIS data portals provided by the State or city departments of transportation. Each of these sites provides data in a format suitable for GIS software. The analyst conducting these tasks may identify additional sources necessary to complete the linkage.

Table 3. Potential Data Sources for Characterized CVPD Sites.

Data Source	URL
Florida Department of Transportation GIS	https://www.fdot.gov/statistics/gis/default.shtm
Tampa Open Data	https://city-tampa.opendata.arcgis.com/
NYC DOT GIS	https://gis.ny.gov/gisdata/inventories/member.cfm?organizationID=539
NYC Planning Open Data	https://www1.nyc.gov/site/planning/data-maps/open-data.page
WYDOT GIS	http://gis.wyoroad.info/
University of Wyoming's Wyoming Geospatial Hub	https://www.geospatialhub.org/
USDOT's Bureau of Transportation Statistics	https://www.bts.gov/maps

Figure 6 shows an example of nationwide data representing a high volume of commercial routes. This database may be a potential data source used for information such as Wyoming's criteria for highways with significant volumes of truck traffic.

Source: US Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.4, 2013.

Figure 6. Example of Nationwide Data Representing High Volume Commercial Routes.

After the acquisition of the data, several processes can be used to determine site locations. The analysis may have to be conducted State by State since the format of the data from each State may be different. The assumption for this recommendation is that the site selections will be made in the United States only. Also, there may not be a data set for a specific attribute like pedestrian crossings for some States (which is important for finding a comparable site for the New York deployment). The TTI Evaluation Team may need to reduce the criteria for site selection, depending on the geographic region that is being queried.

The GIS workflow for the data would be similar to the following:

1. Preprocess the data if necessary by conducting tasks like re-projecting the data into a common coordinate system or clipping to the extent of the study area if needed.
2. Overlay all pertinent data sets for a specific site query in a single map (i.e., Wyoming data sets are wind polygons, average snowfall raster, elevation data, major routes in the State, etc.)
3. Convert raster data sets to vector formats to enable queries.
4. Conduct Structured Query Language (SQL) queries of each layer’s attribute data to narrow the data sets to only those that meet the criteria.

5. Perform buffer operations, if needed, to specify a distance from certain features that would be appropriate.
6. Conduct an intersect operation to produce derived data sets that contain the junction of where those data sets meet

The resulting data would include only those features that meet the criteria and intersect within a certain distance those other features that meet the criteria. The criteria for distances between features can be adjusted if needed. Criteria can be added or removed depending on the availability of data sets. This process would potentially need to be done one State at a time. However, this process presents the issue of not being able to determine sites that overlap State boundaries. Overlapping boundaries are acceptable if the site location is desired to be within only one State at a time. An analyst may mitigate this constraint if there are overlapping or connecting data sets from one State to an adjacent State. These must have the same data format (point, line, polygon, or raster) and identically formed attributes (i.e., the same attribute field names and categorical/numerical values). Similarity in data between States is rare. At this point in the planning process, the CVPD sites have not yet uploaded complete samples of their deployment data. Therefore, the TTI Evaluation Team does not yet know what data are available for the site-specific evaluations or the national-level evaluation. As more data are uploaded, the team can revise this plan with more details on the data sources and the parties responsible for collecting and providing the data.

The national evaluation is also very dependent on benefits data coming from the independent evaluation of the CVPDs. Specifically, examples of the types of data the research plans to use from the CVPD independent evaluations include the percentage of change in:

- Crash rate (or CRFs).
- Travel times and/or travel speeds.
- Traffic demands.
- Travel time reliability measures (95th percentile).
- Speed compliance.
- Vehicle-pedestrian interactions.
- Vehicle emissions.
- Fuel consumption.
- Event notifications (incidents, weather events, etc.).

Finally, much of the methodology for this analysis requires detailed travel demand and mobility measures available through private sources such as INRIX. These data are needed not only for the CVPD sites but also for other locations nationwide. The TTI Evaluation Team can access these data through a contractual arrangement with INRIX. The team will explore how these data can be used and uploaded into the Secure Data Commons (SDC).

Chapter 5. Financial and Institutional Frameworks and Models

As part of Task C, the TTI Evaluation Team plans to analyze the financial models used by the sites. The team expects that this financial evaluation will produce a report highlighting the results of the financial evaluation model deployed at each site. Each report is expected to include the following sections (*13*):

- A qualitative description of the pilot site's current business plan approach (as gathered from interviews, data collection efforts, and roundtable discussions).
- A list of the relevant financial factors that were evaluated along with the current data associated with each, as provided by the pilot sites.
- A list of any assumptions made as part of the analysis.
- An overview of the financial evaluation model results, including the identified metrics and an interpretation of whether the site is projected to achieve financial sustainability as currently modeled.
- Suggestions for factors that could be changed/improved to improve financial performance.

The team will also examine various financial models available that can facilitate the deployment of the CVPD applications to other locations. The team will estimate how factors such as market forces; technology adoption and usage; local, State, and Federal laws and regulations; and the use of incentives might impact the widespread deployment of the CVPD applications at the national level. The team will also outline potential options that agencies may use to obtain capital funds for supporting initial system deployment, and ongoing funds to sustain operations and maintenance into the future. The team will also examine the role that potential public/private partnerships might play in facilitating the adoption of the CVPD applications at a national level.

The TTI Evaluation Team will use a similar approach for identifying the institutional frameworks, which might be needed to promote the wide-scale deployment of the CVPD applications across the Nation. In Task C, the team will examine and document the institutional arrangement the core agencies (WYDOT, THEA, and NYC DOT) have put in place to support their developments. The team will use the findings from this evaluation to identify a core set of institutional factors that influence the success of the deployments. The team will also use the best practices and lessons learned from the Task C evaluation to provide suggested institutional frameworks for agencies desiring to deploy applications similar to the sites.

Chapter 6. Lessons Learned and Recommendations

The TTI Evaluation Team will synthesize the findings of the national evaluation to highlight the issues, challenges, and potential solutions associated with deploying the applications tested in the CVPDs at a national level. The team will summarize the best practices from the deployments and examine how agencies might apply them at the national level. The team will provide recommendations on strategies, tactics, and practices focused on the short, medium, and long term. Because locations across the United States have different levels of capability and experience with technology, the team will focus on identifying the base-level institutional and financial requirements needed to extend the CVPD to the national level. This analysis will be done primarily through the knowledge and experience of the TTI Evaluation Team. The team will also rely on information collected during the post-deployment interviews and workshops in Task C. The team will use the lessons learned and experiences published by USDOT to provide recommendations on processes and procedures for extending the deployments to the national level.

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Appendix. Methodology for Computing Urban Mobility Report Performance Measures

This appendix describes the methodologies that researchers used to compute mobility-related measures for the *2019 Urban Mobility Report*.

Travel Delay

The *Urban Mobility Report* (*UMR*) uses travel delay (in person-hours) as a measure of the magnitude of congestion problems in a region. Travel delay is a combination of congestion intensity (as measured by travel speed) and magnitude (as measured by the number of people suffering that congestion). The *UMR* uses the following formula to compute travel delay:

$$Delay = \left(\frac{Vehicle\ Miles\ Travel}{Speed}\right)_{Segment} - \left(\frac{Vehicle\ Miles\ Travel}{Free\ Flow\ Speed}\right)_{Segment}$$

The hourly speed and volume data were combined to calculate the total travel time for every 15 minutes. The 15-minute volume for each segment was multiplied by the corresponding travel time to get the number of vehicle-hours. The analyst can sum the delays for all 24 hours for every road segment in the analysis area.

Person Delay

The *UMR* calculates person-hours of delay by multiplying each day-of-the-week delay estimate by the average occupancy and by 52 weeks per year.

Delay per Auto Commuter

Delay per auto commuter is a measure of the extra travel time endured by auto commuters who make trips during the peak period. In the *2019 Urban Mobility Report*, researchers apply estimates of the number of people and trip departure times during the morning and evening peak periods from the National Household Travel Survey to the urban area population estimate to derive the average number of auto commuters during the peak period.

The delay calculated for each commuter comes from delay during peak commute times and delay that occurs during other times of the day. All the delay that occurs during the peak hours of the day (6:00 a.m. to 10:00 a.m. and 3:00 p.m. to 7:00 p.m.) is assigned to the pool of auto commuters. The delay that occurs outside of the peak period is assigned to the entire population. The Texas A&M Transportation Institute Evaluation Team will use the following equation to compute delay per auto commuter:

$$Delay\ per\ Auto\ Commuter = \left(\frac{Peak\ Period\ Delay}{Auto\ Commuter}\right) + \left(\frac{Remaining\ Delay}{Population}\right)$$

The reason that the off-peak delay is assigned to the commuters is that their trips are not limited to peak driving times; they also contribute to the delay that occurs during other times of the weekdays and weekends.

Travel Time Index

The travel time index (TTI) compares peak-period travel time to low-volume travel time. The TTI includes both recurring and incident conditions and is an estimate of the conditions faced by travelers, particularly urban travelers. The TTI is computed by comparing total travel time to the free-flow travel time. The index can also be calculated by dividing the sum of the delay time and low-volume travel time by the low-volume travel time. The TTI is computed using the following equation:

$$Travel\ Time\ Index = \frac{Peak\ Travel\ Time}{Low\ Volume\ Travel\ Time}$$

$$Travel\ Time\ Index = \frac{Delay\ Time + Low\ Volume\ Travel\ Time}{Low\ Volume\ Travel\ Time}$$

The change in TTI values is computed by subtracting 1.0 from all the TTI values so that the resulting values represent the change in extra travel time rather than the change in the numerical TTI values.

Commuter Stress Index

Most of the roads and public transportation networks operate with much more volume or ridership (and more congestion) in one direction during each peak period. Averaging the conditions for both directions in both peaks (as with the TTI) provides an accurate measure of road congestion but does not always match the experience of the majority of commuters. The commuter stress index (CSI) combines the travel speed from the direction with the most congestion in each peak period to illustrate the conditions experienced by the commuters traveling in the predominant directions (e.g., inbound from suburbs in the morning and outbound to the suburbs in the evening). The calculation uses the same formula as the TTI but uses travel times for the peak directions of travel only. The CSI is more indicative of the work trip experience by each commuter daily.

Planning Time Index

The planning time index (PTI) is based on the idea that travelers want to be on time for an important trip 19 out of 20 times. The PTI is computed using the following equation:

$$Planning\ Time\ Index\ (PTI) = \frac{95th\ Percentile\ Travel\ Time\ (minutes)}{Free - flow\ Travel\ Time\ (minutes)}$$

The *2019 Urban Mobility Report* used the following procedure to compute the 95th percentile travel time:

1. The speeds for every 15 minutes during the eight peak hours of the five workdays are ranked from worst to best for each freeway segment (a total of 160 values).
2. The 95th percentile work value (number 152 of the 160) is chosen to represent the road segment.
3. A regional average is obtained by weighting each segment's 95th percentile value by the peak-period vehicle miles traveled on that segment.

Time of Congestion

Providing a time when congestion might be encountered is one method of explaining both the congestion problem and illustrating some of the solutions. The measure uses times of day when each road direction speed is below 75 percent of the street free-flow speed or 80 percent of the freeway free-flow speed (e.g., below 48 mph on a 60-mph freeway). The times are calculated using 15-minute travel speeds.

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