Connected Vehicle Pilot Deployment Program Independent Evaluation:

Analysis, Modeling, and Simulation Plan—Tampa

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Research Report—August 3, 2018
FHWA-JPO-18-665

U.S. Department of Transportation

Produced by Texas A&M Transportation Institute
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
Intelligent Transportation System (ITS) Joint Program Office

Notice

Technical Report Documentation Page

1. Report No. FHWA-JPO-18-665	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Connected Vehicle Pilot Deployment Program Independent Evaluation: Analysis, Modeling, and Simulation Plan—Tampa	**5. Report Date** August 3, 2018
	6. Performing Organization Code
7. Author(s) Abby Morgan (KAI), Richard Dowling (KAI), Geoff Morrison (The Cadmus Group), Mark Burris (TAMU), and Kevin Balke (TTI)	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Texas A&M Transportation Institute Texas A&M University System 3135 TAMU College Station, TX 77843-3135	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. DTFH6116D00045
12. Sponsoring Agency Name and Address ITS Joint Program Office 1200 New Jersey Avenue, S.E. Washington, DC 20590	**13. Type of Report and Period Covered** Research Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Work Performed for Walter During (Federal Highway Administration)

16. Abstract

The purpose of this analysis, modeling, and simulation (AMS) plan is to provide a well-defined and unambiguous set of steps to be followed for modeling, simulating, and evaluating the mobility and environmental impacts of the pilot deployment as outlined in the refined evaluation plan for Tampa, created in Task 2 of this project. The plan describes the data requirements and sources of data for the AMS work and the analysis framework that the Texas A&M Transportation Institute (TTI) Connected Vehicle Pilot Deployment (CVPD) Evaluation Team will follow. The TTI CVPD Evaluation Team will conduct the AMS part of its evaluation employing the model(s) developed and calibrated by the Tampa Deployment Team for the Tampa deployment. The TTI CVPD Evaluation Team will extend this model to address scenarios to represent various combinations of the following confounding factors: incident types, weather types, and demand levels. Sensitivity tests will evaluate various levels of connected vehicle onboard unit market penetration of the vehicle fleet for the Tampa test site. The evaluation team is conservatively recommending that market penetration rates achievable within the next 7 years be evaluated.

17. Key Words Connected Vehicle Pilot Deployment, Independent Evaluation, Simulation, AMS Planning, Tampa CV Pilot Deployment	**18. Distribution Statement**

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages** 84	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Acknowledgements

The authors would like to thank the following individuals for their assistance in developing this plan in support of the independent evaluation of the Connected Vehicle Pilot Deployment Program:

- Walter During, Federal Highway Administration (FHWA).
- Kate Hartman, Intelligent Transportation Systems Joint Program Office (ITS JPO).
- John Halkias, FHWA.
- Gabriel Guevara, FHWA.
- Jonathan Walker, ITS JPO.
- Govindarajan Vadakpat, FHWA.
- Douglas Laird, FHWA.
- Ariel Gold, ITS JPO.
- Tom Kearney, FHWA.
- James Colyar, FHWA.
- James Sturrock, FHWA.
- Fessmann Volker, FHWA.
- Emily Nodine, Volpe.
- Margaret Petrella, Volpe.
- Wassim Najm, Volpe.
- Karl Wunderlich, Noblis.
- Meenakshy Vasudevan, Noblis.
- Sampson Asare, Noblis.
- Kathy Thompson, Noblis.
- Peiwei Wang, Noblis.

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List of Acronyms

Acronym	Definition
AAA	American Automobile Association
AIS	Abbreviated Injury Scale
AMS	Analysis, Modeling, and Simulation
APU	Auxiliary Power Unit
ASD	Aftermarket Safety Device
BRT	Bus Rapid Transit
CBD	Central Business District
CO_2	Carbon Dioxide
CPI	Consumer Price Index
CV	Connected Vehicle
CVPD	Connected Vehicle Pilot Deployment
CVPEP	Connected Vehicle Performance Evaluation Platform
EPA	Environmental Protection Agency
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
GUI	Graphic User Interface
HCM	Highway Capacity Manual
IE	Independent Evaluator
I-SIG	Intelligent Signal System
ME	Mobility and Environmental
MOE	Measure of Effectiveness
MOVES	Motor Vehicle Emission Simulation Model
NO_X	Nitrogen Oxide
NHTSA	National Highway Traffic Safety Administration
OD	Origin-Destination
PDM	Project Data Manager
PM	Particulate Matter
REL	Reversible Express Lane

Acronym	Definition
RSU	Roadside Unit
SDC	Secure Data Commons
SO_X	Sulfur Oxide
THEA	Tampa-Hillsborough Expressway Authority
TMC	Transportation Management Center
TSP	Transit Signal Priority
TTI	Texas A&M Transportation Institute
USDOT	U.S. Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VHT	Vehicle-Hours Traveled
VMT	Vehicle-Miles Traveled
VOC	Volatile Organic Compound

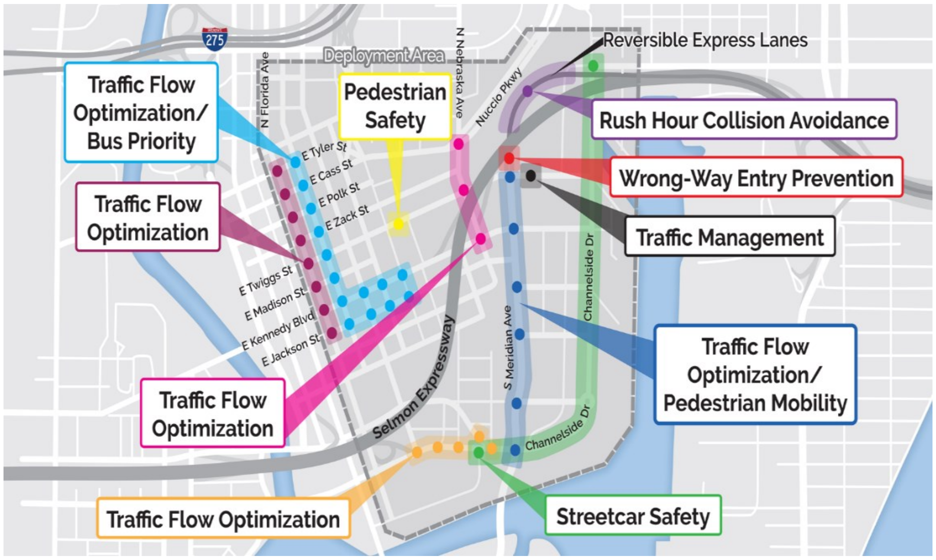
Chapter 1. Introduction

The Texas A&M Transportation Institute (TTI) Connected Vehicle Pilot Deployment (CVPD) Evaluation Team expects that analysis, modeling, and simulation (AMS) will play a prominent role in assessing the effects of the CVPD on mobility and the environment. AMS involves the use of advanced simulation tools and statistical analysis techniques to estimate and quantify effects of having vehicles equipped with connected vehicle (CV) technologies on mobility and the environment in the corridor. This report documents the plan that the TTI CVPD Evaluation Team will follow for modeling, simulating, and evaluating the mobility and environmental (ME) impacts of the Tampa-Hillsborough Expressway Authority (THEA) pilot deployment. The TTI team has structured the AMS plan based on processes and procedures described in the Federal Highway Administration's (FHWA's) *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*).

1.1 The Tampa (THEA) Connected Vehicle Pilot Deployment

The goal of the Tampa (THEA) pilot 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 (*2*). 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.

Figure 1 shows the corridors where THEA plans to deploy CV technologies in the downtown areas.



Source: Tampa Connected Vehicle Pilot. Website

Figure 1. The Tampa (THEA) CVPD Deployment Corridors

To support these objectives, THEA will be deploying the following applications as part of its CVPD (*2*):

- **Emergency Electronic Brake Light Warning (EEBLW)**—This application alerts drivers when connected vehicles ahead are braking hard.
- **End of Ramp Deceleration Warning (ERDW)**—This application warns drivers to slow down to a recommended speed as the vehicle approaches the end of a queue.
- **Forward Collision Warning (FCW)** —Using V2V communications, this application warns drivers if a rear-end crash is imminent with a connected vehicle ahead.
- **Intelligent Signal System (I-SIG)**—This application optimizes traffic signal timing based on real-time connected vehicle data.
- **Intersection Movement Assist (IMA)**—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.
- **Pedestrian in a Crosswalk Vehicle Warning** (Ped-X)—This application identifies conflicts between pedestrians in a crosswalk and approaching vehicles.
- **Pedestrian Mobility** (PED-SIG) —This application allows pedestrians equipped with a smartphone application to request service from the traffic signal when approaching a crosswalk at a signalized intersection.
- **Pedestrian Transit Movement Warning** (PTMW)—This application warns pedestrians when a bus or streetcar is starting up or stopping at a nearby intersection.
- **Probe Data Enabled Traffic Monitoring**—This application gathers traffic data from connected vehicles in real time and provides the data to traffic managers to assist in optimizing traffic flow.
- **Transit Signal Priority (TSP)**—This application gives buses priority at traffic signals to keep them running on schedule.
- **Vehicle Turing Right in Front of Transit Vehicle** (VTRFTV)—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 reversible express lane (REL) from the wrong direction. The application will also broadcast a warning to other equipped vehicles on the REL to be alert for wrong-way vehicles.

The Tampa Deployment Team plans to deploy CV technologies in 1,600 privately owned vehicles, 10 buses, and 10 streetcars. The deployment team also plans to equip up to 500 pedestrians with mobile devices and to install 40 roadside units (RSUs) at strategic locations in the downtown area to support the CV applications (*2*).

1.2 Purpose of AMS

AMS is intended to supplement, not replace, the analysis of observed field data in quantifying the effects of the deployments on traffic operations in the corridor. The TTI CVPD Evaluation Team still plans to use direct comparison of observed data as the primary means of quantifying the extent to which the field deployment impacts the mobility and environment in the deployment corridors; however, limitations exist with using only field observations, namely:

- It is difficult to capture system-wide benefits directly from field measures due to the complexity and costs associated with the data collection.
- It is difficult to account for and potentially isolate the influence of confounding factors on direct field observations.
- Direct field observations cannot be used to project future impacts of the deployment (e.g., higher penetration rate and sustained usage of the current applications).

Therefore, the TTI CVPD Evaluation Team will use AMS to overcome these shortcomings associated with observational data. Specifically, the TTI team will use AMS to accomplish the following:

- Quantify the system-wide ME impacts related to deploying CV technologies in the Tampa (THEA) deployment corridors.
- Answer questions and provide insight into conditions and situations that affect the ME benefits associated with deploying CV technologies in corridors.
- Examine how changes in market penetration, both from a vehicle perspective and an infrastructure perspective, impact the ME benefits associated with deploying CV technologies in the deployment corridors.

The TTI CVPD Evaluation Team will focus solely on quantifying the changes on ME impacts associated with the deployment and not on examining potential changes in safety (e.g., crash reductions, time-to-collision projections, etc.) associated with the deployment of the different CV applications. The Volpe Safety Evaluation Team will be looking at the effectiveness of the deployments in changing crash histories and improving safety in the deployment areas. While the TTI team will not be directly modeling safety improvements (e.g., reductions in time to collisions), the TTI team will attempt to capture the mobility benefits associated with reducing the collision frequencies at each site. To do this, the TTI team plans to model different safety-related situations and scenarios both with and without the technology to estimate the mobility benefits that come from improving safety as a result of the technology. For this analysis, the simulation models will assume that all drivers obey all traffic laws and always drive safely (e.g., will never crash, will never get close enough to need emergency braking, and will never run red lights).

In addition to quantifying the changes in mobility associated with the deployment, the TTI team will also use simulation to quantify the extent to which having vehicles equipped with CV technologies in the traffic stream changes vehicle emissions and fuel consumption in the Tampa deployment corridors. The U.S. Environmental Protection Agency (EPA) has shown that a direct correlation exists between mobility and vehicle emissions and fuel consumption. Therefore, changes in mobility also equate to changes in vehicle emissions and fuel consumption. Because the TTI team is not directly measuring vehicle emissions and fuel consumption in the corridor, the TTI team will use AMS to estimate the changes in vehicle emissions and fuel consumption associated with the mobility changes.

The final purpose of using AMS as part of the overall CVPD evaluation approach is to estimate the cumulative ME benefits over the life cycle of the deployment. To do this, the TTI team will use AMS to project the short- and long-term impacts of the deployment under multiple deployment scenarios (e.g., slow, moderate, and aggressive levels of deployments).

1.3 Organization of Report

The organization of this report is as follows:

- Chapter 2 provides a brief overview of the framework that the TTI CVPD Evaluation Team will follow in performing the AMS analysis of the deployment sites. This chapter gives a high-level overview of the activities performed during each step of the analysis.
- Chapter 3 identifies the specific goals, objectives, evaluation hypotheses, and performance measures that the TTI team will examine using AMS.
- Chapter 4 describes the data requirements and sources of data for the AMS work. This chapter also contains information on the approach that the TTI CVPD Evaluation Team will use in conducting a cluster analysis of both the pre- and post-deployment data for identifying the operational scenarios for the simulation modeling for the site.
- Chapter 5 describes the process that the TTI CVPD Evaluation Team will use to calibrate the traffic simulation modeling tool for the identified operational scenarios.
- Chapter 6 describes the processes and procedures that the TTI CVPD Evaluation Team will use to assess the site deployment performance measure output by the simulation model runs.
- Chapter 7 describes how the TTI CVPD Evaluation Team will use the output of the traffic simulation modeling to estimate changes in vehicle emissions and fuel consumption in the deployment. The TTI CVPD Evaluation Team will construct the environmental model using the EPA's Motor Vehicle Emissions Simulator (MOVES) model.
- Chapter 8 describes the techniques the TTI CVPD Evaluation Team will use to aggregate the findings from each of the various scenarios to estimate system-wide benefits. This chapter also describes the process that the team will use to conduct a benefit-cost analysis of the deployment.
- Chapter 9 describes the risks and challenges identified by the TTI CVPD Evaluation Team associated with completing the AMS for the deployment site.

Chapter 2. AMS Analysis Framework

This chapter provides a brief description of the framework the TTI CVPD Evaluation Team will use to conduct the AMS. Figure 2 shows an overview of the framework. The TTI team adapted this framework from *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*). Below is a description of the steps in the framework.

2.1 Step 1. Obtain Base Model from Site

The first step in the AMS process is to determine and obtain copies of the microscopic simulation model developed by the site. The TTI team assumes that the site will provide at least some level of a microscopic simulation model that can serve as a base model. The base model includes the following types of input data:

- Basic road and network configuration data (e.g., the number of lanes, length and design speed, link and node information, special lane designations, etc.).
- The types and locations of traffic control devices, including background traffic signal timings of different time-of-day and operating conditions (e.g., weather-responsive timing plans, time-of-day coordination plans, etc.).
- Typical vehicle mix and performance information of traffic traveling in the corridor.
- Typical operator characteristics (e.g., driver aggressiveness, reaction times, etc.) for the current vehicle mix that exists in the corridor.
- Typical traffic operations and traffic management strategies for different types of operational events (such as incidents, crashes, weather events, etc.).
- Typical traffic demands and origin-destination (OD) patterns for different times during the day.

If a base model does not exist for the deployment site or if the Tampa CVPD Team no longer plans to develop a model, the TTI team will work with the Tampa Deployment Team and the U.S. Department of Transportation (USDOT) to develop a model that can be used to conduct the AMS.

2.2 Step 2. Verify Error-Free Operations

After receiving the base model(s) from the Tampa CVPD Team, the TTI team will test the base model to verify that the model is operating error free. This test will involve running the model to ensure that it produces realistic results without generating any error or warning messages. If an error occurs during this test, the TTI team will work with the Tampa CVPD Team to determine the source of the error and have the Tampa team correct it before continuing with the analysis.

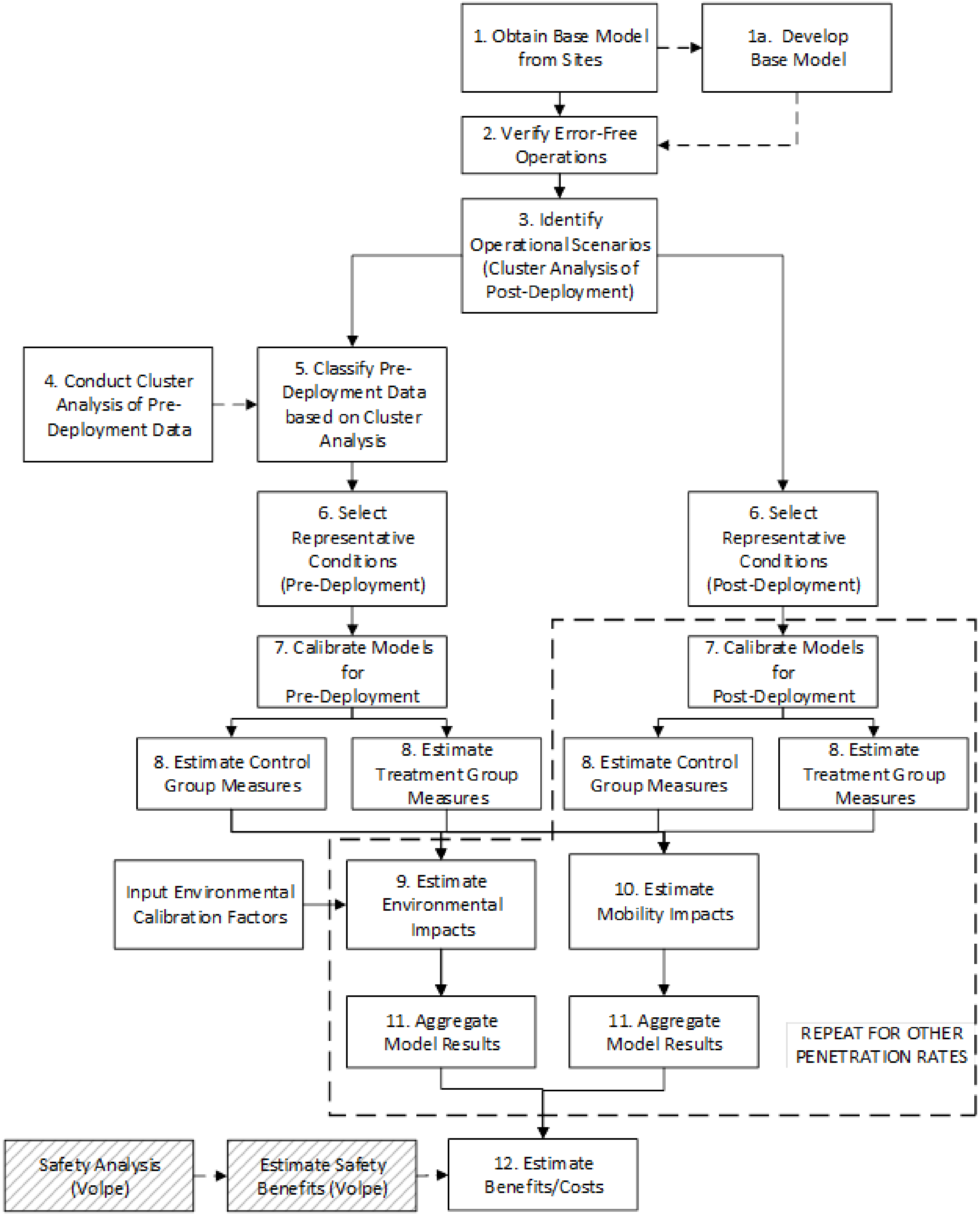


Figure 2. AMS Framework for the Tampa CVPD

In addition to correcting any errors, the TTI team will inspect the model to verify the following:

- The basic geometry and network connectivity adequately represent the analysis area.
- The traffic control data and traffic operations and management data accurately reflect the current strategies deployed in the corridor.
- The driver behavior and vehicle characteristic models accurately represent the performance of the non-equipped vehicles in the network under the base conditions.

The TTI team will also conduct a visual inspection of the animation of the model results. In this review, the TTI team will run the model and view the simulation to see if the modeled vehicle behavior and network configuration seem reasonable. The TTI team will be watching for any aberrant behavior from the vehicles, such as unexpected stops, slow-downs, and lane changes. The team will also be looking for any unexpected bottlenecks or congestion on the network. The purpose of the visual inspection is to ensure that the model provides a realistic representation of the base conditions.

2.3 Step 3. Identify Operational Scenarios

After ensuring that the simulation models provided by the site operate error free, the TTI CVPD Evaluation Team will perform the next step in the AMS analysis, which is to identify the operational scenarios. The operational scenarios represent the cases/situations that the team will model specifically in the analysis. The intent of the operational scenarios is to represent the "use cases" where the CV technology is most likely to have an operational impact as well as account for the different operating conditions (e.g., demand conditions, weather conditions, etc.) that might confound the performance of the CV technologies. These situations/cases are likely to vary between deployment sites.

To identify the operational scenarios to be modeled for the Tampa deployment, the TTI team will conduct a cluster analysis. A cluster analysis is a statistical technique used to segregate large, disparate data to groups that exhibit similar characteristics based on the attributes of the data (such as travel demand, weather conditions, etc.). For this analysis, each cluster represents a specific operating condition or situation where the performance of the system might be affected by the CV technologies deployed at the site. Chapter 4 describes the process that the TTI team will use to conduct the cluster analysis.

The TTI CVPD Evaluation Team will define the identification of operational scenarios based on the attributes of the post-deployment data. The TTI team will use the post-deployment data set as the basis for identifying the operational scenarios (and not the pre-deployment conditions). The TTI team plans to use the post-deployment data to cluster conditions because the post-deployment period is when the CV technologies are deployed and when data are available for a longer period of time (15–18 months).

2.4 Step 4. Classify Pre-deployment Data Based on Post-deployment Clusters

Once the cluster analysis has identified the operational scenarios in the post-deployment data, the TTI team will group the pre-deployment data based on the same attributes to identify comparable situations/conditions in the pre-deployment data. This process should allow for a more direct comparison of the effects of the CV technologies under similar conditions in both the pre- and post-deployment. This analysis approach will also limit the impact and number of confounding factors between the two analysis periods.

After completing the cluster analysis of the post-deployment data, the TTI team will classify the data from the pre-deployment period into the categories identified in the cluster analysis. This process permits the TTI team to compare the before and after effects of deploying CV technologies under similar operating conditions. Grouping the pre-deployment data based on the operational scenarios identified in the post-deployment data helps to control for the impacts of confounding factors that may exist between the two analysis periods. The TTI team will also investigate different temporal aggregations for clustering purposes to ensure that selected temporal aggregation of demand and other data do not create uninformative clusters.

2.5 Step 5. Select Representative Condition(s) within Each Cluster

Once the TTI CVPD Evaluation Team has clustered the data into groups of similar operating conditions, the TTI team will identify one or more scenarios or situations that are representative of the conditions contained in the cluster. For clusters with relatively small within-cluster variance (i.e., tight clusters), the TTI team may select only one situation to represent the entire cluster. For clusters with relatively large within-cluster variance (i.e., clusters that are spread out), and for those clusters that have many members, the TTI teams may select multiple situations to represent the complete range of conditions covered by the cluster. Chapter 4 provides more information on the selection of representative conditions within a scenario.

2.6 Step 6. Calibrate Base Model to Operational Scenarios

Once the TTI CVPD Evaluation Team has identified the representative conditions/situation for each operational scenario, the Team will calibrate the base model to the selected representative condition for each selected operational scenario. For the Tampa site where control group information is available (i.e., vehicles that are equipped but do not have the CV applications active), the TTI team will calibrate separate control and treatment models for each operational scenario. To do this, the TTI team will first establish appropriate acceptability criteria for each operational scenario. The TTI team will then adjust the appropriate input parameters to the base model and then execute the model. The TTI team will compare the output results of the model run to the established acceptance criteria. Using an iterative approach, the TTI team will continue to adjust the input parameters of the model until the model results fall within the range of the acceptance criteria. This process represents a data-driven approach to calibrating the model to the operational scenario. The TTI team will complete this process for both the pre- and post-deployment conditions. Chapter 5 of this report provides the details of the model calibration process.

2.7 Step 7. Estimate Pre- and Post-deployment Impact

In this step, the TTI CVPD Evaluation Team will execute the experimental plan to estimate impacts of the deployment based on the pre- and post-deployment analysis. The TTI team will execute the model multiple times with different random seeds to assess system performance pre- and post-deployment. The team will examine the output of these initial runs to determine the required number of runs to provide statistically valid comparisons. The team will repeat this process for each operational condition identified in the cluster analysis (Step 4). Once the team has performed the required number of runs, the TTI team will conduct a statistical analysis of the output to determine whether any differences are statistically significant.

2.8 Step 8. Estimate Mobility Benefits

After the TTI CVPD Evaluation Team has calibrated both the pre- and post-deployment models and performed the appropriate number of replications per operational scenario, the team will conduct a statistical comparison of the model results to estimate mobility benefits. The purpose of the comparison is to determine whether a statistical difference existed in the performance measures (e.g., travel time, travel time reliability, delays, etc.) in the post-deployment (i.e., after the CV technologies were deployed and activated) compared to the pre-deployment condition (before the site implemented the CV technologies). The TTI team will use traditional comparisons of mean techniques to determine whether the differences in pre- and post-deployment conditions are statistically significant. The TTI team will use a 95th percentile confidence interval to test for significant differences in model output results. Chapter 6 describes this process for conducting the statistical analysis process in more detail.

2.9 Step 9. Estimate Fuel Consumption and Air Quality Benefits

Using the results of the comparison, the TTI CVPD Evaluation Team will estimate the change in fuel consumption and emissions associated with the deployment. The TTI team will construct the environmental model using EPA's MOVES model. The TTI team will use the output results from the VISSIM model as input to the MOVES model.

MOVES is a project-level simulator that uses a vehicle's operating mode—including idling, acceleration, deceleration, cruise, and hoteling—to measure emissions and petroleum consumption at the national, county, or project scale. MOVES assigns an emission rate for each unique combination of source and operating mode bins and calculates the total emissions and energy use over a specified period.

The TTI team will parameterize the MOVES model according to the local vehicle population, simulation model output, and meteorological conditions. The difference between the with and without connected vehicle application scenarios will be the estimated environmental impact of emissions and energy use. The TTI team will enter the data as input parameters in the MOVES graphic user interface (GUI). When a distribution of a variable is required (e.g., vehicle speed), data will be imported using tables into the project data manager (PDM).

The TTI team will inspect the environmental model to verify the following:

- Magnitudes of emissions reflect expected values for the modeled region.
- Model inputs for traffic speed, volume, and vehicle mix accurately represent expected values.

The TTI team will report the following model outputs from MOVES in emissions or energy consumption per hour:

- Carbon dioxide (CO_2).
- Volatile organic compounds (VOCs).
- Particulate matter (PM).
- Nitrogen oxide (NO_X).

- Sulfur oxide (SO_X).
- Petroleum energy consumptions.

Similarly, the TTI CVPD Evaluation Team will compare the operational scenarios from the environmental model. Again, the TTI team will use traditional comparisons of mean techniques to determine whether the differences in pre- and post-deployment conditions are statistically significant. The TTI team will use a 95th percentile confidence interval to test for significant differences in model output results.

Chapter 7 describes the process that the TTI team will use to estimate the fuel consumption and air quality benefits associated with the pilot deployment.

2.10 Step 10. Aggregate Model Results

After statistically comparing the results of the pre- and post-deployment models, the TTI CVPD Evaluation Team will aggregate the model results from each scenario to estimate the overall benefits of deploying the CV technologies for the Tampa deployment. The TTI team will aggregate the model results based on the relative frequency that each operational scenario occurred in the measured data. For example, if there are five clusters in the pre-deployment data set and six clusters in the post-deployment data set, and if x_i is the average performance measure estimate output by the simulation model (averaged over all random number seed runs) and n_i is the number of days in cluster *i*, the average annualized estimates for the measure for pre-deployment and post-deployment would be:

$$\bar{x}_{Post} = \frac{\sum_{i=1}^{6}\left(x_{i,Post} \times n_{i,Post}\right)}{\sum n_{i,Post}}$$

The impact of CV deployment on performance measure *x* is then:

$$Delta\ x = \bar{x}_{Post} - \bar{x}_{Pre}$$

The TTI team will repeat this process for all the scenarios showing significant differences between the pre- and post-deployment conditions. The TTI team will include benefits from only those scenarios showing the statistically significant differences in the overall aggregation of benefits.

2.11 Step 11. Estimate Benefit/Cost

Using the results of the simulation modeling as well as the observed field data, the TTI CVPD Evaluation Team will conduct a benefit-cost analysis associated with the deployment. The purpose of the benefit-cost analysis is to determine whether the safety, mobility, environmental, and public agency efficiency benefits exceeded the total costs associated with deploying the CV technologies in the deployment corridors. The benefit-cost analysis will incorporate safety, mobility, and environmental benefits as well as cost information obtained from the stakeholder interviews. To the extent public agency efficiency benefits can be quantified, the TTI team will include them in the benefit-cost analysis. The benefit-cost analysis assumes a 7-year life of the technologies. The TTI Evaluation Team is using the lifespan of a typical personal computer (3 to 5 years) as the basis for this assumption. CV technologies are likely to evolve in the near term, and the Tampa Deployment Team will likely need to revise its initial deployment within 7 years as the technology and applications mature. The TTI team will include all known short-term and projected long-term benefits and costs for multiple deployment scenarios (i.e., levels of market penetration). Chapter 8 describes the process that the TTI team will use to assign monetary values to the benefits and to identify costs associated with the pilot deployment.

Chapter 3. Goals, Objectives, and Performance Measures

The key USDOT goals for the CV pilots are to:

- Improve safety.
- Improve mobility.
- Reduce negative environmental impacts.
- Improve end-user satisfaction with travel.

This chapter discusses the goals and objectives of the AMS study that the TTI CVPD Evaluation Team will perform. The TTI team will use simulation and modeling to answer the following questions:

- To what extent did the CVPD improve **mobility** in the study area?
- To what extent did the CVPD improve **air quality** along the deployment corridors?
- What are the **projected** mobility and air quality **benefits** expected over the next 7 years in the study area for future traffic and different market penetration rates of CVs and RSUs?

3.1 Objectives of the Tampa CVPD

According to THEA's *Connected Vehicle Pilot Deployment Program Phase 1, Deployment Readiness Summary—Tampa (THEA)* (*4*), the goals and objectives for the Tampa CV pilot are as follows:

- Goal 1: Develop and deploy CV infrastructure to support the applications identified during Phase 1.
    - Objective 1: Deploy dedicated short-range communications technologies to support V2V, vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) applications.
    - Objective 2: Upgrade traffic management center (TMC) software to ensure compatibility with CV applications.
    - Objective 3: Recruit a fleet of transit and private vehicle owners and individuals carrying V2X-enabled mobile devices to participate in the CV pilot by installing and using CV technology offered in the pilot.
- Goal 2: Improve mobility in the central business district (CBD).
    - Objective 1: Replace existing traffic controllers and control systems at key intersections with I-SIG CV technology to improve traffic progression at identified problem areas.
    - Objective 2: Provide TSP applications to help Hillsborough Area Regional Transit (HART) buses stay on a predictable schedule.

  - Objective 3: Provide bus rapid transit (BRT) applications to improve overall operation and encourage increased ridership.
- Goal 3: Reduce the number of safety incidents within the pilot area.
  - Objective 1: Provide detection of pedestrians and warnings to drivers of potential pedestrian conflicts.
  - Objective 2: Provide detection of potential vehicle conflicts and warnings to pedestrians.
  - Objective 3: Provide early detection of wrong-way drivers and issue warnings to wrong-way drivers and upstream motorists.
  - Objective 4: Give drivers warnings of the REL exit curve and stopped vehicles ahead.
  - Objective 5: Provide detection and warning of potential conflicts between streetcar vehicles and autos/pedestrians/bicycles.
- Goal 4: Reduce environmental impacts within the pilot area.
  - Objective 1: Provide CV mobility and safety applications to improve overall mobility and reduce stops and idle time within the CBD, thus reducing emissions.
  - Objective 2: Provide TSP applications to reduce idle time of HART buses.
  - Objective 3: Provide BRT applications to improve overall operation and encourage increased ridership.
- Goal 5: Improve agency efficiency.
  - Objective 1: Improve traffic data collection capability, reducing the costs of collecting data.
  - Objective 2: Reduce the number of incidents and police and rescue responses to incidents.
  - Objective 3: Reduce crashes and time agencies take to gather data.
  - Objective 4: Improve technology for crash statistics gathering.
  - Objective 5: Improve scheduling and dispatching of HART vehicles with improved trip times and vehicle information.
  - Objective 6: Reduce overhead of THEA responding to wrong-way entries and crashes on REL exit ramps.
- Goal 6: Develop business environment for sustainability.
  - Objective 1: Work with the Crash Avoidance Metrics Partnership, original equipment manufacturers, and third-party developers to develop business cases for advancing CV-ready vehicles.
  - Objective 2: Work with industry sectors that will benefit from CV implementation (e.g., insurance carriers, fleet managers, safety organizations, etc.) to provide education on the benefits and seek support for advancement of the system.
  - Objective 3: Work with chambers of commerce and other business organizations to educate members on the return on investment from increased mobility.
  - Objective 4: Work with state and local governments to encourage positive legislation and funding in support of CV technology.

3.2 IE Evaluation Objectives of the Tampa CVPD

Both the Tampa CVPD Deployment Team and TTI CVPD Evaluation Team, as the USDOT's independent evaluator (IE), are responsible for evaluating the effectiveness of the deployment to achieve the mobility, environmental, and public agency efficiency objectives. Both teams are using field-measured observations as well as simulation modeling to conduct these assessments. For the USDOT's independent evaluation, the TTI team is using AMS to perform the following:

- Quantify the system-wide impacts of the deployment.
- Test hypotheses that the data collected by the sites cannot answer.

The TTI team is not responsible for assessing, through either direct observations or simulation and modeling, the safety benefits associated with the different CV applications deployed by the Tampa Deployment Team. The Volpe Institute is responsible for conducting the safety assessment.

Appendix A provides a mapping of the overall evaluation hypotheses to the AMS modeling scenarios. The information is preliminary in that the clustering analysis has yet to be performed on data that have yet to be collected.

3.3 AMS Objectives for the Tampa CVPD Evaluation

The ME goals and objectives of the simulation models relate to mobility, travel time reliability, weather-related delay, and environmental impacts. Specifically, the TTI team will use the AMS analysis to perform the following:

- Estimate the impacts of deploying **I-SIG** on travel time, travel time reliability, and corridor throughput under the different operating conditions and time of day that prevail in the corridor (Tampa Deployment Goal #2).
- Estimate the impacts of **TSP** and other connected **BRT** applications on transit and vehicular mobility, travel time reliability, and corridor throughput under the different operating conditions and times of day that prevail in the corridor (Tampa Deployment Goal #2).
- Estimate the impacts **of reducing crash frequency and severity on the REL** on mobility, travel time reliability, and corridor throughput under the different operating conditions and times of day that prevail in the corridor (Tampa Deployment Goal #3).
- Estimate the impacts on the **environment** due to changes in mobility under different operating conditions that prevail in the corridors (Tampa Deployment Goal #4).
- Estimate the **cumulative effects** of different market penetration levels of connected vehicles and changes in background traffic levels on system performance on the deployment corridors in Tampa.

To estimate these impacts, the TTI CVPD Evaluation Team will use the base model that the Tampa Deployment Team will develop. Based on the information shared by the Tampa Deployment Team to date *(5)*, the base VISSIM model will include:

- Six intersections on Meridian from Channelside to Twiggs.
- Three intersections on Twiggs from Jefferson to Meridian.

- Traffic volumes—AM peak hours.
- Turning movement counts—AM peak hours.
- Signal timing plans.
- Reversible lane at Twiggs/Meridian.
- Rail route.
- Preemption and barrier gates at Kennedy, Jackson, and Twiggs on Meridian.
- Pedestrian crossing near courthouse at Twiggs-Jefferson.

The TTI CVPD Evaluation Team will first verify that the model is functioning properly and will then calibrate the model to the operational scenarios identified through the cluster analysis. The TTI team will be responsible for any model enhancements, calibration, and measurement estimations that diverge from what the Tampa Deployment Team plans to do.

3.4 Performance Measures

The following subsections describe how the TTI team will compute the mobility-related performance measures for each operational scenario. The TTI team will compute these performance measures using data from multiple simulation runs for each operational condition. The TTI Team will use these measures to estimate environmental performance measures. Chapter 7 describes the process that the team will use to estimate the environmental performance measures.

3.4.1 Total Vehicle-Miles Traveled

Total vehicle-miles traveled (VMT) is a direct output of the simulation model. Traditionally, transportation agencies use VMT as a measure of throughput. The TTI CVPD Evaluation Team will collect VMT for the different operational scenarios identified for the site. The TTI team will simulate each operational condition using the appropriate number of replications to estimate VMT for both the pre- and post-deployment periods. The TTI team will average the VMT output from each repetition across all the repetitions to obtain an average VMT for each operational condition. The TTI team will use the projected probability of each operational condition to weight the average VMT for each operational condition to obtain a whole-year average performance for the future scenario. The team will note the variation in results and standard deviation for each operational condition.

3.4.2 Total Vehicle-Hours Traveled

Like VMT, total vehicle-hours traveled (VHT) is also a direct output of the simulation model. However, since most models exclude vehicles denied entry to the network during the run from their VHT accumulations, post-model adjustments will be necessary to obtain the true VHT for each run. The adjustments will vary from run to run. The TTI team will make the adjustments based upon the model reported number of vehicles denied entry every hour of the simulation. Once the TTI team has made the adjustments, the TTI eam will use the same process as described for VMT to compute the whole-year VHT for each future scenario.

3.4.3 Travel Time

The TTI CVPD Evaluation Team will use average travel time as one of the primary measures of performance for the mobility analysis. Average travel time is a measure that is easily understood by practitioners and decision makers alike. Travel time is the time required for vehicles to traverse a given distance and is sensitive to changes in both capacity and operating conditions. The TTI team will configure the simulation model to collect the time required for different classes of vehicle to traverse the modeled segment during the operating conditions. The TTI team will use the collected travel time to compute both the average and 95th percentile travel times during the different modeled operational conditions.

3.4.4 Average Operating Speed

The TTI CVPD Evaluation Team will use simulation to compute the average operating speed associated with the different operational scenarios in the Tampa CVPD corridors. From a modeling perspective, the TTI team will use field data to develop simulation models to estimate operating speeds both with and without CV technologies under different operating scenarios prevalent in the corridor. The TTI team will compute average system speed by dividing total VMT by total VHT.

3.4.5 Average System Vehicle-Hours of Delay

The TTI CVPD Evaluation Team will use the simulation model to estimate the total amount of system delay experienced in the corridor under different operating scenarios, both with and without CV technologies. The TTI team will code the simulation model to accumulate the VHT of delay over the course of each run employing the VISSIM default definition of delay. The TTI team will determine delay by comparing the actual travel time over a link to the hypothetical travel time at either the driver’s desired speed or the posted speed limit for the link.

3.4.6 Average System Speed Variance

The TTI CVPD Evaluation Team will record VMT by 5-mph speed bins to compute (post-model run) the system speed variance under the different CV market penetration levels and operating conditions (e.g., weather, incidents, demand, etc.).

3.4.7 Average System Time (VHT) Spent in Queue

The TTI CVPD Evaluation Team will use the simulation model to estimate the average time that queues are present in the corridor under different operating conditions and scenarios. The TTI team will program the simulation to accumulate the amount of time the system operates with queues over the course of each run. The TTI team will use (and document) the default VISSIM simulation software definition of queue. To be in a “queue state,” Vehicle 2 must be within 20 m of the lead vehicle and have a speed that is below 5 km/hr. Vehicle 2 must accelerate to 10 km/hr before the vehicle is defined as having left the queue. While these values are user adjustable by specific link, the TTI team plans to use the default values for all freeway and street links.

Chapter 4. Data Collection and Analysis

This chapter outlines the data collection needs and the analysis framework for conducting the ME impact assessments using simulation. The process follows the data collection and analysis guidance in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*). This process includes four steps:

1. Identify data sources.
2. Assemble contemporaneous data.
3. Verify data quality.
4. Identify operational conditions using cluster analysis.

4.1 Identify Data Sources

The TTI CVPD Evaluation Team is writing this plan before the pre-deployment site data are available. This plan outlines the ideal data needs that the team expects to receive. There is a risk that the site may not be able to provide enough data for model calibration, in which case alternative data collection methods may be necessary. The primary concern at this time relates to data needed to calibrate driver behavior models. If there are not enough CV observations, the TTI team may need to consider an alternative data collection method, such as having participants drive on a closed course. As data become available, the TTI team may update this plan to reflect the better understanding of the data availability and demands.

4.1.1 Required Model Input Data for Mobility Analysis

To perform the AMS analysis, the TTI CVPD Evaluation Team will need to receive a site-developed base mobility model (or microsimulation input files) and the following information to validate the base model development:

- Data for base model development (including model network geometry, signal timing plans, volumes, and turning movement count data for vehicles, pedestrians, and bicyclists).
- Data for determining operational conditions.
- Data for calibration.

The Tampa Deployment Team will upload all the data and the model input files to the Secure Data Commons (SDC). Assuming USDOT, Volpe, the deployment sites, and the TTI team can overcome microsimulation software licensing issues and the strict prohibition on the electronic export of processed data from the SDC, the TTI team will analyze the data, build the simulation models, conduct the analysis within the SDC, and then export the results for reports, tables, and graphs. Otherwise, the TTI team will obtain the necessary data directly from the Tampa Deployment Team, posting copies of inputs and outputs on the SDC.

Personally identifiable information will not be required (or used) by the TTI team for microsimulation model input, output, or calibration.

The TTI CVPD Evaluation Team is assuming that the Tampa Deployment Team will deliver a VISSIM model of the downtown Tampa area containing the deployment corridors listed in Section 3.3. The TTI CVP Evaluation Team is expecting that the Tampa CVPD Team will have coded the simulation model to represent “before” conditions. The TTI team expects the model to contain not only the roadway network but also the REL operations and pedestrian and bicycle lanes and movements. The Tampa Deployment Team has not indicated that it will simulate the TELCO streetcar line in its base model. The TTI team expects to receive from the Tampa Deployment Team a VISSIM model that is free from errors and that adequately portrays the signal operations before and after the implementation of the I-SIG and TSP algorithms. Integrating this logic into the signal control feature of VISSIM is important to quantify the value added by these applications in the post-deployment evaluation. The model(s) will be calibrated to some level of performance, to be defined by the Tampa Deployment Team in future documentation. The TTI team will follow the procedures specified in the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*) to calibrate the model.

4.1.2 Data Required for Model Calibration

The TTI CVPD Evaluation Team expects the site to calibrate the models to simulate the observed operational scenarios in the study area, both in terms of traffic demands (observed traffic counts) and speeds for a normal, non-incident day. At this time, the TTI team assumes that the site will deliver two base models: one model based on the pre-deployment conditions (existing conditions) and one model based on the post-deployment conditions. The TTI team will assess the models delivered by the Tampa Deployment Team to determine if the model calibration is consistent with FHWA guidance. The TTI team will coordinate with the Tampa Deployment Team to verify that the TTI team correctly understands the extent to which the models are calibrated.

After completing its examination of the calibrated models, the TTI team will prepare a brief memo for FHWA review and approval identifying the additional calibration needs (if any), benefits, budget, and schedule. Upon receipt of FHWA approval to proceed with the recalibration effort described in the memo, the TTI team will recalibrate the models to simulate the before (pre-deployment) and after (post-deployment) scenarios using the models delivered by the Tampa Deployment Team and field observations from the pre- and post-deployment periods.

If recalibration is needed, the TTI team may need additional data to calibrate the new models. Appendix B lists the data needs and potential data sources, based on the information known to the TTI team at this time. The TTI team expects to perform the calibration based on the types of operational scenarios identified through the cluster analysis.

The TTI CVPD Evaluation Team understands that perfect data may not be available. Ways exist to work around unavailable data (such as accepting less accuracy in the scenario selection). Therefore, one should not interpret this list of data as rigid. Section 4.3 further discusses the expected data attributes.

4.1.3 Required Input Data for Environmental Analysis

The evaluation of the environmental impacts of the CV applications will require the following data in addition to the data cited above for traffic simulation model development and calibration. These are inputs to the MOVES vehicle emissions model.

- Number, location, and length of links (obtained from the simulation model[s]).

- Link road types: urban versus rural, restricted versus unrestricted, running versus hoteling (obtained by the TTI team from examination of the site).
- Link volumes: total number of vehicles per hour on each link (obtained from output of simulation model).
- Link average speed: speeds of vehicles on links (obtained from output of simulation model).
- Average grade of each link (obtained by the TTI team from examination of the site).
- Vehicle mix in the study area by buses, motorcycles, light-duty vehicles, single-axel trucks, and combination trucks. The TTI team will request these data from the sites. Failing that, the TTI team will select appropriate default values that are representative of the site conditions.
- Age distribution of vehicles in the study area by vehicle type. The TTI team will request these data from the sites. Failing that, the TTI team will select appropriate default values that are representative of the site conditions.
- Meteorological data on humidity and temperature (obtained from online historical records).

4.2 Assemble Contemporaneous Data

The TTI CVPD Evaluation Team expects the sites to upload the following data to the SDC for a 1-year history before and after deployment, unless those data are readily available to the TTI team through a public source:

- National Weather Service or Weather Underground hourly weather reports.
- City of Tampa Traffic Management Center incident management/event management logs.
- City of Tampa traffic signal system logs (including travel time and traffic volume data).
- City of Tampa construction/maintenance lane closure logs.
- City of Tampa transportation advisories and road closures.
- HART ridership and performance statistics.
- City of Tampa office of special events.
- City of Tampa crash statistics, including type, vehicle type, severity, location, and time.
- Regional WAZE travel time data sets.

4.3 Verify Data Quality

This section describes the steps that the TTI CVPD Evaluation Team will take to verify the quality of the data. Before uploading data to the SDC, each site will verify its data. The TTI team will spot-check the data to ensure the quality of the data is satisfactory for the analysis. The TTI team will use the following error-checking process, as outlined in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*), to validate the site-provided simulation model input files:

- Review software errors.
- Review input coding errors, including geometry, control, demand, and driver behavior and vehicle characteristics.

- View animation.

The TTI CVPD Evaluation Team will review the model input files for the following data quality:

- Geometric data—spot-check the geometric and traffic control type data using Google Earth; look for apparent violations of design standards and practices.
- Traffic control data—spot-check the traffic signal phase and timing data using site-provided signal timing plans.
- Traffic count data—spot-check traffic counts for internal consistency (balancing within 10 percent).
- Traffic operations and management data—spot-check travel time and speed data from CV data or control vehicle probe data if available.

If the sites do not share these detailed data required for model validation, then the TTI team will be unable to validate the driver behavior model. If that is the case, then the sites must develop their own process to demonstrate that the driver behavior model they developed is accurately calibrated to the existing conditions.

4.4 Identify Operational Conditions Using Cluster Analysis

The TTI CVPD Evaluation Team will follow the condition selection procedures presented in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*) when conducting the AMS analysis. The procedure includes the following six steps:

1. Identify attributes.
2. Process data.
3. Normalize data.
4. Down-select attributes.
5. Perform clustering.
6. Identify stopping criterion.

The key inputs to the environmental impact analysis model are the outputs from the mobility models. If no mobility changes are observed, it is expected that there are no environmental changes. Therefore, the identification of operational conditions will focus on identifying scenarios that affect mobility.

4.4.1 Step 1: Identify Attributes

The TTI CVPD Evaluation Team will identify the key attributes for defining the operational or travel conditions at the site. These attributes are the underlying conditions at the site, not the measures of system performance.

The TTI CVPD Evaluation Team will explore various attributes in the data set for clustering. The following list is our initial candidate list of attributes that we will explore during the cluster analysis. As we explore the data, we may drop some of the less meaningful attributes in this candidate list. We may substitute others.

The anticipated key attributes include the following:

- Daily travel demand

- Weather conditions (type, duration, severity, amount of precipitation, pavement conditions, time-lag of weather effects)
- Incident conditions (type, duration (e.g., total lane-minute closure), severity)
- Work zone conditions (type, duration, severity of impacts)
- Special event conditions (type, duration, severity of impacts)
- Freight (number of trucks)
- Road closure conditions
- Holidays
- Day of week
- Market penetration observed

The TTI team will conduct its cluster analysis around these key attributes.

4.4.2 Step 2: Process Data

After identifying key attributes, the TTI CVPD Evaluation Team will transform qualitative data into quantitative or numeric data. The team will be sure not to over-process the qualitative data so that the relationship between the attribute and the key measure of interest is captured.

In Step 2, the TTI CVPD Evaluation Team will simply transform the data onto a numeric or binary scale.

For weather data, the TTI CVPD Evaluation Team will use the numeric value associated with measures that can be quantitatively measured (such as visibility distance, precipitation rate, wind speed, temperature, etc.) when available, rather than sorting into bins. For those measures that are qualitative in nature (such as wind situation, precipitation type, pavement condition situation, etc.), the TTI team will define a numeric or binary scale to process qualitative weather data.

4.4.3 Step 3: Normalize Data

The TTI CVPD Evaluation Team will use the data normalization tool from open-source statistical analysis software (such as R or WEKA) in the SDC to normalize the data, or to transform all data to a common scale so that no single attribute dominates.

4.4.4 Step 4: Down-Select Attributes

After normalizing the data, the TTI CVPD Evaluation Team will use the software tools to down-select attributes. In this step, the tool removes attributes that are redundant or have no impact on the site-specific key measure of interest. In this way, the team will base its analysis on those attributes that are highly correlated with the key measures of interest and have low correlation with each other. The team will use the various software tools to assess the extent to which the attributes are correlated. The team will use this list of attributes for the clustering analysis in Step 5.

4.4.5 Step 5: Perform Clustering

After down-selecting the key attributes, the TTI CVPD Evaluation Team will perform clustering analysis on the data using an open-source statistical and data mining tool in the SDC (such as R or WEKA). The team will conduct the clustering analysis based on several algorithms to determine if the clusters vary based on the algorithm used.

Based on the characteristics of the observed data, clustering may be hierarchal (based on predetermined ordering). The TTI team may base the clustering analysis on single, complete, or average linkage or on partitive grouping (group based on distance from centroid). Partitive grouping minimizes the total intra-cluster variance to ensure dissimilarity between clusters. The TTI team will explore various clustering concepts using the post-deployment data.

The TTI CVPD Evaluation Team expects that some of the clusters will not be clean or have distinct indicator characteristics. Therefore, the TTI team will work with the data to describe to the best of its abilities the commonalities among the data within a cluster.

The TTI team expects that weather variables and demand will be significant factors around which the clusters form. However, modeling demand may be challenging because demand data may not be available, and instead, the team may need to use proxies for demand, such as volume or throughput data. The method for estimating demand variation from counted volumes is described in Chapter 6.

4.4.6 Step 6: Identify Stopping Criterion

The TTI CVPD Evaluation Team will use the cluster analysis tool's built-in stopping criterion to determine the correct number of cluster groups or optimal cluster size for the site. The team will cross-validate the stopping criterion to determine that an appropriate cluster distribution was achieved. The team will start with three or four clusters and work incrementally out toward a pre-specified number of clusters, such as 10 clusters. The maximum number of clusters is a function of the number of days (or records) and cannot be determined with certainty at this time.

To reduce costs, the TTI team will focus its evaluation on the scenarios with the greatest impact on the ME evaluations. For each site, the TTI team will review the selected clusters to be modeled with USDOT before beginning model development.

Chapter 5. Model Development Process

This chapter presents the process that the TTI CVPD Evaluation Team will follow to develop the simulation models for conducting the AMS analysis, including base model development, error checking, and calibration. It describes the base model(s) that the site will provide to the TTI team to assess the mobility and emissions impacts of the deployment. This section also describes the tools and analysis techniques that the TTI team will use to develop any new models (if applicable) as part of a forthcoming task order. Finally, this chapter discusses whether any enhancements will be made to the existing traffic and emissions simulation models available from the sites.

5.1 Base Model Development

This section provides a brief description of the base model that the TTI CVPD Evaluation Team will use for the pre- and post-deployment periods. The general description of the simulation model is taken from the available sources provided by the Tampa Deployment Team *(5)*. The TTI team expects the Tampa CVPD Team to follow the base model development guidance in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*).

5.1.1 Model Input and Calibration Data

The data needs are coordinated with the refined evaluation plan in Task 2 and the data collection plan in Task 4 of this contract. The TTI CVPD Evaluation Team needs the following general data types for the simulation modeling effort:

- **Model network geometry**—The TTI team is assuming that the Tampa Deployment Team will code this geometry during its model development effort.
- **Traffic signal timing plans**—The TTI team is assuming that the Tampa Deployment Team will code all signal timing plan information for each signalized intersection. This includes both basic signal timing parameters as well as coordination timing plans. The TTI team is expecting that different models will be available for different times of day.
- **Travel time data for model calibration**—The TTI team is assuming that the Tampa Deployment Team will collect these data for its initial model calibration. The TTI team will expand this data set for extended calibration by drawing from the deployment team's archives.
- **Special control algorithms**—The TTI team is assuming that the Tampa Deployment Team's model will include any special control algorithms that may become active with CV deployment, such as the I-SIG application.
- **Special behavior of connected vehicles**—The TTI team is assuming that the Tampa Deployment Team will collect data to measure how drivers respond to CV messages.

- **Traffic demands**—The TTI team is assuming that the Tampa Deployment Team is collecting traffic data at 15-minute intervals and will code these data into its base model. To be able to verify the accuracy of the microsimulation model, the TTI team needs basic traffic demand data.
- **Vehicle stock**—The TTI team is assuming that the Tampa Deployment Team is including the distribution of age and vehicle types for both the CVs and non-CVs.
- **Data for calibration of model to varying operating conditions**—The TTI team is assuming that the Tampa Deployment Team has synchronized all data collection so that demand, crashes, lane closures, weather, work zones, special events, and travel times are all simultaneously known for each 15-minute time slice within each peak period within each day to be simulated. Ideally, the TTI team would like to use 365 days of data. At a minimum, the team can work with 100 days of data to be able to predict to the nearest 1 percent the probability of a particular combination of demand, weather, and crash events occurring for the site in the future. The TTI team will investigate the aggregation intervals to make sure the timestep is appropriate (e.g., 15-minute interval or other). Following are the data that the TTI team will consider in the calibration process:
    - Traffic demands: 15-minute turning movement counts for signalized intersections, all-way stops, and roundabouts; 15-minute on-ramp and off-ramp counts for freeways with mainline counts every half mile.
    - Road weather conditions: primarily hourly rate of rainfall, hourly miles of visibility for rain or fog conditions, and any available weather-related pavement condition data.
    - Crashes and work zones: mile-post location and direction, start time, end time, and number of lanes blocked each 15-minute period over duration of incident.
    - Special events: venue, attendance, start time, end time, hourly arrival and departure volumes over duration of event, and any special lane and signal controls before, during, or after event.

5.1.2 Traffic Simulation Models

This section provides descriptions of the simulation models likely to be available for each of the sites based on the published information available to the TTI team at the time of drafting this AMS plan.

The Tampa CVPD Team is developing a VISSIM microsimulation model to evaluate the primary I-SIG routes in the CBD along Meridian Avenue, Florida Avenue, and Nebraska Avenue. The Tampa Deployment Team shared the following information about its base model development plans *(5)*:

- Six intersections on Meridian from Channelside to Twiggs.
- Three intersections on Twiggs from Jefferson to Meridian.
- Traffic volumes—AM peak hours.
- Turning movement counts—AM peak hours.
- Signal timing plans.
- Reversible lane at Twiggs/Meridian.
- Rail route.
- Preemption and barrier gates at Kennedy, Jackson, and Twiggs on Meridian.
- Pedestrian crossing near courthouse at Twiggs-Jefferson.

THEA is also in the process of developing a simulation model for the Selmon Expressway. To the extent that this model may or may not include the signals at the foot of the expressway ramps, there may be some overlap between the intersections of the CV deployment and the Selmon Expressway simulation model. However, the expressway model will include a lot of overhead (expressway links) not necessary for the CV pilot deployment evaluation. Consequently, the TTI team does not plan to employ extensions of the Selmon Expressway model for evaluation of the CV deployment.

The TTI CVPD Evaluation Team will maintain communications with THEA over the course of the deployment to learn more about its model development plans and will revise the AMS plan accordingly as it gets closer to developing the simulation model(s) for evaluating the CV deployment in Tampa.

The TTI team will use a half-hour warm-up period before run statistics are gathered for the selected peak period. Depending on the levels of congestion, the team may use an additional 1-hour run-on period after the end of the peak period to enable inclusion in the run statistics of the time required to dissipate built-up congestion.

The TTI team will use local data on street and ramp capacities to the extent that the data are available. Otherwise, the team will use the *Highway Capacity Manual* (HCM) recommended adjustment factors to identify the capacity targets it wants the simulation model to achieve under fair weather conditions for the base model development.

5.1.3 Model Enhancements

At this time, the TTI CVPD Evaluation Team does not envision requiring any enhancements for the base traffic simulation model; however, this may change as the TTI team begins working with the model(s) provided by the Tampa site. The TTI team needs more information about the study area and intersections the Tampa CVPD Team will include in its base model development to understand if the TTI team will need to make any significant enhancements to the base model.

5.1.4 Key Simulation Modeling Assumptions

The key assumptions employed within the traffic simulation models relevant to evaluating the effects of CVs are:

- All connected and unconnected drivers always keep safe car-following distances, do not enter intersections unless safe, obey lane markings, and obey all traffic control devices. This assumption is standard simulation modeling practice. It may be modified by the Tampa Deployment Team based on before and after evidence from its deployment.
- The onboard units or aftermarket safety devices (ASDs) within each vehicle will not distract drivers from the driving task. This assumption may be modified if observed data from deployment or driver simulator suggest otherwise.
- Drivers are equally aware of congestion ahead, whether through the onboard unit or through alternative devices and apps such as cell phones, radio, and Waze.
- Drivers with active ASDs in their vehicles may follow other vehicles with ASDs less closely and change lanes less frequently than similar drivers without active ASDs in their vehicle if those ASD-equipped drivers receive alerts, such as FCW or lane departure warning. The intent of the ASDs is to improve safety by reducing imminent crashes, rather than to improve capacity. At this time, the TTI team does not anticipate that the logic employed in the ASDs will encourage drivers to follow other ASD-equipped vehicles more closely. The team expects that the CV data will provide the number of FCW alerts a driver receives, but not necessarily the actual following distance between vehicles (especially when no warning is issued). The team will use the number of FCW alerts as a surrogate for following distance and will determine if the number of FCW alerts changes over time

because of the FCW application. The team may then adjust the car-following parameters in the simulation model accordingly. No data are being collected to enable the team to measure a change in car-following behavior of ASD-equipped vehicles following non-ASD-equipped vehicles.

These assumptions are driven by the driver behavior theory coded into the traffic simulation models. That theory presumes that all drivers are attentive to the driving task, always obey traffic control devices, and always keep safe following distances. The traffic simulation model software is generally set up to model vehicle-to-vehicle interactions. For the Tampa CVPD, pedestrian/vehicle interactions can be modeled but require special effort to do so. Because vehicles do not crash in the simulation environment, the TTI team will estimate potential safety benefits of pedestrian crashes outside of simulation.

Appendix C provides more details on modeling driver behavior in traffic simulation for the CV and non-CV drivers.

The safety-oriented CV deployments will not affect modeled driver behavior (car following, lane changing). The mobility effects of the CV safety applications will be estimated outside of the simulation models. For example, if the Volpe Center estimates that there will be a reduction in frequency of crashes at different levels of CV market penetration, then the simulation model runs involving crashes will be given a proportionally lower weight in the computation of the mobility effects of CV application deployment.

5.1.5 Key Environmental Modeling Assumption

The key assumption employed within the environmental model relevant for evaluating the effects of CV applications is that vehicle distribution and proportions of the vehicle mix remain the same between the pre- and post-deployment periods. The evaluation is also limited to the operational conditions during the deployment period. Projections of higher penetration rates will assume the same traffic volumes and vehicle composition as the deployment period. The TTI team will not conduct traffic forecasting analysis or make assumptions on a different vehicle age distribution or vehicle size proportions.

5.2 Error Checking

The processes and procedures that the TTI CVPD Evaluation Team will use to verify that the models delivered by the deployment site are operating free of errors that might distort the simulation analysis include the following:

- Reviewing the model for any types of software errors that may exist with the version of the model provided. (Note: The TTI team will not have access to commercial software code, so its review will be limited to a high-level review of any custom software developed by the deployment team. The review will be limited to noting when the software produces fatal errors during the various simulation model runs and requesting fixes by the authors of the software or developing workarounds.)
- Reviewing the input parameters to ensure the model reasonably and accurately reflects the existing network (geometry, intersection control, and lane restrictions), demand, travel behavior, and vehicle characteristics.
- Reviewing the animation to assess the reasonableness of the model to replicate observed behaviors of both equipped and unequipped vehicles. The TTI team will review the animation for errors in the analyst's expectations, errors in the analyst's data coding, or residual errors.

A key decision point follows the completion of error checking. If the TTI team discovers any errors in the base model development during the error-checking process, the TTI team will communicate those errors with USDOT.

The TTI team expects that USDOT will work with the deployment team to resolve all errors in the base model before the TTI team continues to the calibration phase.

5.3 Calibration

This section describes the calibration approach and criteria using the data identified in Task 4 and following the calibration procedures described in Chapter 5 of the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*). Section 4.3 of this AMS plan addresses the identification of operational conditions for calibration. The TTI team expects that the model received from the deployment team will be calibrated; however, additional calibration is anticipated since the deployment team may not follow the processes detailed in the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*).

5.3.1 Identification of Representative Operational Conditions

For the base model development, the deployment team will select a representative condition to simulate based on the pre-deployment data following a calibration process, which the deployment team will define in its upcoming documentation.

The TTI CVPD Evaluation Team will identify the operational conditions for simulation modeling using cluster analysis of pre- or post-deployment data as described in Section 4.4 of this plan. The team will follow this approach for identifying the representative operational conditions for calibration:

1. Cluster the post-deployment data and identify the clusters.
2. Classify the pre-deployment data into the post-deployment clusters.
3. If the cluster has no pre-deployment days, identify the representative post-deployment day closest to the centroid for each cluster.
4. If the cluster has pre- and post-deployment days, identify the pair of pre- and post-deployment days that are closest to each other and closest to the centroid.
5. Calibrate two models for each cluster—one using the representative pre-deployment day and another using the representative post-deployment day (with CV behaviors and CV apps engaged). Calibrate only one model for each cluster that has only post-deployment days (or only pre-deployment days) using the representative post-deployment day (or pre-deployment day).
6. Repeat the process for all clusters.

The TTI team may choose to select more days within each cluster instead of repeating the process for multiple random number seeds. The team will discuss these options and the associated cost implications with FHWA to determine which approach to follow.

The TTI CVPD Evaluation Team will not have observed data for the selected days at higher market penetration rates; therefore, no calibration will be needed. If the team is able to get data on driver behaviors under higher market penetration from other locations (e.g., the other two sites), the team may try to include those behaviors in the assumptions if the two regions have similar characteristics.

5.3.2 Assumptions and Required Data for Calibration

Section 5.1.5 of this chapter lists the assumptions. Section 5.1.1 lists the necessary data inputs needed for the calibration.

5.3.3 Acceptability Criteria

The TTI CVPD Evaluation Team will calibrate the models based on two categories of parameters (*1*):

- Parameters that the analyst is certain about and does not wish to adjust (e.g., incident location and number of lanes closed).
- Parameters that the analyst is less certain about and willing to adjust (e.g., mean vehicle headway under low visibility conditions).

The TTI team will calibrate models by adjusting the parameters that influence bottleneck throughput, including (*1*):

- *Freeway Facilities*: *Mean following headway, driver reaction time, and critical gap for lane changing, minimum separation under stop-and-go conditions.*

The TTI CVPD Evaluation Team will focus on calibrating traffic-operations-related parameters. Changing the demand is not the focus of the calibration effort. However, if the traffic-operations-related parameters prove to be insufficient, the team can look at the demand input.

5.3.4 Process for Applying Acceptability Criteria

The TTI CVPD Evaluation Team will calibrate the models so that the model variant meets four acceptability criteria:

- Control for time-variant outliers—This criterion constrains the number of outliers in simulated results.
- Control for time-variant inliers—This criterion ensures the majority of time-variant simulated results fall close to the representative day, and that during the most congested time periods, the simulated results are close to the observed data.
- Bounded dynamic absolute error—This criterion ensures that, on average, simulated results are close to the observed representative day.
- Bounded dynamic systematic error—This criterion ensures that the simulated data are not excessive over- or under-estimators.

The TTI team will follow the detailed guidance of calibrating to these criteria as outlined in the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*).

5.3.5 Limitations of Calibration

As described earlier, the limitations of simulation modeling prohibit the TTI CVPD Evaluation Team from modeling potential behavioral impacts of safety-related CV applications. The TTI team will focus on modeling the impacts of non-safety-related applications, such as transit signal priority, for Tampa.

5.3.6 Sources of Data for Calibration

For calibration of the simulation models, the TTI CVPD Evaluation Team will use the data and data collection methods described earlier in Chapter 4 of this AMS plan. The team will use local data on capacity in the model calibration, to the extent that the data are available. To the extent no local data are available, the TTI Evaluation Team will use the HCM-recommended adjustment factors to identify the capacity targets for the simulation model to achieve under adverse weather and incident conditions.

5.3.7 Calibration for Driver Behavior Effects of CVs

At this point, little is known about how drivers will adjust their tactical and strategic driving behavior if they have an onboard unit orally or visually giving them driving condition information. Thus, for the base model development, the behavioral models inside the simulation model(s) will be the same for vehicles with or without onboard units.

At this time, the TTI team does not contemplate that connected vehicles will have any exterior markings indicating their connectivity status to drivers without onboard units. Thus, no change in driving behavior is anticipated for non-connected vehicles following connected vehicles.

Appendix C provides a more in-depth discussion of simulation driver behavior models in VISSIM.

5.3.8 Calibration for Signal Control Effects of CVs

At this point, the AMS plan calls for the Tampa Deployment Team to provide the TTI team with the necessary signal control software for I-SIG and TSP for use in simulating signal operations with connected vehicles. The TTI team plans to conduct its own informal verification and validation of the software to ensure that what is delivered by the Tampa Deployment Team operates correctly on the TTI team’s hardware or in the SDC. The TTI team does not anticipate requiring any calibration effort to verify that the delivered software faithfully replicates the operation of I-SIG with TSP software in the field.

5.3.9 Modeling Higher Levels of Market Penetration

Simulation is a powerful tool for estimating the potential benefits of conditions that are not observed. The market penetration rates observed at the deployment site are limited by the size of the deployment. The TTI team will use simulation to estimate potential benefits of higher levels of market penetration, which may be observed in the future as more vehicles and infrastructure are equipped with communication technology.

The TTI CVPD Evaluation Team will not have observed data at higher market penetration rates for the identified representative days from the cluster analysis; therefore, no calibration will be needed. If the team can get data on driver behaviors under higher market penetration from other locations (e.g., the other two sites), the team may try to include those behaviors in the assumptions if the two regions have similar characteristics. The team’s intent is to try not to transfer parameters. If the team feels it must transfer parameters or if it sees some real advantage to this approach, it will work with FHWA and seek approval before considering transferring behavior parameters from one site to another.

For each representative operational condition selected for simulation, the TTI CVPD Evaluation Team will operate the calibrated model to a future scenario in which the market penetration rate is higher for the CV fleet. By increasing the number of CVs in the model, the probability of vehicle-to-vehicle interactions increases, and the number of vehicles that the RSUs detect also increases.

The TTI team anticipates that the site will have RSUs at only limited locations within the simulation model study area. Once the team knows these locations, it will work with FHWA and the site to identify feasible options for a more comprehensive deployment of one or more levels of higher RSU intensity.

Chapter 6. Analysis of Simulation Results

This chapter describes the processes and procedures that the TTI CVPD Evaluation Team will use to assess the site deployment performance measure output by the simulation model runs. It describes the scenarios to be analyzed and the processes and procedures for conducting the sensitivity analyses needed to assess the impacts of confounding factors on the analysis results. This chapter also discusses the types and procedures of any statistical analysis of the modeling results.

This AMS plan is being prepared at the same time the Tampa Deployment Team is still refining its deployments, modeling, and data collection plans. Much is unknown, undefined, or subject to change at the time of preparation of this chapter of the AMS plan. Consequently, this chapter takes a flexible approach to the analysis that allows for uncertainties in the modeling and data collection details that will ultimately come from the deployment site.

6.1 Analysis Scenarios

This section of the site-specific AMS plan provides information on mapping the analysis scenarios to the research questions or key hypotheses to be tested. This section also identifies confounding factors that will be controlled through the AMS effort and discusses how the TTI team will account for confounding factors in the analysis of the scenarios. The TTI team will test alternatives consistent with the refined evaluation plan and will include a baseline/do-nothing alternative, which is the current condition at the site.

6.1.1 Model Scenario Identification

Model scenario identification comes after the clustering analysis of historic data has identified the relevant operating conditions to be included in the model scenarios. Each scenario is then the combination of different CV deployment-level alternatives and the operational conditions determined from the clustering analysis. Operational conditions will have been determined earlier, as described in Chapter 4 (see Section 4.3 of this AMS plan). The influence of confounding factors will be controlled through the selection of operational conditions for the scenarios. Table 1 illustrates the concept of building scenarios from combinations of CV deployment alternatives and operating conditions.

Table 2 is one example of the combinations of conditions that may be evaluated. The number of scenarios that the TTI team will model will be determined and agreed to in collaboration with FHWA at a later date. The cost of model development may be a limiting factor in the number of scenarios that the team develops. Ideally, the team will develop models that look at the impacts of the pre-deployment period, the post-deployment period with no CVs, the post-deployment period with CVs, and the various market penetration levels for a 7- and 10-year expansion, which would consider slow, moderate, and aggressive deployment curves.

Table 1. Framework for Model Scenario Development

Scenario	CV Deployment Alternative	Operational Condition: Demand	Operational Condition: Weather	Operational Condition: Incident	Operational Condition: Other (TBD) (see Note 5)
1a	No Deployment	TBD	TBD	TBD	TBD
1b		(see Note 5)	TBD	TBD	TBD
1c*		TBD	TBD	TBD	TBD
		TBD			
2	Actual Deployment	TBD	TBD	TBD	TBD
2a	(see Note 3)	TBD	TBD	TBD	TBD
2b		TBD	TBD	TBD	TBD
2c*		TBD	TBD	TBD	TBD
3a	7-Year Expansion	TBD	TBD	TBD	TBD
3b		TBD	TBD	TBD	TBD
3c*		TBD	TBD	TBD	TBD
4a	Maximum Expansion	TBD	TBD	TBD	TBD
4b	(see Notes 2 and 4)	TBD	TBD	TBD	TBD
4c*		TBD	TBD	TBD	TBD

* See Note 1.

Notes:

1. The TTI team will determine the number of sub-scenarios (1a, 1b, etc.) needed to adequately capture the range of effects of different operating conditions after the data become available from the clustering analysis. The number of sub-scenarios tested is also dependent on the cost constraints of the evaluation task.
2. The TTI team will better know the number of scenarios needed to accomplish the AMS objectives once the field data come in for the clustering analysis and for the deployed applications. The number of scenarios tested is also dependent on the cost constraints of the evaluation task.
3. Simulating the effects of the actual CV deployment will enable analysts to simulate the field-measured before and after conditions while controlling for confounding factors that may have influenced the results of the field measurements. This information also serves as verification of the accuracy of the simulation model for predicting CV effects on travel behavior and operations.
4. TBD: The TTI team will better know which CV deployment alternatives to test in simulation once the field data come in on the actual deployment effects. The data will no doubt raise questions as to which aspects of the actual deployment were most cost effective, which will drive the identification of additional deployment alternatives for testing.
5. TBD: The TTI team will determine the mix of demand, weather, incident, and other operational conditions once the field data are available for cluster analysis.

The TTI CVPD Evaluation Team will simulate alternatives consistent with the refined evaluation plan and will include a baseline/do-nothing alternative, which is the current condition at the site. At this point, the TTI team recommends the following CV deployment alternatives for testing in simulation:

1. <u>No CV Application Active</u>—Allows for calibration of the simulation model to "before" conditions and to provide a base for comparing the mobility impacts of the CV applications.
2. <u>Deployed CV Applications</u> (the actual numbers of vehicles and roadside units installed and activated during the deployment)—Allows for verifying the simulation model mobility predictions against the "after" field data.
3. <u>Seven-Year Expansion of CV Applications</u>—Provides estimated mobility benefits of feasible expansion of CV applications to more vehicles and more locations within each deployment site. Allows the TTI CVPD Evaluation Team to estimate the cost of modeling multiple penetration rates

for a given site at the 7-year expansion period. The final number of scenarios modeled depends on the budget allocated for this task.

4. Maximum Expansion of CV Applications — Provides estimated mobility benefits of expansion of CV applications to 100 percent of vehicle fleet and locations within each deployment site.

6.2 Treatment of Confounding Factors

Confounding factors are variables that influence both the dependent variables (in this case, the mobility and safety impacts of CVs) and the independent variables (in this case, the demand, crashes, etc.). Confounding factors can cause spurious correlations between independent and dependent variables, or they can mask actual correlations. For example, bad weather may increase the safety value of CVs, but because bad weather can also cause an increase in crashes and a reduction in demand, the effectiveness of CVs in bad weather may be masked by these other effects. Table 2 illustrates how the operating conditions (still to be determined) will be used to control (or account for) the effects of confounding factors. Differences between the sites are noted in the table. The approach, as shown in Table 2, for dealing with the influence of confounding factors on the outcome of the CV impact analysis in simulation will:

- Test the effects of different levels of weather and demand on CV application performance. These levels will be determined as discussed in Section 4.4.
- Test the effects of different levels of pedestrian demand on CV application performance. These levels may be an outcome of the clustering analysis, but if sufficient pedestrian count data are lacking, hypothetical levels of pedestrian demand may be selected.

Weather conditions can affect vehicle travel speed (e.g., traveling slower than usual). Not controlling for the effects of changes in weather conditions has the potential to invalidate conclusions about the effectiveness of the CV pilot deployment in addressing the needs of the pilot site. The TTI team will compare similar (adverse/non-adverse) weather conditions, as well as other known confounding factors listed in Table 2, to help ascertain the true impacts of CV technology. The team will select levels of impact for work zones and special events for all model run scenarios to control for the confounding effects of these factors.

Table 2. Treatment of Confounding Factors in Scenario Analysis

Factors	Tampa
Weather changes	The weather types and number of levels of each type that are to be assigned specific model scenarios for each CV deployment alternative will be determined via clustering analysis.
Vehicle demand changes due to variety of causes: economic conditions (jobs, etc.), fuel price, fare/toll changes, weather, season of year, day of week, etc.	The values of demand and the number of levels of demand that are to be tested in specific model scenarios for each CV deployment alternative will be determined via clustering analysis.
Pedestrian demand changes	Depending on the pedestrian data available for each site, one or more levels of pedestrian demand will be identified for testing in each scenario. This will be done only where CV applications are expected to be influenced by pedestrian demands.
Random variation crashes	Scenarios involving operating conditions with crashes will model the same specific crash condition (location, timing, lanes closed) for all CV deployment (and non-deployment) levels to control for the influence of random variation in crash rates. Non-random variations due to differing CV deployment levels will be treated in post-processing of model results.
Work zone changes	Model runs will use the same work zones for evaluating base and different CV deployment levels.
Economic condition changes	Effects will be included in demand operational conditions.
Fuel price changes	Effects will be included in demand operational conditions.
Planned special event changes	All model scenarios will assume the same planned events.
Planned waterfront construction	All model scenarios will assume the same level of construction.

Note: The purpose of this table is to address how the confounding effects of these factors will be controlled in the simulation model runs used in the analysis. A later step addresses how the impacts of these factors on CV performance will be determined.

As described earlier in Chapter 5 and elaborated on in more detail in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*1*), the TTI team will account for the real-world correlations between weather, congestion, demand, and crashes by treating each operating condition within each scenario as “a whole.” Different demand levels will not be modeled independently of the weather, congestion, and crashes. A set of historical study periods (called historic “days” for convenience) will be selected, based on the clustering analysis. The TTI CVPD Evaluation Team will input traffic counts, crash data, and weather collected simultaneously for those selected days into the simulation model. The TTI team will calibrate the model’s performance results on a day-by-day basis to the speeds observed simultaneously for those same days.

6.3 Extrapolation of Model Results to System Results

There are known limitations to simulation, which this AMS plan has begun to address with the current knowledge of the deployments. Once the role of the AMS tools is more refined in the comprehensive evaluation plan, the TTI CVPD Evaluation Team can more thoroughly address the mitigating actions that it can take to help overcome these limitations for estimates specifically called for in the comprehensive evaluation plan.

Some of the CV applications (specifically the V2V detection and warning applications) may be active outside of the study area. However, it is not cost effective to extend the simulation models to each participant's home and work locations.

The benefits of the CV applications may also extend beyond the feasible timeframe for simulation modeling of the site. The CV applications may have weekend and overnight benefits as well that may not be cost effective for simulation modeling.

While it is desirable to trap all reasonably anticipated system impacts within the simulation models, given the number of research questions to be answered, it will not be cost effective to cover all the reasonably anticipated impacts of the CV applications at existing or higher market penetration levels.

Consequently, it is recommended that the analysis conservatively assume that the CV applications have no benefits outside of the time periods and road network included in each site's simulation model. The model results showing the effects of CV applications (compared to the base) will be assumed to be representative (on a percentage basis) of the system impacts.

6.4 Estimation of Mobility Impacts of Safety Apps

Microsimulation models of mobility are designed to predict the mobility effects of specific demand, weather, and crash conditions. However, they are not designed to predict the weather, demand, or crashes. Therefore, specific demand levels, weather, and crashes commensurate with each specific operational condition cluster to be modeled will be coded into the analysis scenarios.

The mobility effects of reduced crash frequencies will be captured by adjusting the probabilities used to weight the scenarios with crashes to estimate annual performance.

Figure 3 shows an example computation of the total peak-period VHT for a hypothetical deployment site gathered over 100 non-holiday weekdays before activation of the CV devices. Each day experiences a variety of demand levels, weather conditions, and crash conditions. Together, these daily conditions contribute to the observed VHT for the day.

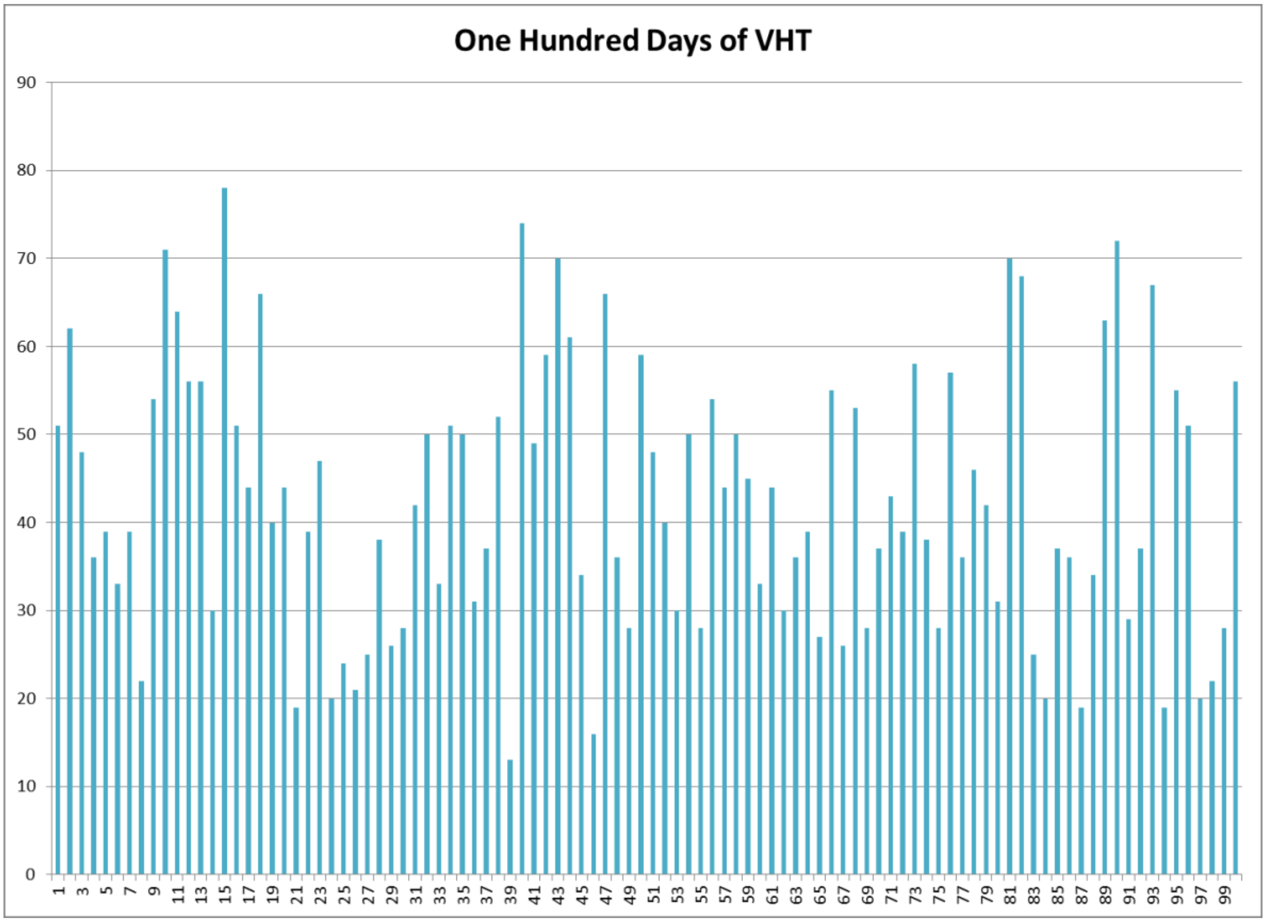


Figure 3. Example of 100 Days of Data

For the purposes of this example, the 100 days of data are grouped (clustered) into five clusters based on VHT. To illustrate this clustering, the days are ranked by VHT from lowest to highest in Figure 4.

As can be seen, clustering is not guaranteed to produce clusters that are composed exclusively of crashes or no crashes, so analysts must deal with mixed clusters, separating out the days with crashes from those without crashes within each cluster.

The average VHT for each cluster is a mix of crash and non-crash days (see Figure 4). Days with significant crashes are tagged as the red columns in Figure 4. The average VHT is computed separately for the crash days and the non-crash days within each scenario cluster.

The average VHT for each cluster is then recomputed using the Volpe National Transportation Systems Center estimated reductions in crash frequencies for the given CV market level. The new crash and non-crash probabilities are applied to the average VHT for crash days and non-crash days, and the results are combined into a new estimate of average VHT for each cluster.

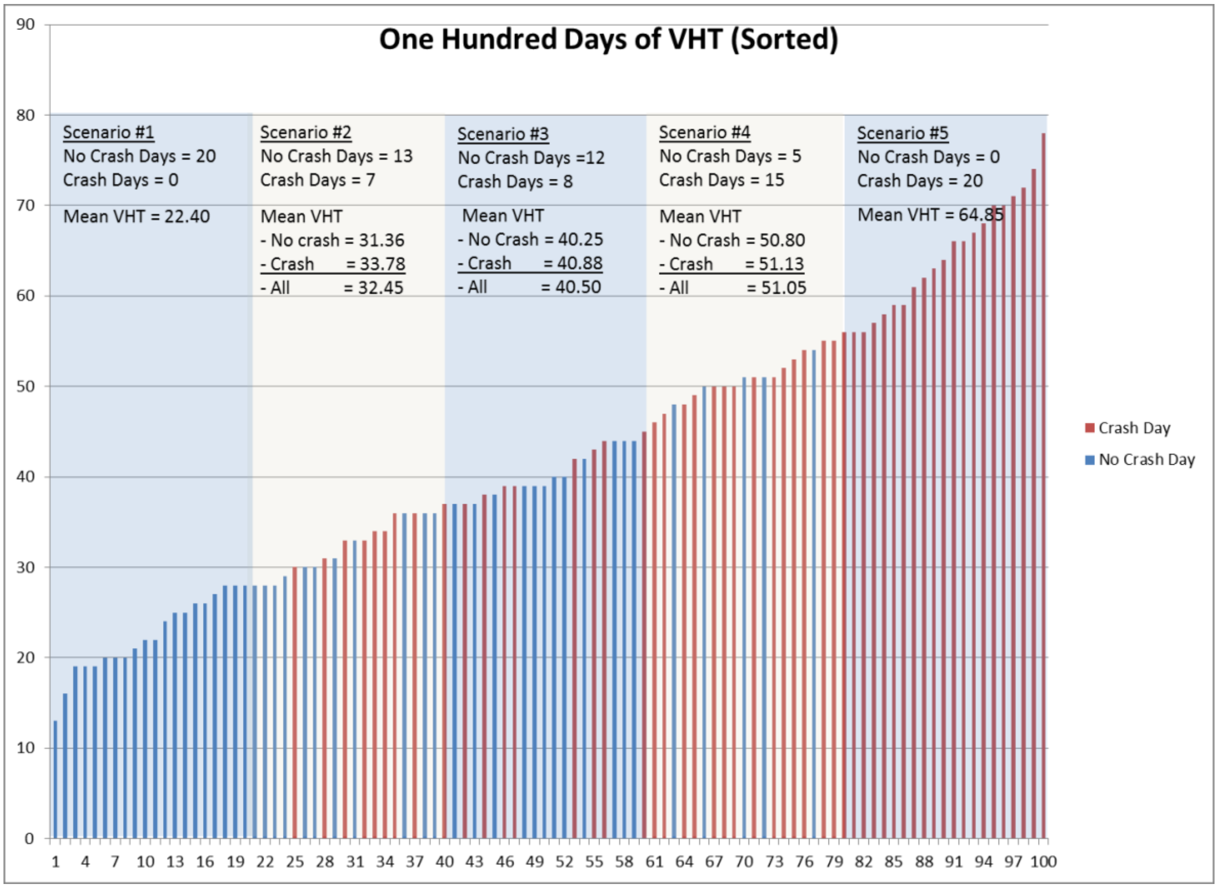


Figure 4. Example of Days Sorted by Degree of Congestion, Clustered into Scenarios

6.5 Extrapolation of System Results to Whole-Year Results

The system results for each scenario will be computed as described in the previous section. This section describes how the results for specific scenarios (each scenario combines a specific CV implementation alternative with a specific set of integrated demand, weather, crash, work zone, and special event operational conditions) are extrapolated to system performance for the whole year.

The key is to associate each set of integrated operational conditions with a specific future probability for the whole year. This is accomplished by examining the cluster data to determine the number of days that the specific integrated operational condition was observed to occur in that cluster for the before and after deployment periods for the site.

Since the pre- and post-deployment periods will probably not cover a full year, the observed probabilities for these periods will be expanded to full-year probabilities. A full year of hourly demands will be gathered from one or more selected permanent count stations representative of the site. A full year of archived crash data will be gathered from agency archives. A full year of weather data will be gathered from a nearby airport. The data by time and day will then be used to construct a full year's worth of daily operational conditions for the site. will aggregate weather and traffic data to 15-minute intervals. The full year's probability for each cluster will then be computed by dividing the total number of days in each cluster by the total number of days in the year (may be less than 365 days if the analysis focuses only on non-holiday weekdays, and may be less than 24-hour days if the analysis focuses on only the peak periods).

Once the annual probabilities are obtained for the clusters used in the simulation runs, the model performance results will be translated into estimates of annual performance by multiplying the average performance observed in the repeated model runs by the estimated annual probability for the integrated operational conditions represented in that scenario.

$$AP(MOE, cv) = \sum_{s} P_{s,cv} * \frac{\sum_r MOE_{s,r,cv}}{R}$$

Where:

AP = annual performance for selected *MOE* and selected CV market penetration level.

P = annual probability of operational scenario *s* for the given CV market penetration level.

MOE = measure of effectiveness produced by repetition *r* for given scenario *s* and market penetration level CV.

R = total number of repetitions of model run for given scenario and market penetration level.

The mobility impacts of the mobility-related CV applications will be measured directly from the model runs. The mobility impacts of the safety-related CV applications will be estimated outside of the simulation model runs.

6.6 Statistical Analysis

Hypothesis testing will be conducted using standard statistical analysis methods.

6.6.1 Determination of Required Number of Repetitions

The required number of repetitions of model runs using different random number seeds (for a fixed set of operational conditions and a given CV application alternative) will be determined based on a statistical analysis of the variance in the performance measures between repetitions, and the desired confidence interval for hypothesis testing.

To estimate the required number of repetitions, the standard deviation of the results and the desired confidence interval for hypothesis testing are required.

6.6.2 Estimation of the Standard Deviation of the Run Results

The pooled standard deviation for the CV alternatives to be evaluated is estimated according to the following equation:

$$s_p^2 = \frac{s_x^2 + s_y^2}{2}$$

Where:

s_p = the pooled standard deviation of model run results for the alternative scenarios.

s_x = the standard deviation of model run results for the base scenario *x*.

s_y = the standard deviation of model run results for CV alternative *y*.

The likely standard deviation in travel times or speeds can be estimated before model runs are completed by examining the travel time data from the field (if sufficient data are available) or from a few preliminary model runs for before and during CV activation to determine the likely magnitude of effects to be observed in the simulation models with CV activation.

6.6.3 Selection of Confidence Interval

A 95 percent confidence level is recommended for hypothesis testing. This means that there is a 5 percent chance (often called alpha error in textbooks) that the analyst will mistakenly reject the null hypothesis when it really is true (Type I error). If a higher confidence level is desired, it comes at the cost of increasing the likelihood of making a Type II error, accepting the null hypothesis when it really is false (see Table 3).

Table 3. Type I and Type II Errors

	True	**False**
Accept Hypothesis	OK	Type II Error
Reject Hypothesis	Type I Error	OK

6.6.4 Identification of Minimal Mean Differences

The before and after field data for each performance measure (delay, travel time, speed, etc.) will be examined to determine the mean differences between CV and base for the deployment. This is likely to be the minimum difference in means that the hypothesis testing will need to test.

6.6.5 Estimate of Number of Repetitions Needed

Based on the observed model variation and the field-observed CV effects, a target sample size (in terms of repetitions of model runs for a given set of operational conditions) can be estimated using standard statistical procedures (*6*).

The following equation will be used to arrive at a preliminary estimate (on the low side) of how many repetitions will be required:

$$n > \frac{2 \cdot t^2_{(1-\alpha/2);2n-2}}{\left(\frac{|\bar{x}-\bar{y}|}{s_p}\right)^2}$$

Where:

n = the number of model repetitions required for each alternative.

t = the *t* statistic for a confidence level of (1-alpha) and 2n-2 degrees of freedom.

$\left|\bar{x}-\bar{y}\right| =$ the absolute value of the estimated difference between the mean values for the two most similar alternatives *x* and *y*.

s_p = the pooled estimate of the standard deviation of model run results for each alternative.

A two-sided *t* test is being used because the CV apps may have either positive or negative mobility benefits.

6.6.6 Hypothesis Testing

The acceptance and rejection of hypotheses will follow standard statistical analysis procedures to quantify the Type I error, the Type II error, and the power of the test (*7*). The TTI team's target for rejecting the null hypothesis of no CV effect will be on the order of 95 percent, depending on the feasible sample size and the impacts of this confidence level on the power of the test.

An analysis of variance of the alternatives will be used to test each mobility-related hypothesis across the range of market penetration levels.

Hypothesis testing will deal with the confounding effects of weather, demand, and crashes on mobility by testing only CV application alternatives with identical operational conditions (same levels of demand, weather, and crashes).

This will require parsing the conclusions of the hypothesis analysis by the sets of operational conditions tested. For example, it may be found that CV applications have a significant effect on only one or more mobility performance measures when market penetration reaches a certain level, and for only operational conditions combining high demand levels with poor weather and a crash.

6.7 Sensitivity Analyses

As alluded to in the previous section, the analysis will test the sensitivity of the conclusions to the following factors: level of market penetration, level of demand, level of poor weather, and presence of and severity level of a crash. Table 4 illustrates the planned framework for the sensitivity analysis. The TTI team will discuss with FHWA the number of scenarios to evaluate in the modeling discussed previously and to consider for the sensitivity analysis presented here, and the two will come to an agreement. As funding is available, the TTI team may analyze more scenarios than those listed in Table 4, such as multiple market penetration rates (e.g., slow, moderate, and aggressive growth).

Table 4. Framework for Presenting Sensitivity Test Results for Each MOE

Scenario	CV Deployment Level	Operational Condition: Demand	Operational Condition: Weather	Operational Condition: Incident	Hypothesis Test Results Impact on MOE
1a	No Deployment	Low	Snow	None	N/A
1b	No Deployment	Medium	Rain	Minor	N/A
1c	No Deployment	High	Fair	Major	N/A
2a	Actual Deployment	Low	Snow	None	+1%, LTS
2b	Actual Deployment	Medium	Rain	Minor	+2%, LTS
2c	Actual Deployment	High	Fair	Major	+3%, LTS
3a	Seven Year Expansion	Low	Snow	None	+2%, LTS
3b	Seven Year Expansion	Medium	Rain	Minor	+4%, S
3c	Seven Year Expansion	High	Fair	Major	+6%, S
4a	Maximum Expansion	Low	Snow	None	+4%, S
4b	Maximum Expansion	Medium	Rain	Minor	+6%, S
4c	Maximum Expansion	High	Fair	Major	+9%, S

Notes:

1. A separate sensitivity analysis results table will be prepared for each mobility MOE tested.
2. N/A = not applicable. This is the base case against which the CV deployment alternatives are compared.
3. +1%, LTS = a 1% increase in the mean value of the MOE was observed, but it was less than significant.
4. +6%, S = a 2% increase in the mean value of the MOE was observed, and it was significant.
5. All entries are illustrative.

The TTI CVPD Evaluation Team will determine the number of levels and the specific levels of demand, weather, and incidents to be evaluated in the sensitivity tests using the clustering analysis described in Chapter 4. The clustering analysis on the field data may also reveal other factors or additional factors to include in the sensitivity analysis.

Chapter 7. Environmental Analysis Model

The environmental analysis will use mobility outputs as its inputs. Therefore, the TTI team does not expect to find measurable environmental benefits in cases where there are no mobility changes. As a result, the environmental analysis will model the same scenarios as the mobility analysis as long as mobility changes are observed in the scenario.

The TTI CVPD Evaluation Team will construct the environmental model using EPA's MOVES model. The team will use output data from the VISSIM model as input to the MOVES model.

MOVES is a project-level simulator that uses a vehicle's operating mode—including idling, acceleration, deceleration, cruise, and hoteling—to measure emissions and petroleum consumption at the national, county, or project scale. MOVES assigns an emission rate for each unique combination of source and operating mode bins and calculates the total emissions and energy use over a specified period of time.

The TTI CVPD Evaluation Team will parameterize the MOVES model according to the local vehicle population, simulation model output, and meteorological conditions. The difference between the "with" and "without" connected vehicle application scenarios will be the estimated environmental impact on emissions and energy use. The team will enter input parameters in the MOVES GUI. When a distribution of a variable is required (e.g., vehicle speed), data will be imported using tables into the PDM.

The smallest unit of analysis in the MOVES model is a "link." A link is a segment of road or an off-network location where a similar type of vehicle activity occurs. Figure 5 provides examples of links.

Freeway

Intersection

Source: U.S. Environmental Protection Agency

Figure 5. Examples of MOVES Links

The TTI CVPD Evaluation Team will report the following model outputs from MOVES in emissions or energy consumption per hour:

- CO_2.
- PM-2.5.
- PM-10.
- NO_X.
- Petroleum energy consumptions.

MOVES can model four separate conditions of hoteling loads:

- Extended idle.
- Auxiliary power units (APUs).
- Battery power.
- Engine off.

Additionally, MOVES has the ability to model number of engine starts (the more starts, the higher the emissions, all else equal) and the soak time with the engine off. The TTI team will work with the site to obtain the best values for the following input variables:

- Operating mode distribution (%)—fraction of time trucks spend in each operating mode (e.g., APU, grid-supported, etc.), if applicable.
- Vehicle population (#)—number of trucks in hoteling (i.e., stationary) mode, if applicable.
- Start fraction (%)—average fraction of the population that has been started during the hour.
- Road type of link (restricted/unrestricted rural/urban)—Cadmus will select.
- Length of link (miles)—Cadmus will manually select for each site.
- Volume of link (vehicles/hour)—output from microsimulation model.
- Grade of link (optional, %)—grade of link, obtained from site and expected to be relatively negligible for the Tampa site.
- Vehicle mix on link (%)—fraction of VHT for each vehicle/fuel combination, must sum to 1 for each link; obtained from site.

Chapter 8. Benefit-Cost Analysis

The TTI CVPD Evaluation Team will also conduct a benefit-cost analysis associated with the Tampa CVPD. The purpose of the benefit-cost analysis is to determine whether the safety, mobility, environmental, and public agency benefits exceeded the total costs associated with deploying the CV technologies in the deployment corridors. If the project were to increase the cost of travel, result in other increased user costs, or cause any other negative benefits, then those results would also be entered as a benefit, but as a negative benefit.

The analysis will use multiple sources of available data to monetize the benefits associated with the deployment. Not all the detailed data for the most precise benefit/cost will be available, but this project is also an opportunity to identify data needs for future ITS deployments, and the TTI team will likely uncover data sources that have not been used or considered in past technology projects. Sampling, generalized data, or modeling can be used where specific data cannot be obtained.

For many transportation projects, the value of travel time savings is the largest benefit category. In this case, though, the team will look at a broader picture. In addition to potential travel time savings, other important potential benefits include safety in the form of reduced crashes or reduced severity, reduced emissions, fuel usage, vehicle operating costs, and reduced cost to commercial carriers from reduced freight delay.

The benefit-cost analysis will encompass the planning, implementation, and 7 years of post-deployment operations. The TTI team will use a combination of field data and simulation data to estimate the benefits and costs. The analysis will assume that the measured impacts of the projects (such as travel time savings) from the early years will continue at the same level in the later years of the project. The analysis will use a 7 percent discount rate for most items in accordance with Office of Management and Budget guidance.

The TTI CVPD Evaluation Team will discount all monetary amounts to a common year, generally the start of project operations. The TTI team will use the following equation to convert costs from nominal dollars into real (constant) dollars for the deployment:

$$(Year\ Z\ \$) = (Year\ Y\ \$) * [\frac{Year\ Z\ CPI}{Year\ Y\ CPI}]$$

Where CPI = consumer price index for the target year.

The team will use CPI numbers from the Department of Labor Statistics, available at http://www.bls.gov/cpi.

8.1 Estimating Mobility Costs

The TTI CVPD Evaluation Team will use travel time as a means of estimating the economic impacts associated with deploying CV technologies in the Tampa CVPD corridors. The TTI team will estimate travel times for all travel modes— automobiles, trucks, and buses—based on the current traffic distribution in the corridor. The TTI team will use changes in before and after travel times for each operational condition likely to produce specific benefits from deploying CV technologies. The TTI team will estimate mobility costs associated with each type of operational scenario identified through the cluster analysis. The TTI team will estimate total mobility costs with the deployment by multiplying the costs of individual events by the frequency of occurrence of the event in the evaluation period.

The TTI CVPD Evaluation Team will use local values of time provided by THEA to monetize the mobility benefits. If local values of time are not available, the TTI team will use the values derived from the *TIGER Benefit-Cost Analysis (BCA) Resource Guide* (*8*). Table 5 shows the values of time provided in the *TIGER Benefit-Cost Analysis (BCA) Resource Guide* (*8*).

Table 5. Recommended Hourly Values of Travel Time Savings (2013 U.S. dollars per person-hour)

Category	Surface Modes* (Except High-Speed Rail)	Air and High-Speed Rail Travel
Local Travel		
Personal	$12.50	
Business	$24.40	None
All Purposes**	$13.00	
Intercity Travel		
Personal	$17.50	$33.20
Business	$24.40	$60.70
All Purposes*	$19.00	$44.30
Truck Drivers	$25.80	
Bus Drivers	$26.70	
Transit Rail Operators	$46.30	None
Locomotive Engineers	$38.70	
Airline Pilots and Engineers	$84.20	

*Surface figures apply to all combinations of in-vehicle and other transit time. Walk access, waiting, and transfer time in personal travel should be valued at $24.97 per hour for personal travel when actions affect only those elements of travel time.

**These are weighted averages, using distributions of travel by trip purpose on various modes. Distribution for local travel by surface modes is 95.4% personal, 4.6% business. Distribution for intercity travel by conventional surface modes is 78.6% personal, 21.4% business. Distribution for intercity travel by air or high-speed rail is 59.6% personal, 40.4% business. Surface figures are derived using annual person-miles of travel data from the 2001 National Household Travel Survey at http://nbts.ornl.gov/. Air figures use person-trip data.

Source: *TIGER Benefit-Cost Analysis (BCA) Resource Guide*.

The TTI CVPD Evaluation Team will also include the cost for freight delays in the analysis. Although the availability of this information is limited, the team will investigate sources of information. The FHWA Office of Operations has generalized figures for the cost of freight delay; however, the TTI team hopes that better and more specific information can be obtained from the sites. One potential method is to include questions on the survey of the operators asking for the most detailed delay cost information they are willing to provide.

8.2 Estimating Safety Benefits

The TTI CVPD Evaluation Team will also include the benefits associated with any reductions in crashes resulting from the deployment. The TTI team will apply the crash reduction predictions for the corridor developed by Volpe to estimate the changes in different types of collisions. (The TTI team will capture the mobility benefits associated with those reductions in crashes in the mobility costs.) The TTI team will use the methodology contained in the *TIGER Benefit-Cost Analysis (BCA) Resource Guide* (*8*) to estimate safety costs. Unless local values are available, the TTI team will use the cost values shown in Table 6 for estimating the safety costs associated with the Tampa CVPD. The values shown in Table 6 are based on a value of statistical life of $9,400,000 (in 2013 dollars). The TTI team will convert these values (shown in 2013 dollars) to baseline dollars using the formula above.

This methodology estimates safety benefits using the Abbreviated Injury Scale (AIS) to assign costs to different types of injury severities associated with collisions. Developed by the Association for the Advancement of Automotive Medicine, the AIS is an anatomically based, consensus-derived, global scoring system for rating the severity of injuries associated with automobile collisions.

Table 6. Recommended Monetized Values Associated with Different AIS Levels

AIS Level	Severity	Fraction of Value of Statistical Life	Unit Value (2013 Dollars)
0	Non-injury	—	$3,927*
1	Minor	0.003	$28,200
2	Moderate	0.047	$441,800
3	Serious	0.105	$987,000
4	Severe	0.266	$2,500,000
5	Critical	0.593	$5,574,000
6	Not survivable	1.000	$9,400,000

Source: *TIGER Benefit-Cost Analysis (BCA) Resource Guide*.

The *TIGER Benefit-Cost Analysis (BCA) Resource Guide* (*8*) provides a methodology for distributing these costs for different types of crash severity indices commonly used by departments of transportation. The National Highway Traffic Safety Administration (NHTSA) has developed a matrix (see Table 7) that allows traditional accident statistical data to be reinterpreted as AIS data. Each column in the matrix represents a probability distribution of different AIS-level injuries that are statistically associated with a corresponding KABCO-scale injury, an injury rating scale commonly used by law enforcement personnel to rate the severity of accidents in the field, or a generic accident. The premise of the matrix is that injuries observed and reported on scene may actually end up being more or less severe than originally reported by the investigating officer at the crash site. Likewise, the matrix also recognizes that any accident can result in a number of different types of injuries. The TTI team will combine Table 6 and Table 7 to estimate the costs associated with each different type of KABCO classification of crashes.

Table 7. KABCO to AIS Conversion Matrix

AIS-Level	O (No injury)	C (Possible Injury)	B (Non-incapacitating Injury	A (Incapacitating Injury)	K (Fatal Injury)	U (Injured Severity Unknown)	# Non-Fatal Accidents (Unknown if Injured)
0	0.92534	0.23437	0.08347	0.03437	0.00000	0.21538	0.43676
1	0.07257	0.68946	0.76843	0.55449	0.00000	0.62728	0.41739
2	0.00198	0.06391	0.10898	0.20908	0.00000	0.10400	0.08872
3	0.00008	0.01071	0.03191	0.14437	0.00000	0.03858	0.04817
4	0.00000	0.00142	0.00620	0.03986	0.00000	0.00442	0.00617
5	0.00003	0.00013	0.00101	0.01783	0.00000	0.01034	0.00279
Fatality	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000

Source: National Highway Traffic Safety Administration, July 2011

8.3 Estimating Emissions Benefits

The TTI CVPD Evaluation Team will also include the benefits associated with any changes in emissions due to deploying the CV technology in the corridor. The TTI team will use simulation to estimate the effects of the deployments on emission. The TTI team will project changes in emissions between the actual case (with the CV demonstration projects) and a hypothetical base case (with no CV technologies deployed) for a 7-year timeframe. The TTI team will include the following pollutants in the benefit-cost analysis: CO_2, VOCs, NO_X, PM, SO_X, and carbon monoxide.

The TTI CVPD Evaluation Team will monetize the changes in these pollutants using the same federal guidance as noted above. Table 8 shows the cost values that the TTI team will use for different types of emissions. The TTI team will update these values to the baseline analysis year using the methods described previously.

Table 8. Costs Associated with Emission Types

Emission Type	$ / short ton (2013 dollars)	$ / metric ton (2013 dollars)
CO_2	Varies*	Varies*
VOC	$1,813	$1,999
NO_X	$7,147	$7,877
PM	$326,935	$360,383
SO_X	$42,240	$46,561

* The value of carbon dioxide emissions changes over time. One should consult the Office of Management and Budget for the latest procedures on estimating the social costs of carbon dioxide.

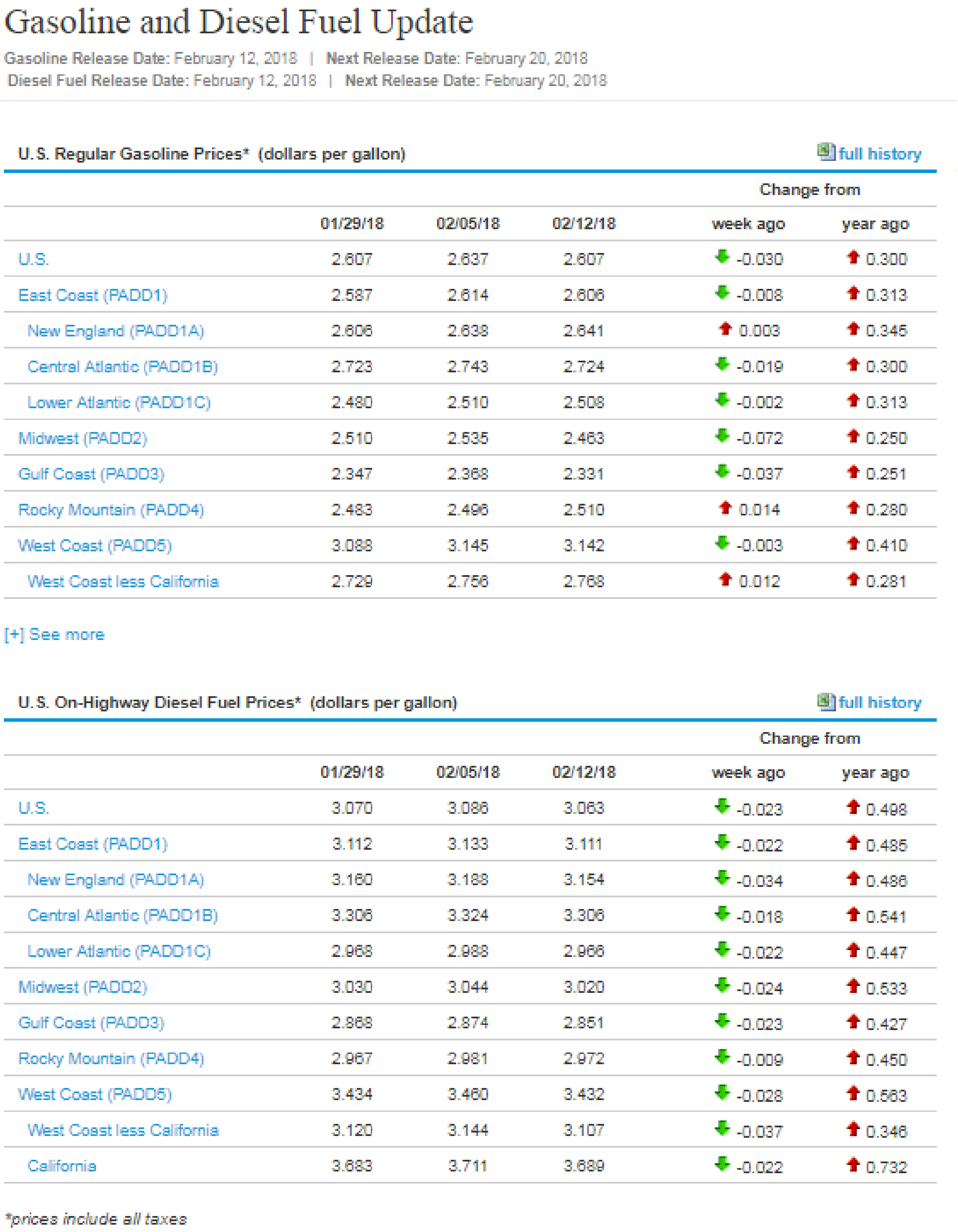
Source: *TIGER Benefit-Cost Analysis (BCA) Resource Guide*.

8.4 Estimating Fuel Usage Costs

The TTI CVPD Evaluation Team will also include the estimated fuel usage costs in the benefit cost analysis. The TTI team will base the current and predicted costs for fuel on information from the U.S. Energy Information Administration website (*9*). As shown in Figure 6, this website includes current and historical gasoline and diesel fuel prices. The TTI team will use data from this site to develop average fuel costs during the evaluation period. For the Tampa CVPD, the TTI team will use fuel prices from the Florida analysis region. The TTI team will remove the portion of the cost of fuel that is taxed prior to calculations since that cost is a transfer and not a change in societal benefits.

8.5 Estimating Vehicle Operating Costs

The TTI CVPD Evaluation Team will also include the vehicle operating costs as part of the benefit-cost analysis. The TTI Evaluation Team will base these costs on data published by the American Automobile Association (AAA) (*10*) annually. Table 9 shows the costs published from 2008 to 2017. Any reduction/increase in VMT will result in reduced/increased maintenance, tires, and depreciation based on average per-mile vehicle operating costs as calculated by AAA. The costs *will not* include ownership costs because the team assumes that those costs would be the same whether or not the vehicle were equipped with CV technologies. Ownership costs include items such as insurance; license, registration, and taxes; vehicle depreciation; and finance charges.



Gasoline and Diesel Fuel Update

Gasoline Release Date: February 12, 2018 | Next Release Date: February 20, 2018
Diesel Fuel Release Date: February 12, 2018 | Next Release Date: February 20, 2018

U.S. Regular Gasoline Prices* (dollars per gallon)

				Change from	
	01/29/18	02/05/18	02/12/18	week ago	year ago
U.S.	2.607	2.637	2.607	↓ -0.030	↑ 0.300
East Coast (PADD1)	2.587	2.614	2.606	↓ -0.008	↑ 0.313
New England (PADD1A)	2.606	2.638	2.641	↑ 0.003	↑ 0.345
Central Atlantic (PADD1B)	2.723	2.743	2.724	↓ -0.019	↑ 0.300
Lower Atlantic (PADD1C)	2.480	2.510	2.508	↓ -0.002	↑ 0.313
Midwest (PADD2)	2.510	2.535	2.463	↓ -0.072	↑ 0.250
Gulf Coast (PADD3)	2.347	2.368	2.331	↓ -0.037	↑ 0.251
Rocky Mountain (PADD4)	2.483	2.496	2.510	↑ 0.014	↑ 0.280
West Coast (PADD5)	3.088	3.145	3.142	↓ -0.003	↑ 0.410
West Coast less California	2.729	2.756	2.768	↑ 0.012	↑ 0.281

U.S. On-Highway Diesel Fuel Prices* (dollars per gallon)

				Change from	
	01/29/18	02/05/18	02/12/18	week ago	year ago
U.S.	3.070	3.086	3.063	↓ -0.023	↑ 0.498
East Coast (PADD1)	3.112	3.133	3.111	↓ -0.022	↑ 0.485
New England (PADD1A)	3.160	3.188	3.154	↓ -0.034	↑ 0.486
Central Atlantic (PADD1B)	3.306	3.324	3.306	↓ -0.018	↑ 0.541
Lower Atlantic (PADD1C)	2.968	2.988	2.966	↓ -0.022	↑ 0.447
Midwest (PADD2)	3.030	3.044	3.020	↓ -0.024	↑ 0.533
Gulf Coast (PADD3)	2.868	2.874	2.851	↓ -0.023	↑ 0.427
Rocky Mountain (PADD4)	2.967	2.981	2.972	↓ -0.009	↑ 0.450
West Coast (PADD5)	3.434	3.460	3.432	↓ -0.028	↑ 0.563
West Coast less California	3.120	3.144	3.107	↓ -0.037	↑ 0.346
California	3.683	3.711	3.689	↓ -0.022	↑ 0.732

*prices include all taxes

Source: U.S. Department of Energy

Figure 6. Screen Capture of U.S. Energy Information Administration Fuel Cost Website (*9*)

Table 9. Vehicle Maintenance, Repair, and Tire Costs (cent/mile) for Different Automobile Types

Vehicle Type	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Small Sedan	4.53	4.87	4.86	4.78	4.86	5.24	5.45	5.76	5.51	6.83
Medium Sedan	5.52	5.39	5.33	5.40	5.45	6.03	6.06	6.31	7.64	7.94
Large Sedan	5.84	5.74	5.94	5.94	6.09	6.68	6.59	6.61	6.67	8.44
Small SUV (FWD)	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.09
Medium SUV (4WD)	6.40	5.89	5.93	5.94	6.15	6.75	6.81	7.23	7.22	8.27
Minivan	5.43	5.61	5.61	5.26	5.20	5.69	5.75	6.03	6.20	7.81
½-ton, Crew-Cab Pickup (4WD)	NA*	NA	NA	NA	NA	NA	NA	NA	NA	8.33
Hybrid Vehicle	NA	NA	NA	NA	NA	NA	NA	NA	NA	6.99
Electric Vehicle	NA	NA	NA	NA	NA	NA	NA	NA	NA	6.55
Average	**5.29**	**5.38**	**5.37**	**5.40**	**5.47**	**5.97**	**6.06**	**6.09**	**6.28**	**7.91**

*Not Available

Source: American Automobile Association

8.6 Estimating Implementation Costs

The implementation costs used for the benefit-cost analysis will include the costs associated with deploying the CVPD. These costs will include the following:

- The costs to plan, implement, operate, and maintain the CV deployment projects.
- The marginal costs that the agencies and users incurred due to the project.

If applicable, the TTI team will subtract salvage value from the cost of the equipment. The team will not include items such as fees for the travelers to use part of the CV deployment project in the benefit-cost analysis.

The study will use simulations based on data collected from the CV deployment project. In addition to examining changes in performance with different penetration rates, the team will also project the effects of changes in background traffic demands on mobility performance in the corridor.

8.7 Projecting Future Costs

In addition to examining the benefits/costs associated with the current deployment, the TTI CVPD Evaluation Team will also use modeling to examine the extent to which different market penetration rates are likely to affect changes in mobility, safety, and the environment in the deployment corridors. The team will estimate the benefits and costs for both the observed CV penetration rate and higher CV penetration rates. The growth scenarios will use only the existing suite of applications being deployed, and no new applications will be added to the vehicles. At a minimum, the study will use the following:

- The cost to increase the penetration rate (additional purchases of CV equipment, labor, maintenance, etc.).
- Estimates of safety, mobility, fuel, and emissions impacts of higher penetration rates.

Chapter 9. Risks and Challenges

This chapter describes the anticipated risks and recommended strategies for reducing the impacts of the risks on the project results.

Risk #1: CV effects may be less than the random effects of weather, demand, and incidents.

Strategy to Reduce the Risk: Simulation modeling will be used to isolate the effects of CVs on traffic performance from those of weather, demand, and incidents. Analysis of how CVs affected specific weather, demand, and incident scenarios will provide the needed information.

Risk #2: CV effects may be smaller than the calibration error of the simulation model.

Strategy to Reduce the Risk: The simulation runs will test higher levels of CV market penetration to see if CV effects that exceed the calibration error of the simulation models can be identified.

Risk #3: Simulation and demand models may not adequately reflect the travel demand behavior, strategic driving behavior, and tactical driving behavior effects of CVs.

Strategy to Reduce the Risk: The surveys of CV driver participants will be examined for indications of behavioral effects of CVs on travel demand, strategic driving, and tactical driving. Where effects are observed, they may be translated into changes in the calibrated simulation model driver behavior parameters.

Risk #4: A major weather or other event may occur before or during the deployment stage.

Strategy to Reduce the Risk: The simulation model will be calibrated to historic data. If there is a major weather or other event during the "before" stage, the TTI team will select days that avoid that event. If there is a major weather or other event during the deployment of CVs, the team will select days that avoid that event for evaluating how CVs may have affected travel behavior.

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Appendix A. Mapping of Analysis Scenarios to Hypotheses

Table 10 presents the preliminary mapping of the model scenarios to the hypotheses for the Tampa CVPD site. The notes explain when mapping is not possible for a specific hypothesis. Chapter 6 describes the analysis scenarios for this AMS plan.

Table 10. Preliminary Mapping of Simulation Analysis Scenarios to Key Hypotheses—Tampa

USDOT Hypotheses for Tampa	Analysis Scenarios
1. Reduce vehicle-to-vehicle and vehicle-to-trolley crashes and incidents (or other safety surrogate measures if crashes are rare) in the pilot deployment area through connected vehicle deployment.	See Note 1
2. Reduce crashes and incidents (or other safety surrogate measures if crashes are rare) due to wrong-way entries into the RELs.	See Note 1
3. Reduce crashes and incidents (or other safety surrogate measures if crashes are rare) by giving drivers warnings of the REL exit curve speed and stopped vehicles ahead.	See Note 1
4. Reduce pedestrian-to-vehicle and pedestrian-to-trolley conflicts in the pilot deployment area by warning vehicles as well as pedestrians.	See Note 1
5. Increase transit schedule reliability.	See Note 1
6. Improve transit ridership.	See Note 1
7. Improve traffic signal progression through use of connected vehicle data.	1—Base 2—Deploy 3—Seven Year 4—Max Deploy
8. Reduce negative environment impacts through reductions in crashes and improvement in signal progression, which will lead to reduced idle times and fewer acceleration and deceleration events.	1—Base 2—Deploy 3—Seven Year 4—Max Deploy
9. Improve decision-making by transportation managers.	See Note 2
10. Improve customer satisfaction of end users.	See Note 2

Notes:

1. Speed compliance, specific crash details, and driver response to improved information are inputs to the mobility simulation model, not outputs.
2. User satisfaction is not a mobility simulation model output.

Appendix B. Clustering Data Needs and Potential Sources—Tampa

Attributes	Captured	Data Set	Potential Data Sets	Notes
Traffic demand or congestion	Partial	Traffic counts	Available from City of Tampa WAZE partnership	• Demand proxy: VMT. • Congestion proxy: system VMT/VHT (in other words, speed).
Weather conditions (type, duration, severity, pavement conditions, time-lag of weather effects)	Partial	Traveler information message	Weather Underground historical weather data based out of the University of Tampa	None
Incident conditions (type, duration, severity)	Partial	Traveler information message	Crash data available from Web CDMS through FDOT or GF	None
Work zone conditions (type, duration, severity of impacts)	No	None	City of Tampa transportation advisories and road closures	None
Special event conditions (type, duration, severity of impacts)	Partial	Traveler information message	City of Tampa Office of Special Events	None

Attributes	Captured	Data Set	Potential Data Sets	Notes
Travel time (system data and CV-specific data)	Partial	Traveler information message	• Available from City of Tampa WAZE partnership • CV BSM data	• Weekday peak-period end-to-end travel times along each key study corridor (in 15-minute aggregations) for model calibration, for the same days as for the turning counts listed above. Ideally, each 15-minute travel time is the average of 5 or more data points within that period. Data should be available from TMC archives; if not, the sites need to inform the TTI CVPD Evaluation Team that they must collect. • Separated CV travel times along each key study corridor for driver behavior model calibration.
Freight (number of trucks)	No	None	None	None
Road closure conditions	Partial	Traveler information message	City of Tampa transportation advisories and road closures	None
Holidays	No	No data set needed	None	None
Day of week	No	No data set needed	None	None
Market penetration observed	No	None	Post-deployment number of observations during analysis period compared to total volume	None
Transit (ridership rates, on-time performance rates)	Partial	On-time performance rates may be able to be calculated based on the number of TSP calls made	Average bus ridership rates for study routes during analysis time periods	None
Bottleneck throughput	Partial	Traffic counts at bottlenecks	None	None

Attributes	Captured	Data Set	Potential Data Sets	Notes
Traffic signal detection and controller logic, including I-SIG	No	None	• City/THEA traffic signal phase and timing plans • I-SIG logic detailed descriptions, including pedestrian activations	Needed for all signalized intersections within model analysis area.
Pedestrian and bicycle counts	No	Pedestrian and bicycle volumes and movements at intersections	None	Needed for model calibration, especially for pedestrian applications.

Appendix C. Simulation Driver Behavior Models in VISSIM

Prepared by Richard Dowling, Kittelson & Associates, Inc. (November 2017)

This white paper presents an overview of the driver behavior models in the VISSIM microsimulation software package and the available parameters for modifying those models to reflect the unique driving behavior characteristics of drivers in CV-equipped vehicles. The information in this white paper (including the referenced page numbers) is based on the PTV VISSIM 6 User Manual, Copyright 2013 by PTV AG, Karlsruhe, Germany.

C.1 Customizing Strategic Driver Behavior in VISSIM

In VISSIM, the user tells the software where and when to add vehicles to the network, what types of vehicles they are, and their destination.

The user can specify connected and unconnected versions of any vehicle type and generate them at different locations and times and with different destinations, if desired.

The user can vary the proportion of connected vehicles by location, time of day, and destination.

It is 100 percent the responsibility of the user to decide if connected vehicles might have different generation rates, generation locations, generation times, and destinations than unconnected vehicles.

The user has the choice of pre-specifying the routes the vehicles take through the network (called static routes) or having VISSIM dynamically select the routes the vehicles take during the course of the simulation (dynamic assignment; page 273).

Dynamic assignment requires OD tables (can be multiple tables, varying by time of day and by vehicle type; page 451).

A variety of methods are provided in VISSIM for dynamically determining the routes taken between each OD pair (Section 7.5, Simulated Travel Time and Generalized Costs, page 457; and Section 7.6, Process Path Selection, page 461). These methods attempt to smooth out the extreme variations in route travel times as vehicles are first assigned to one route and then a few minutes later to another route. Section 7.8, Controlling Dynamic Assignment, specifies the parameters available to the user for affecting route selection. Different assignment parameters can be assigned to different matrices (page 478).

It is possible to mix dynamic assignment with fixed routes and time-dependent detours to reflect any dynamic path guidance that connected vehicles receive.

Note that if a vehicle is stopped, unable to change lanes to continue on its route for 60 seconds, it is vaporized (removed from the simulation) to avoid unrealistically blocking other vehicles.

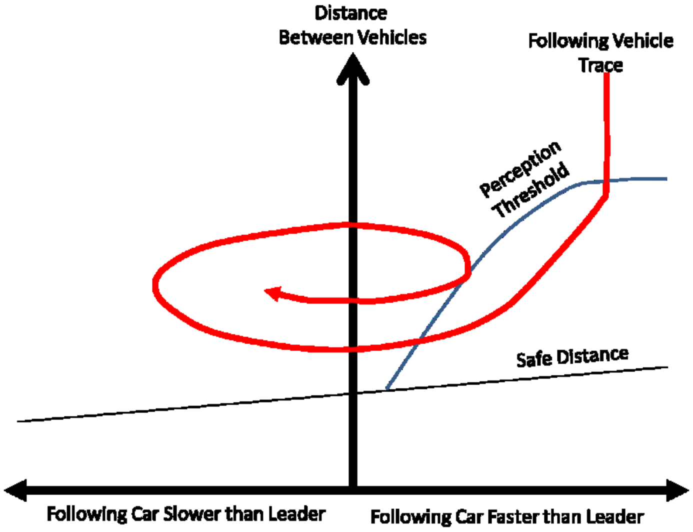
C.2 Customizing Tactical Driving Behavior in VISSIM

VISSIM employs a Traffic Flow Model to simulate the movement of vehicles on a road network. The Traffic Flow Model is composed of two submodels, a car following model and a lane changing model.

The user can also code a separate, external driver model to completely replace the built-in driver model in VISSIM. The external driver model must be a dll file written in the C or C++ languages (see page 166 of VISSIM User Manual for details).

C.2.1 VISSIM Car Following Models

As noted on page 22 of VISSIM User Manual, "VISSIM uses the psycho-physical perception model developed by Wiedemann (1974). Figure 7 shows the Wiedemann car following mode. The basic concept of this model is that the driver of a faster moving vehicle starts to decelerate as he reaches his individual perception threshold to a slower moving vehicle. Since he cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. There is a slight and steady acceleration and deceleration. The different driver behavior is taken into consideration with distribution functions of the speed and distance behavior."



Source: Adapted from VISSIM User Manual

Figure 7. Wiedemann Car Following Model

For multilane links, the car following model also takes into account vehicle speeds in the two adjacent lanes. Traffic signals will also affect car following behavior within 100 meters of the stop bar (page 23).

The car following model takes into account the driver's characteristics (desired speed, memory, willingness to take risk, etc.) and the technical specifications of the vehicle (length, maximum speed, acceleration power; page 23).

The maximum acceleration, desired acceleration, maximum deceleration, and desired deceleration can vary between vehicle types. The user can code different acceleration and deceleration values and functions for CV and non-CV vehicles (pages 139-141, 160-170).

Trucks may be assigned different weight and power distributions, which affect speeds on grades.

The user is given direct access to the following driver behavior parameters:

- Look ahead distance (page 174).
- Look back distance (page 175).
- Temporary lack of attention (page 175).
- Choice of car following models to employ (Wiedemann 74, Wiedemann 99; page 176–177).
    - The Wiedemann 99 model is used for freeway car following with no merging. The Wiedemann 74 model is used for all other segments.

The Wiedemann 74 Car Following Model predicts the distance between following and lead vehicles as:

$$d = ax + bx$$

Where:

d = the predicted distance between vehicles (m).
ax = the standstill distance (m).
bx = (bx_add + bx_mult * z) * SQRT(v).

Where:

v = vehicle speed (m/s).
z = is a random variable of range (0.1), which is normally distributed around 0.5 with a standard deviation of 0.15.

Table 11 shows the calibration parameters available for the Wiedemann 74 model. Table 12 shows the calibration parameters for the Wiedemann 99 model.

Table 11. Calibration Parameters for Wiedemann 74 Car Following Model

Parameter	Description
Average standstill distance	(ax): Defines the average desired distance between two cars. It has a variation between −1.0 m and +1.0 m, which is normally distributed at around 0.0 m with a standard deviation of 0.3 m.
Additive part of safety distance	(bx_add): Value used for the computation of the desired safety distance *d*. Allows for adjusting the time requirement values.
Multiplicative part of safety distance	(bx_mult): Value used for the computation of the desired safety distance *d*. Allows for adjusting the time requirement values.

Table 12. Available Calibration Parameters for Wiedemann 99 Car Following Model

Parameter	Description
CC0 (standstill distance)	The average desired standstill distance between two vehicles. It has no variation.
CC1 (following distance)	The distance in seconds that a driver wants to maintain at a certain speed. The higher the value, the more cautious the driver is. Thus, at a given speed v (m/s), the average safety distance is computed as dx_safe = CC0 + CC1 • v. The safety distance is defined in the car following model as the minimum distance a driver will maintain while following another vehicle. In case of high volumes, this distance becomes the value that has a determining influence on capacity.
CC2	Restricts the distance difference (longitudinal oscillation) or how much more distance than the desired safety distance a driver allows before he intentionally moves closer to the car in front. If this value is set to 10 m, for example, the following behavior results in distances between dx_safe to dx_safe + 10 m. The default value is 4.0 m, which results in a stable following behavior.
CC3	Controls the start of the deceleration process (i.e., the number of seconds before reaching the safety distance). At this stage, the driver recognizes a preceding slower vehicle.
CC4	Defines negative speed differences during the car following process.
CC5	Defines positive speed differences during the following process. Enter a positive value for CC5 that corresponds to the negative value of CC4. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
CC6	Influence of distance on speed oscillation while in the following process. If set to 0, the speed oscillation is independent of the distance. Larger values lead to a greater speed oscillation with increasing distance.
CC7	Oscillation during acceleration.
CC8	Desired acceleration when starting from standstill (limited by maximum acceleration defined within the acceleration curves).
CC9	Desired acceleration at 80 km/h (limited by maximum acceleration defined within the acceleration curves).

Source: PTV VISSIM 6 User Manual, page 177.

C.2.2 VISSIM Lane Changing Model

VISSIM distinguishes between “necessary” lane changes needed to follow the designated route for the vehicle and “free” lane changes when a vehicle may change lanes to pass a slower vehicle. The user has direct access to the following parameters of the lane changing model (pages 178–181):

- General behavior.
    - Right side, left side, or free lane choice for overtaking behavior. The right side or left side lane change options reflect German traffic code for freeways. The free lane option allows vehicle to choose either left or right side for lane change.
- Necessary (route-driven) lane change behavior.
    - Maximum and accepted deceleration rates.
- All lane change behavior.
    - Diffusion time: the maximum time a vehicle can be at full stop in a travel lane waiting for a gap in traffic before the vehicle is removed from the simulation (vehicle is vaporized).
    - Minimum headway that must be available for a lane change after lane change.
    - Safety distance reduction factor: reflects that vehicles may temporarily accept tighter headways when initially changing lanes; changes to this parameter will cause more aggressive or less aggressive lane changing.
    - Maximum deceleration for cooperative braking.
    - Advanced merging.
    - Cooperative speed distance and collision time for cooperative lane changing.
    - Lateral correction of rear-end position for lane changes that take place at a lower speed than specified by the maximum speed.

C.2.3 Varying Behavior in VISSIM by Link and Junction

Link-specific driving behavior parameters can be defined by vehicle class (page 196). The car following model assigns each vehicle a desired speed based on the coded attributes of the link, the randomly assigned characteristics of the driver, and the used coded technical capabilities of the vehicle. The user can override the VISSIM default driver-desired speed distributions. Different distributions of desired speeds can be assigned to different vehicle types (page 144).

The network can be coded so that the different vehicle types react differently to signal controls, have access to certain lanes at different times of day, and act differently at junctions in the network.

Movements of vehicles at junctions and yielding to other vehicles at the junctions is handled by user coded stop bars and conflict markers. The placement and spacing between the stop bars and conflict markers determine the size of the conflict zone, which affects the capacity and yielding of vehicles through the junction. Different vehicle types can be associated with different minimum headways and time gaps at the junction. Thus, connected vehicles (if coded as a unique vehicle type) can be made to act differently than unconnected vehicles at a junction.

The user can enter how each vehicle type reacts to an amber signal display (page 192).

The saturation flow rate for signals in the network can be specified by the selection of the appropriate car following parameters (pages 193–196).

C.2.4 Interaction of CV with Signal Controllers in VISSIM

VISSIM comes with a pre-packaged standard Ring Barrier Controller. Users can also acquire an Econolite ASC signal controller emulator for VISSIM. Finally, users can create their own custom controller logic using VISSIM's vehicle actuated programming module (page 26). SCAT and SCOOT signal coordination interfaces are available (page 27).

The user can custom code connected vehicle signal controller logic in VISSIM or interface with external signal controller software (page 27).

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