

Connected Vehicle Pilot Deployment Program Independent Evaluation:

Analysis, Modeling, and Simulation Plan—Wyoming

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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 Wyoming, 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 deployment team for Wyoming. 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 Wyoming test site, the I-80 corridor. The evaluation team is conservatively recommending that market penetration rates achievable within the next 7 years be evaluated.					
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Chapter 1. Introduction

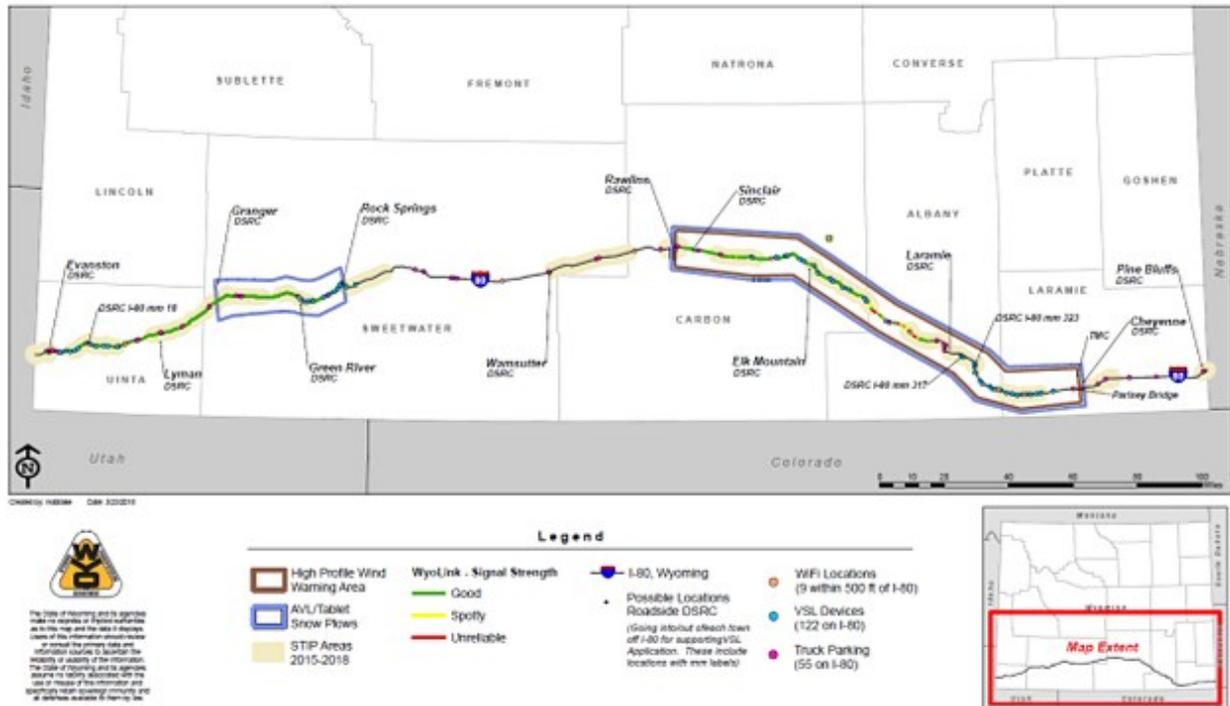
The Texas A&M Transportation Institute (TTI) Connected Vehicle Pilot Deployment (CVPD) Evaluation Team expects that analysis, modeling, and simulation (AMS) will play a prominent role in assessing the effects of the CVPD on mobility and the environment. AMS involves the use of advanced simulation tools 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 Wyoming Department of Transportation's (WYDOT's) CVPD. The TTI CVPD Evaluation Team has structured the AMS plan based on processes and procedures described in the Federal Highway Administration's (FHWA's) *Traffic Analysis Toolbox III: Guidelines for Applying Traffic Microsimulation Modeling Software* (1).

1.1 The Wyoming Connected Vehicle Pilot Deployment

The goal of the Wyoming CVPD is to improve driver safety, particularly for commercial vehicle operators, on I-80 (2). I-80, which runs the entire length of the southern edge of the state, is susceptible to multivehicle collisions and roadway closures during winter weather due to icy roads and low visibility from blizzard conditions. The corridor also experiences extreme wind gusts that can cause trucks and other high-profile vehicles to blow over. These events can result in fatalities, extended closures, and significant economic loss. The Wyoming CVPD includes a variety of applications to support a range of existing and new services, including traveler information, roadside alerts, and dynamic travel guidance for freight and passenger travel. These applications include the following (2):

- **Forward Collision Warning (FCW)**—Using vehicle-to-vehicle (V2V) communications, this application alerts drivers if a rear-end crash is imminent with a connected vehicle ahead.
- **Infrastructure-to-Vehicle (I2V) Situational Awareness**—This application allows connected vehicles to receive information about downstream conditions that may impact their travel. This application provides drivers with information about downstream road conditions, weather alerts, speed restrictions, vehicle restrictions, incidents, parking, and road closures.
- **Work Zone Warning**—This application extends the I2V situational awareness application to provide information to vehicles approaching work zones. The approaching connected vehicle will receive information about work zone conditions, including obstructions in the travel lane, lane closures, lane shifts, speed reductions, and vehicles entering and exiting work zones.
- **Spot Weather Impact Warning**—This application broadcasts localized road condition information to drivers. The purpose of this application is to alert drivers of fog and icy roads that may exist only at isolated locations on I-80.
- **Distress Notification**—This application enables connected vehicles to communicate a distress message if the vehicle's sensors detect an event that might require assistance from others or if the driver initiates a distress request.

To support this pilot, WYDOT is deploying 75 roadside units (RSUs) in various sections of I-80 that can receive and broadcast messages using dedicated short-range communications. WYDOT will install these RSUs at locations upstream of identified hotspot areas. Through its collaboration partners, WYDOT will also equip 400 vehicles that regularly use I-80 with onboard equipment designed to provide connected vehicle information and to receive alerts and advisories issued by WYDOT. A portion of the equipped vehicles will have additional capabilities to collect and transmit environmental and road weather condition information through mobile weather sensors (2). Figure 1 shows the deployment corridor.



Source: (3)

Figure 1. Wyoming CVPD Area

As part of its Phase 2 development efforts, the Wyoming Deployment Team is developing a microscopic simulation model for a select portion of the I-80 corridor (4). The deployment team plans to develop this model using the VISSIM microscopic simulation software. The deployment team plans to use the simulation model to perform a surrogate safety assessment as well as evaluate how the introduction of CV technology influenced corridor performance during adverse weather conditions. The TTI CVPD Evaluation Team plans to use this model as the foundation for conducting its simulation and modeling activities.

1.2 Purpose of AMS

The TTI CVPD Evaluation Team plans to use AMS to supplement, not replace, the analysis of observed field data in quantifying the effects of the deployment on traffic operations in the corridor. The TTI team still plans to use direct comparison of observed data as the primary means of quantifying the extent to which the field deployment impacts mobility 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.
- The TTI team cannot use direct field observations to project longer-term impacts of the deployment.

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

- Quantify the system-wide ME impacts related to deploying CV technologies in the Wyoming 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.

1.3 Scope of AMS Plan

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 (i.e., crash reductions, time-to-collision projections, etc.) associated with the deployment of the different CV applications. Volpe will be looking at the effectiveness of the deployments at changing crash histories and improving safety in the deployment areas. While the TTI team will not be modeling the potential changes in safety, it will attempt to capture the mobility benefits associated with changes in safety at each site. To do this, the team plans to model different safety-related situations and scenarios both with and without the technology to estimate the relative savings that the technology provides. For this analysis, the simulation models will assume that all drivers obey all traffic laws and always drive safely (i.e., vehicles will never crash, vehicles never get close enough to need emergency braking).

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 changed vehicle emissions and fuel consumption in the I-80 deployment corridor. 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 team will use AMS to estimate the changes in vehicle emission and fuel consumption associated with the mobility changes.

Finally, the TTI team will use AMS as part of the overall CVPD evaluation approach to estimate the cumulative ME benefits over the life cycle of the deployment. To do this, the 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).

1.4 Organization of Report

The organization of this report is as follows:

- Chapter 2 provides a brief description of the overall framework that the TTI CVPD Evaluation Team will follow in performing the AMS analysis of the deployment site. This chapter gives a high-level overview of the activities performed during each step of the analysis.
- Chapter 3 identifies the specific goal(s), 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 the TTI team will use in conducting a cluster analysis of both the pre- and post-deployment data for identifying the operational scenarios that they team will use in the AMS for the site.
- Chapter 5 describes the process the TTI team will use to calibrate the traffic simulation modeling tool for the identified operational scenarios.
- Chapter 6 describes how the TTI team will use the output of the traffic simulation modeling to estimate changes and assess the mobility benefits associated with the deployment.
- Chapter 7 describes how the TTI team will construct the environmental model using EPA's Motor Vehicle Emissions Simulator (MOVES) model.
- Chapter 8 describes the techniques that the TTI 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 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 CVPD Evaluation 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 deployment team no longer plans to develop a model, the TTI team will work with the 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 Wyoming Deployment Team, the TTI CVPD Evaluation 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 deployment team to determine the source of the error and have the deployment team correct it before continuing with the analysis.

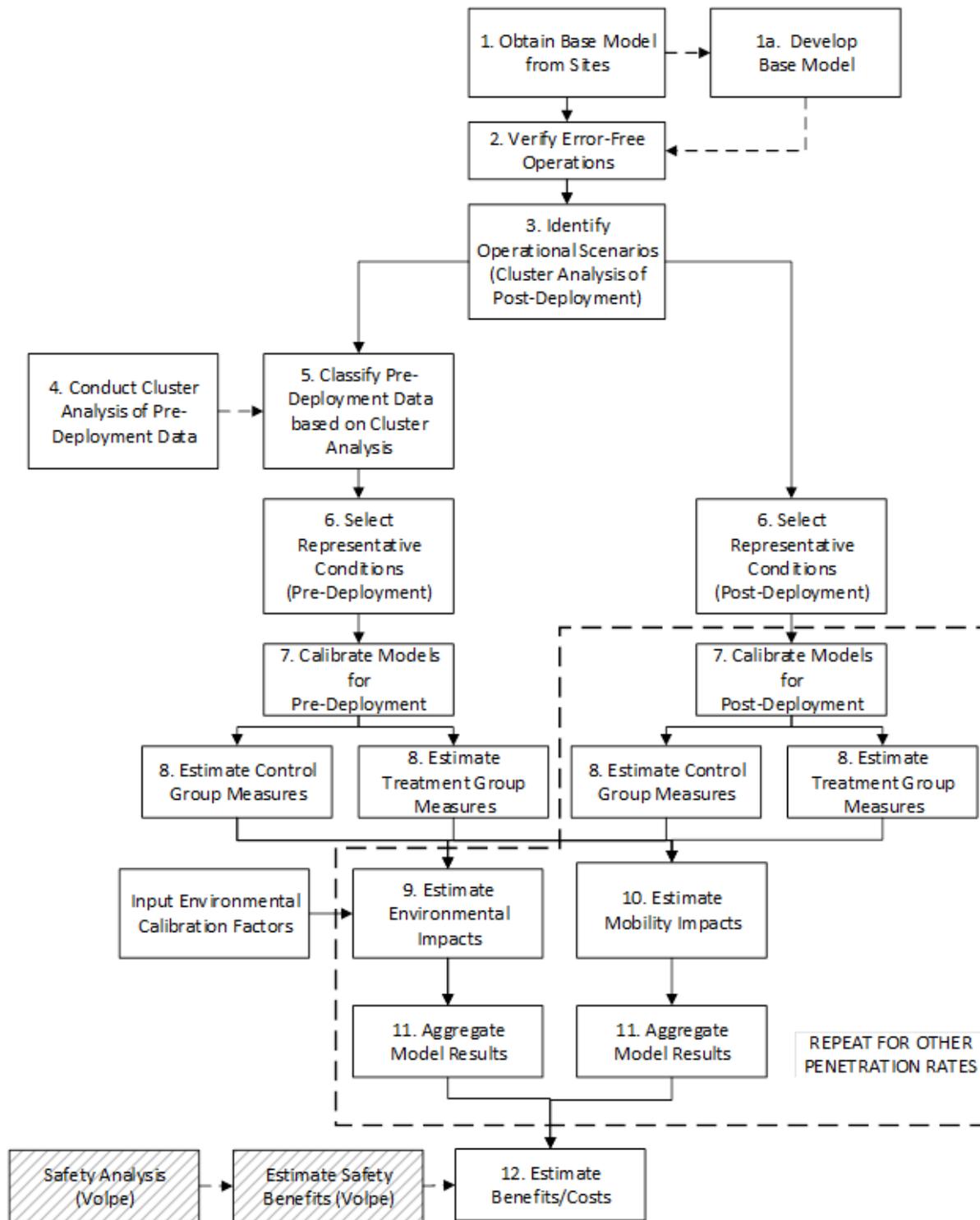


Figure 2. CVPD AMS Framework for Wyoming (Counterfactual Design)

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 team will run the model and view the simulation to see if the modeled vehicle behavior and network configuration seem reasonable. The 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 Wyoming 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 team will define the identification of operational scenarios based on the attributes of the post-deployment data. The team will use the post-deployment data set as the basis for identifying the operational scenarios (and not the pre-deployment conditions). The 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 CVPD Evaluation 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 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 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, it 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 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), the team 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. To do this, the team will first establish appropriate acceptability criteria for each operational scenario. The team will then adjust the appropriate input parameters to the base model and then execute the model. The team will compare the output results of the model run to the established acceptance criteria. Using an iterative approach, the 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 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 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, it 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, it 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 team will use traditional comparisons of mean techniques to determine whether the differences in pre- and post-deployment conditions are statistically significant. The 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 team will construct the environmental model using EPA's MOVES2014a model and 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 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 team will report the following model outputs from MOVES in emissions or energy consumption per hour:

- Carbon dioxide (CO₂).
- Volatile organic compounds (VOCs).
- Particulate matter (PM).
- Nitrogen oxide (NO_x).
- Sulfur oxide (SO_x).

- Petroleum energy consumptions.

Similarly, the team will compare the operational scenarios from the environmental model. Again, the team will use traditional comparisons of mean techniques to determine whether the differences in pre- and post-deployment conditions are statistically significant. The 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 Wyoming deployment. The 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:

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

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

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

The team will repeat this process for all the scenarios showing significant differences between the pre- and post-deployment conditions. The 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 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 Wyoming Deployment Team will likely need to revise its initial deployment within 7 years as the technology and applications mature. If the Wyoming

Deployment Team has its own life-cycle estimates for its deployment, the TTI team may consider using Wyoming's number. 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 goal of the USDOT CV Pilot Deployment Program is to show that connected vehicle technologies can:

- Improve safety.
- Improve mobility.
- Reduce negative environmental impacts.
- Improve public agency efficiency and decision-making by transportation managers.
- Improve end-user satisfaction with their travel.

This chapter discusses the goals and objectives of the AMS study that the TTI CVPD Evaluation Team will perform. The 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 IE Evaluation Objectives of the Wyoming CVPD

As defined in the *Connected Vehicle Pilot Deployment Program: Mobility, Environmental, and Public Agency Efficiency (MEP) Refined Evaluation Plan: Wyoming Pilot Deployment Site (5)*, the objectives of the independent evaluation for the Wyoming pilot deployment are as follows:

1. Assess the extent to which deploying CV technologies improved mobility, travel reliability, and throughput in the I-80 corridor during adverse weather conditions.
2. Estimate the extent to which reductions in crash frequency and severities contributed to improvements in mobility and travel reliability along the I-80 corridor as a result of equipping commercial fleet vehicles and WYDOT maintenance vehicles with CV technologies.
3. Estimate the extent to which deploying CV technologies improved travel and freight reliability for commercial fleet vehicles equipped with CV technologies.
4. Quantify the extent to which CV technologies helped improve emergency management on the I-80 corridor through early identification of conditions and improved messaging and communication.
5. Assess the extent to which improved traveler information on road weather conditions and construction activities in the corridor improved freight drivers' ability to better plan and adjust their trips (e.g., locate truck parking locations along the corridor).

6. Assess the extent to which deploying CV technologies in the I-80 corridor helped public agency officials better manage operations and deploy traffic management strategies.
7. Estimate the extent to which improved mobility for connected trucks and for all traffic will reduce negative environmental impacts along I-80 during adverse weather.
8. Estimate that extent to which the life-cycle mobility, environmental, and public agency efficiencies benefit as market penetration and background traffic changes over the 7 years after deployment.
9. Conduct a benefit-cost assessment associated with equipping commercial fleet vehicles with CV technologies in the I-80 corridor.

Both the Wyoming Deployment Team and TTI CVPD Evaluation Team, as USDOT's independent evaluator (IE), are evaluating the effectiveness of the deployment to achieve these 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 field 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 in Wyoming. The Volpe Institute is responsible for conducting the safety assessment.

The TTI team will coordinate with the Wyoming Deployment Team to get the data, models, and estimates of its performance measures at frequencies determined by the deployment team in conjunction with USDOT. The TTI team will share the findings and updates to the model(s) with the Wyoming Deployment Team.

3.2 AMS Objectives for the Wyoming CVPD Evaluation

The ME goals and objectives of the simulation model(s) relate to mobility, travel time reliability, weather-related delay, and environmental impacts. Specifically, the TTI CVPD Evaluation Team will use the AMS analysis to perform the following:

- Estimate the impacts related to CV deployment on **travel time and delay** due to changes in truck-related crashes and incidents and improved freight traveler information along I-80 during adverse weather and other operating conditions (IE Objectives #1 and #2).
- Estimate the impacts related to CV deployment on **travel reliability** due to changes in truck-related crashes and incidents and improved freight traveler information along I-80 during adverse weather and other operating conditions (IE Objectives #1 and #2).
- Estimate the impacts related to CV deployment on **throughput** due to changes in truck-related crashes and incidents and improved freight traveler information along I-80 during adverse weather and other operating conditions (IE Objectives #1 and #2).
- Estimate the impacts related to CV deployment on **freight mobility** due to changes in truck-related crashes and incidents and improved freight traveler information along I-80 during adverse weather and other operating conditions (IE Objective #3).

- Estimate the impacts related to CV deployment on the **environment** due to changes in truck-related crashes and incidents and improved freight traveler information along I-80 during adverse weather and other operating conditions (IE Objective #7).
- Estimate the **cumulative effects** of different market penetration levels of connected trucks and changes in background traffic levels on ME impacts on I-80 during different operating conditions (including adverse weather; IE Objective #8).

In order to estimate these impacts, the TTI team will use the base model that the Wyoming Deployment Team will develop. The TTI 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 Wyoming Deployment Team plans to do.

3.3 Performance Measures

The following subsections describe how the TTI CVPD Evaluation Team will compute the mobility-related performance measures for each operational scenario. The team will compute these performance measures using data from multiple simulation runs for each operational condition. The 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.

3.3.1 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 team will collect VMT for the different operational scenarios identified for the site. The team will simulate each operational condition using the appropriate number of replications to estimate VMT for both the pre- and post-deployment periods. The team will average the VMT output from each repetition across all the repetitions to obtain an average VMT for each operational condition. The 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.

3.3.2 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 team has made the adjustments, the team will use the same process as described for VMT to compute the whole-year VHT for each future scenario.

3.3.3 Travel Time

The TTI 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 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 team will use the collected travel time to compute both the average and 95th percentile travel times during the different modeled operational conditions.

3.3.4 Average Operating Speed

The TTI team will use simulation to compute the average operating speed associated with the different operational scenarios in the Wyoming corridor. From a modeling perspective, the 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 team will compute average system speed by dividing total VMT by total VHT.

3.3.5 Average System Vehicle-Hours of Delay

The TTI 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 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 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.

3.3.6 Average System Speed Variance

The TTI 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 (weather, incidents, demand, etc.).

3.3.7 Average System Time (VHT) Spent in Queue

The TTI 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 team will program the simulation to accumulate the amount of time the system operates with queues over the course of each run. The 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 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

In order to perform the AMS analysis, the TTI team will need to receive site-developed base mobility models (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).
- Data for determining operational conditions.
- Data for calibration.

The deployment site will upload all the data and the model input files to the Secure Data Commons (SDC). Assuming the TTI team can overcome microsimulation software licensing issues and the strict prohibition on the electronic export of processed data from the SDC, the 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 Wyoming 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 team is assuming that the Wyoming Deployment Team will deliver a VISSIM model of one of the variable speed limit (VSL) segments of the deployment corridor, either the Cheyenne-Laramie or Elk Mountain section. The TTI team is expecting to receive from the Wyoming Deployment Team a functioning model that is free from errors and calibrated to some level of performance. The TTI team will then calibrate the model for both speed and throughput for the operational scenarios identified through the cluster analysis. The TTI team will follow the procedures specified in the *Traffic Analysis Toolbox III: Guidelines for Applying Traffic Microsimulation Modeling Software (1)* to calibrate the model. The TTI team anticipates that the model will cover both the eastbound and westbound directions of travel in the corridor.

4.1.2 Data Required for Model Calibration

The TTI 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 Wyoming Deployment Team to determine if the model calibration is consistent with FHWA guidance. The TTI team will coordinate with the Wyoming 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 Wyoming Deployment Team and field observations from the pre- and post-deployment periods.

In the event the TTI team needs to recalibrate the models, it may need additional data. Appendix C 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 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.

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 team through a public source:

- WYDOT Road Weather Information System (RWIS) logs.
- WYDOT snowplow road weather information reports.
- Pikalert[®] system logs.
- WYDOT Traffic Management Center (TMC) incident management/event management logs.
- WYDOT VSL system logs (including traffic volume data).
- WYDOT construction/maintenance work zone logs.

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 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 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 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 team will explore various attributes in the data set for clustering. Following is the initial candidate list of attributes that the team will explore during the cluster analysis. As the team explores the data, it may drop some of the less meaningful attributes in the candidate list and substitute others.

The anticipated key attributes include the following:

- Daily travel demand.
- Weather conditions (type, duration, severity, precipitation amount, pavement conditions, time-lag of weather effects).
- Incident conditions (type, duration [e.g., total lane-minute closure], severity).
- Work zone conditions (type, duration, impact severity).
- Special event conditions (type, duration, impact severity).
- 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 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 team will simply transform the data onto a numeric or binary scale.

For weather data, the TTI 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 team will define a numeric or binary scale to process qualitative weather data.

4.4.3 Step 3: Normalize Data

The TTI 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 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 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 team will explore various clustering concepts using the post-deployment data.

The TTI team expects that some of the clusters will not be clean or have distinct indicator characteristics. Therefore, the 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 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 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 chapter 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.

The TTI team expects to execute this AMS plan if the necessary funding is allocated. If the budget allocated for the evaluation is not sufficient to cover all these actions, the team will work with USDOT to revise the AMS plan accordingly.

5.1 Base Model Development

This section provides a brief description of the base model that the TTI CVPD Evaluation Team will use for both the pre- and post-deployment periods. The general description of the simulation model is taken from the available sources provided by the Wyoming Deployment Team. The team expects the deployment team will follow the base model development guidance in the FHWA *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software (1)*. However, the TTI team understands that the deployment team may use a different calibration process for its base model than what is specified in the *Traffic Analysis Toolbox Volume III*.

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 team needs the following general data types for the simulation modeling effort:

- **Model network geometry**—The TTI team is assuming that the Wyoming Deployment Team will code this geometry during its model development effort.
- **Travel time data for model calibration**—The TTI team is assuming that the Wyoming 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 signal control algorithms active with CV deployment, including weather-responsive VSL system on I-80**—The TTI team is assuming the Wyoming Deployment Team will code this during its model development effort.
- **Special behavior of connected vehicles**—The TTI team is assuming that the Wyoming Deployment Team will collect data to measure how drivers respond to CV messages.
- **Traffic demands**—The TTI team is assuming that the Wyoming 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. For the Wyoming deployment, the TTI team will use the traffic volume counts obtained from WYDOT.

- **Vehicle stock**—The TTI team is assuming that the Wyoming 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 Wyoming 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 CVPD Evaluation Team at the time of drafting this AMS plan (January 2018). The sources for this information are primarily deployment team publications, updated in a few spots with e-mail correspondence relayed to the TTI team by FHWA. Note that the published information generally pre-dates this draft of the AMS plan by 9 to 18 months.

According to the Phase 2 Data Management Plan (6), the Wyoming Deployment Team will develop a VISSIM model of a portion of the I-80 study corridor:

The use of traffic simulation models using VISSIM software is planned as part of the safety-related performance measurement activities. The simulation model analysis will incorporate CV-equipped driver behavior observed during the demonstration period into the modeling parameters to evaluate changes in the system if a larger percentage of vehicles in the corridor were CV-equipped. Driver behavior will be observed from CV equipped vehicles and from the Driver Simulator lab during training activities. Model calibration data, assumptions, network files created for the modeling, as well as outputs from the modeling and simulation runs will be housed in the University of Wyoming and made available to USDOT and the IE as requested.

The Phase 2 model calibration and assumptions will be documented as part of the Pre-Deployment Conditions and will be included in the Phase 2 System Performance Report. Requests for the model or model data can be requested from the University of Wyoming team members.

To conduct the mobility analysis, the TTI team would like to receive from the Wyoming Deployment Team a minimum of two microsimulation models covering two representative 5-mile-long segments of I-80, which include VSL segments and a road closure gate. The TTI team suggests a minimum of two 5-mile segments, rather than one 10-mile model. Using multiple models gives the TTI team an opportunity to capture several different operating conditions along I-80 (e.g., with VSL active; with VSL and gates active), which may not both occur within a single 10-mile segment. These models must include mainline and ramps, but they do not need to include intersections at the foot of the ramps. The signalized intersections at the ramp terminals are not needed because the Wyoming CVPD is focused on the mainline operations only, and they are not expected to impact operations at the ramp intersections.

It is not practical to simulate the entire 402-mile freeway site area at a microscopic level. It takes vehicles an average of 5 hours to traverse the length of the freeway. The time to create and run the model is not justified. Additionally, the TTI team cannot use the *Highway Capacity Manual* (HCM) FREEVAL to conduct the analysis, because it assumes that entering vehicles show up instantly as demand for all downstream sections. Therefore, it is best to simulate the selected short (5-mile) lengths of freeway.

Volpe will determine the potential safety benefits of the applications using before/after crash data to estimate the percent reductions in crashes and blow-overs under snow, ice, and wind conditions.

The TTI team will measure the mobility impacts of the CV applications using the microsimulation models. Based on truck following data in the before/after data, it may be appropriate to adjust the microsimulation model to increase the average spacing between CV-equipped trucks in the model (with no change to non-CV-equipped vehicles). This is because the CV-equipped vehicles will have FCW, which will warn drivers if they are following too closely behind another CV-equipped vehicle. As a result, drivers may increase their spacing. Based on before/after data, the TTI team might adjust the desired speed for some CV-equipped vehicles so that the maximum speed range is closer to the VSL recommended for the weather conditions, compared to the maximum speed range for non-CV-equipped vehicles. The TTI team will explain that this reduction in speed will increase VHT, but this may not be a mobility dis-benefit if the reduced speed also reduces crashes—which may cause even greater delay. Other than these two potential adjustments, the TTI team does not anticipate the need to make other simulation behavior changes.

Volpe or the “after” crash data will determine the effect that the CV applications have on reducing crashes and blow-overs under snow, ice, and wind conditions.

If the deployment team does not deliver the microsimulation models described in this section, the TTI team has an optional extra task to develop the base models for the evaluation.

5.1.3 Model Enhancements

This section describes the enhancements needed to the site simulation model to meet the USDOT objectives for the AMS analysis. At the time when this AMS plan was drafted (January 2018), few details were available for the Wyoming models. Consequently, the description of needed enhancements to these models are speculative at this time.

Currently, the TTI team does not envision requiring any enhancements for the base traffic simulation model(s). However, this may change as the team begins working with the model(s) provided by the site. The earlier sections on hypotheses, performance measures, and confounding factors described the specialized modeling procedures that the team will use to obtain the desired information for the evaluation.

5.1.4 Key Simulation Modeling Assumptions

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

- All connected and unconnected drivers always keep safe car-following distances; do not enter intersections or merging, weaving, or diverging areas unless safe; obey lane markings; and always obey all traffic control devices. This assumption is standard simulation modeling practice. It may be modified by the deployment team based on before/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.
- For the Wyoming CVPD, the observed behavioral effects of ASDs do not apply to the general public because the ASDs are tested in a unique pool of experienced drivers (i.e., taxis, buses, and city vehicles). General public car-following and lane-changing behavior will not change with the CV applications.

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 V2V interactions.

Appendix A 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 applications' 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 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)*. The Identification of Operational Conditions Using Cluster Analysis section of this AMS plan addresses the identification of operational conditions for calibration. The TTI CVPD Evaluation 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 it will define in its upcoming documentation.

The TTI team will identify the operational conditions for simulation modeling using cluster analysis of pre- or post-deployment data as described previously. 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 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

Previous sections of this chapter defined the assumptions and data required for calibration. The section on Model Input Data lists the necessary data inputs the TTI team needs for the calibration.

5.3.3 Acceptability Criteria

The TTI 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 the mean following headway, driver reaction time, and critical gap for lane changing, minimum separation under stop-and-go conditions.

The TTI 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 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)*. The TTI 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.

5.3.5 Limitations of Calibration

As described earlier, the limitations of simulation modeling prohibit the TTI team from modeling potential behavioral impacts of safety-related CV applications. The team will focus on modeling the impacts of non-safety-related applications, such as speed adherence warnings, for Wyoming.

5.3.6 Sources of Data for Calibration

For calibration of the simulation models, the TTI 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 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. For the selected scenario model development, the TTI team will make the simulation modeling assumptions presented in the Key Simulation Modeling Assumptions section of this report.

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

5.3.8 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 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 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 V2V 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 Wyoming 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 CVPD Evaluation 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 the Identification of Operational Conditions Using Cluster Analysis section 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 1 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 (see Note 5)	TBD	TBD	TBD
1b		TBD	TBD	TBD	TBD
1c*		TBD	TBD	TBD	TBD
2	Actual Deployment (see Note 3)	TBD	TBD	TBD	TBD
2a		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 (see Notes 2 and 4)	TBD	TBD	TBD	TBD
4b		TBD	TBD	TBD	TBD
4c*		TBD	TBD	TBD	TBD

* See Note 1.

Notes:

1. The TTI CVPD Evaluation 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.

6.1.2 Selection of CV Application Alternatives for Simulation Testing

The TTI 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 team recommends the following CV deployment alternatives for testing in simulation:

1. No CV Application Active—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. Deployed CV Applications (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. Seven-Year Expansion of CV Applications—Provides estimated mobility benefits of feasible expansion of CV applications to more vehicles and more locations within each deployment site. Allows the TTI 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.

6.1.3 Mapping of Model Scenarios to Research Questions

This section of the AMS plan provides information on mapping the analysis scenarios to the research questions or key hypotheses to be tested (identified in Chapter 3). A table mapping the scenarios to hypotheses is provided in Appendix B. The table is preliminary in that the clustering analysis has yet to be performed on data that have yet to be collected.

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 the Identification of Operational Conditions Using Cluster Analysis section of this report.

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.

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 team will input traffic counts, crash data, and weather collected simultaneously for those selected days into the simulation model. The team will calibrate the model’s performance results on a day-by-day basis to the speeds observed simultaneously for those same days.

Table 2. Factors That Will Influence the Performance Analysis

Factors	Wyoming
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	Not a factor for Wyoming site.
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	Not a factor for Wyoming site.

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.

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.

Note that the site simulation models will not cover the entire state line to state line length of a freeway.

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.

In the case of Wyoming, the proportionate mobility improvements of CV applications reported by the simulation model or a portion of the I-80 freeway will be extrapolated to the rest of the freeway where CV applications will also be active but are not included in the simulation model.

6.4 Estimation of Mobility Impacts of Safety Applications

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.

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.

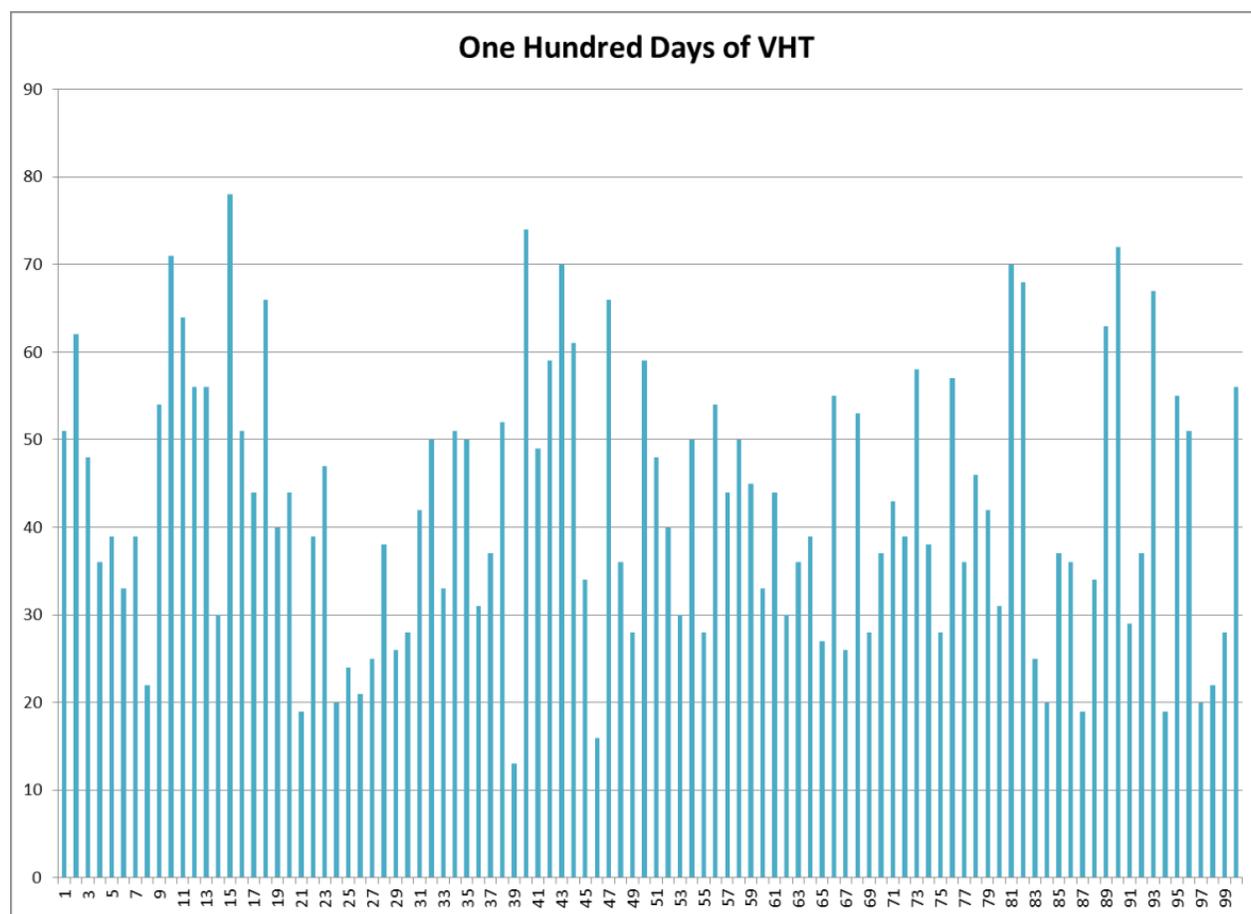


Figure 3. Example of 100 Days of Data

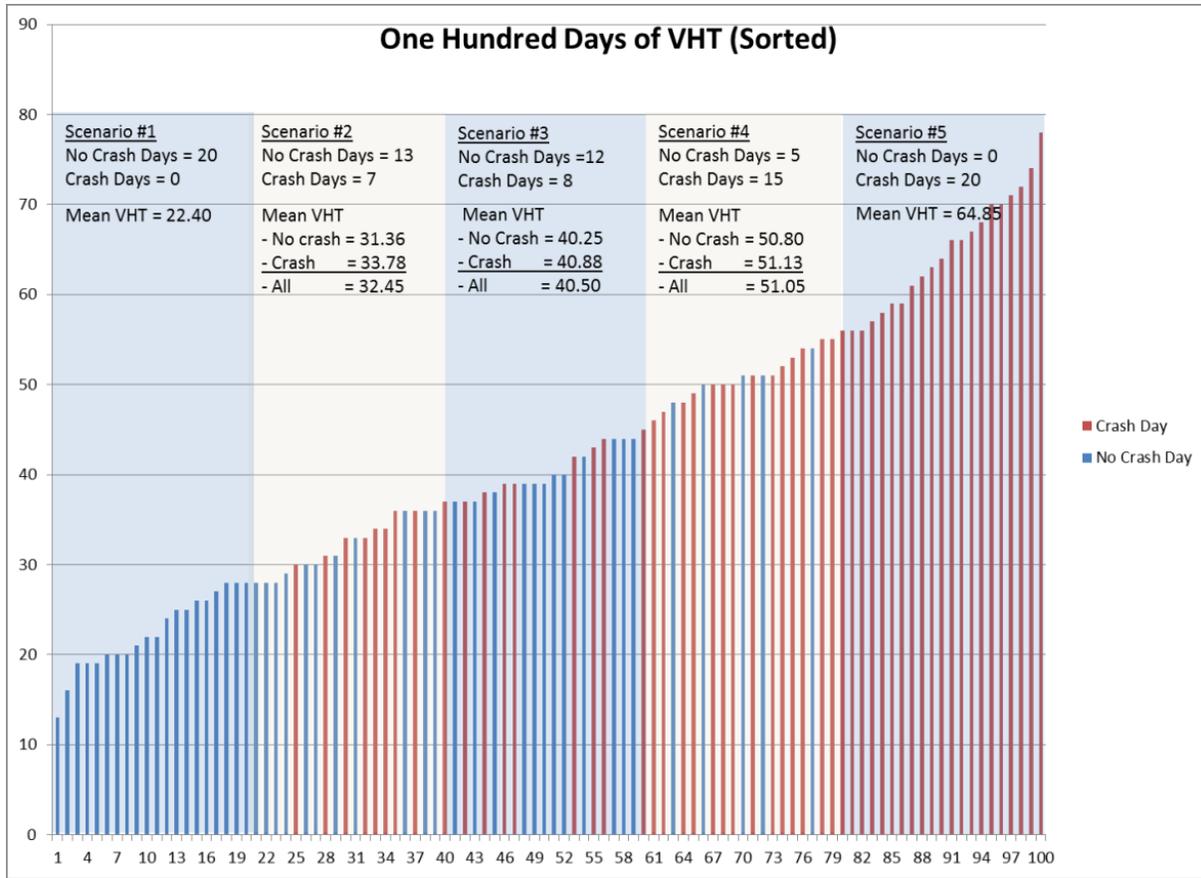


Figure 4. Example of Days Sorted by Degree of Congestion, Clustered into Scenarios

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. The TTI CVPD Evaluation Team 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

The TTI CVPD Evaluation Team will conduct hypothesis testing 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

The TTI team will use a 95 percent confidence level 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/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 (7).

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

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

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.

$$|\bar{x} - \bar{y}| =$$

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 (β). 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 CVPD Evaluation 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).

The number of levels and the specific levels of demand, weather, and incidents to be evaluated in the sensitivity tests will be determined by 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.

Table 4. Framework for Presenting Sensitivity Test Results for Each MOE for Different Operating Conditions

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	7-Year Expansion	Low	Snow	None	+2%, LTS
3b	7-Year Expansion	Medium	Rain	Minor	+4%, S
3c	7-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.

Chapter 7. Environmental Analysis Model

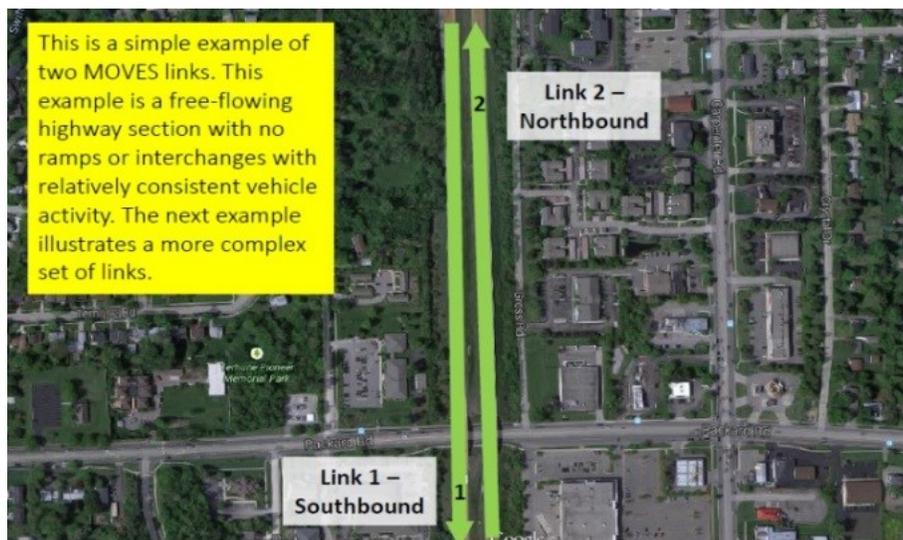
The environmental analysis will use mobility outputs as its inputs. Therefore, the TTI CVPD Evaluation Team does not expect to find measurable environmental benefits in cases where there are no mobility changes. As a result, the environmental analysis will model the same scenarios as the mobility analysis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

The TTI 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 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.



Source: US Energy Information Administration, 2017

Figure 5. Examples of MOVES Freeway Links

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

- CO₂.
- PM-2.5.
- PM-10.
- NO_x.
- Petroleum energy consumptions.

For the Wyoming CVPD, the TTI team's environmental analysis will focus on measuring the impact of heavy-duty trucks along I-80. As discussed with WYDOT during the June 13, 2017, site meeting, these trucks typically idle along the side of the interstate or in designated truck parking areas during road closures (this idling may be referred to as *hoteling*). This idling activity is a source of emissions and petroleum consumption. With an increased penetration of CV apps, the trucks may (to a greater extent) stop in towns along I-80 so that drivers can turn off their engines rather than idling their trucks.

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 Wyoming 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 I-80 deployment. 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.

A particular challenge with the Wyoming I-80 corridor is the large geographic area and the mostly rural nature of the corridor. The performance data will not be as granular as they might be in an urban corridor or district; however, as a pilot project, this is both a challenge and an opportunity. The analysis will use multiple sources of 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 TTI 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, and vehicle operating costs; and reduced costs to commercial carriers from reduced freight delay. Since I-80 is a long, heavy-freight corridor, the TTI team anticipates that several freight-related benefits will be important in determining the overall benefit/cost of a connected vehicle implementation.

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

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

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 Benefits

The TTI CVPD Evaluation Team will use travel time as a means of estimating the economic impacts associated with deploying CV technologies in the I-80 corridor. The team will estimate travel times for all travel modes—automobiles, trucks, and buses—based on the current traffic distribution in the corridor. The team will use changes in before and after travel times for each operational condition likely to produce specific benefits from deploying CV technologies. The team will estimate mobility costs associated with each type of operational scenario identified through the cluster analysis. The 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 team will use local values of time provided by WYDOT 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 (9)*. Table 5 shows the values of time provided in the *TIGER Benefit-Costs Analysis (BCA) Resource Guide*.

The TTI team will also include the benefits associated with reduced 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, it is hoped that better and more specific information can be obtained. One potential method is to include questions on the survey of the commercial carriers specific to the I-80 corridor 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 team will apply the crash reduction predictions for the corridor developed by Volpe to estimate the changes in different types of collisions. (The team will capture the mobility benefits associated with those reductions in crashes in the mobility costs.) The team will use the methodology contained in the *TIGER Benefit-Cost Analysis (BCA) Resource Guide (7)* to estimate safety costs. Unless local values are available, the team will use the cost values shown in Table 6 for estimating the safety costs associated with the Wyoming deployment. The values shown in Table 6 are based on a value of statistical life of \$9,400,000 (in 2013 dollars). The team will convert these values (shown in 2013 dollars) to baseline dollars using the formula above.

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
<i>Local Travel</i>		
Personal	\$12.50	
Business	\$24.40	None
All Purposes**	\$13.00	
<i>Intercity Travel</i>		
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 & 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.oml.gov/>. Air figures use person-trip data.

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

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 Vale of Statistical Live	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* (7) 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.

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 team will use simulation to estimate the effects of the deployments on emissions. The 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 team will include the following pollutants in the benefit-cost analysis: CO₂, VOCs, NO_x, PM, SO_x, and carbon monoxide.

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

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 Transportation Safety Administration, July 2011.

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 estimated the social costs of carbon.

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 team will base the current and predicted costs for fuel on information from the U.S. Energy Information Administration website (10). As shown in Figure 6, this website includes current and historical gasoline and diesel fuel prices. The team will use data from this site to develop average fuel costs during the evaluation period. For the Wyoming deployment, the team will use fuel prices from the Rocky Mountain analysis region, which includes Montana, Wyoming, Colorado, Utah, and Idaho. Note: the portion of the cost of fuel that is taxed will be removed prior to calculations since that portion is a transfer and not a change in societal benefits.

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) [full history](#)

	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	2.483	↓ -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

[+] See more

U.S. On-Highway Diesel Fuel Prices* (dollars per gallon) [full history](#)

	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. Energy Information Administration

Figure 6. Screen Capture of U.S. Energy Information Administration Fuel Cost Website (10)

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 team will base these costs on data published by the American Automobile Association (AAA) (11) 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.

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	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	8.33								
Hybrid Vehicle	NA	6.99								
Electric Vehicle	NA	6.55								
Average	5.29	5.38	5.37	5.40	5.47	5.97	6.06	6.09	6.28	7.91

NA = Not Available

Source: American Automobile Association

Because of the number of trucks utilizing the I-80 corridor, the TTI team will use different cost factors to estimate the costs of the deployment on operations. Table 10 and Table 11 provide average marginal costs per mile and per hour of operation, respectively. Unless specific commercial vehicle operating costs are available from the local site, the TTI team will use these values to reflect the operating costs associated with commercial vehicles. The team will adjust these numbers to the baseline analysis year using the methodology described above. The team will use past trends to project future costs.

Table 10. Average Marginal Costs (in dollars) per Mile, 2008–2015

Motor Carrier Costs	2008	2009	2010	2011	2012	2013	2014	2015
Fuel Costs	0.633	0.405	0.486	0.590	0.641	0.583	0.583	0.403
Truck/Trailer Lease or Purchase Payments	0.213	0.257	0.184	0.189	0.174	0.163	0.215	0.230
Repair and Maintenance	0.103	0.123	0.124	0.152	0.138	0.148	0.158	0.156
Truck Insurance Premiums	0.055	0.054	0.059	0.067	0.063	0.064	0.071	0.092
Permits and Licenses	0.016	0.029	0.040	0.038	0.022	0.026	0.019	0.019
Tires	0.030	0.029	0.035	0.042	0.044	0.041	0.044	0.043
Tolls	0.024	0.024	0.012	0.017	0.019	0.019	0.023	0.020
Driver Wages	0.435	0.403	0.446	0.460	0.417	0.440	0.462	0.499
Driver Benefits	0.144	0.128	0.162	0.151	0.116	0.129	0.129	0.131
Total	1.653	1.451	1.548	1.706	1.633	1.676	1.703	1.593

Source: American Transportation Research Institute

Table 11. Average Marginal Costs (in dollars) per Hour, 2008–2015

Motor Carrier Costs	2008	2009	2010	2011	2012	2013	2014	2015
Fuel Costs	25.30	16.17	19.41	23.58	25.63	25.78	23.29	16.15
Truck/Trailer Lease or Purchase Payments	8.52	10.28	7.37	7.55	6.94	6.52	8.59	9.20
Repair and Maintenance	4.11	4.90	4.97	6.07	5.52	5.92	6.31	6.23
Truck Insurance Premiums	2.22	2.15	2.35	2.67	2.51	2.57	2.89	3.70
Permits and Licenses	0.62	1.15	1.60	1.53	0.88	1.04	0.76	0.78
Tires	1.20	1.14	1.42	1.67	1.76	1.65	1.76	1.72
Tolls	0.95	0.98	0.49	0.69	0.74	0.77	0.90	0.79
Driver Wages	17.38	16.12	17.83	18.39	16.67	17.60	18.46	19.95
Driver Benefits	5.77	5.11	6.47	6.05	4.64	5.16	5.15	5.22
Total	66.07	58.00	61.90	68.21	65.29	67.00	68.09	63.70

Source: American Transportation Research Institute

8.6 Estimating Implementation Costs

The implementation costs used for the benefit-cost analysis will include the costs associated with deploying the Wyoming 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 CVPD Evaluation 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.

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:

- 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.

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.

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 CVPD Evaluation 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.

References

1. Wunderlich, K., M Vasudevan, and P. Wang. *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software—2017 Update*. FHWA-HOP-16-070. U.S. Department of Transportation, Washington, DC. November 2017.
2. Connected Vehicle Pilot Deployment Program: Wyoming. Factsheet. U.S. Department of Transportation, ITS Joint Program Office. Available at https://www.its.dot.gov/factsheets/pdf/WyomingCVPilot_Factsheet_020817.pdf. Accessed August 13, 2017.
3. Connected Vehicle Pilot Deployment Program: Wyoming (WY) DOT Pilot. Website. Available at https://www.its.dot.gov/pilots/pilots_wydot.htm. Accessed August 13, 2017.
4. Presentation by the Wyoming CVPD Team at the CVPD Performance Evaluation and Human Use Roundtable, January 16, 2018.
5. *Connected Vehicle Pilot Deployment Program: Mobility, Environment, and Public Agency Efficiency (MEP) Refined Evaluation Plan: Wyoming Pilot Deployment Site*. U.S. Department of Transportation, Intelligent Transportation Systems Joint Program Office, Washington, DC, Revised March 2018.
6. *Connected Vehicle Pilot Deployment Program Phase 2: Data Management Plan—Wyoming*. FHWA-JPO-470, April 2017.
7. National Institute of Standards and Technology (NIST). SEMATECH e-Handbook of Statistical Methods: Sections 1.3.5.2, 3.3.3.3, and 7.2.2.2. Available at <http://www.itl.nist.gov/div898/handbook/>.
8. National Institute of Standards and Technology (NIST). SEMATECH e-Handbook of Statistical Methods: Section 7.1.3. Available at <http://www.itl.nist.gov/div898/handbook/>.
9. *TIGER Benefit-Cost Analysis (BCA) Resource Guide*. U.S. Department of Transportation, Federal Highway Administration. Washington, DC. Updated 3/27/15. Available at https://www.transportation.gov/sites/dot.gov/files/docs/Tiger_Benefit-Cost_Analysis_%28BCA%29_Resource_Guide_1.pdf. Accessed August 13, 2017.
10. U.S. Energy Information Administration. Gasoline and Diesel Fuel Update: Petroleum and Other Liquids. Available at <https://www.eia.gov/petroleum/gasdiesel/>. Accessed February 15, 2018.
11. American Automobile Association. AAA's Your Driving Costs. Available at <https://exchange.aaa.com/automotive/driving-costs/>. Accessed February 15, 2018.
12. American Transportation Research Institute. *Analysis of the Operational Costs of Trucking: 2016 Update*. September 2016. Available at <http://atri-online.org/wp-content/uploads/2016/10/ATRI-Operational-Costs-of-Trucking-2016-09-2016.pdf>. Accessed February 15, 2018.

Appendix A. 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.

A.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.

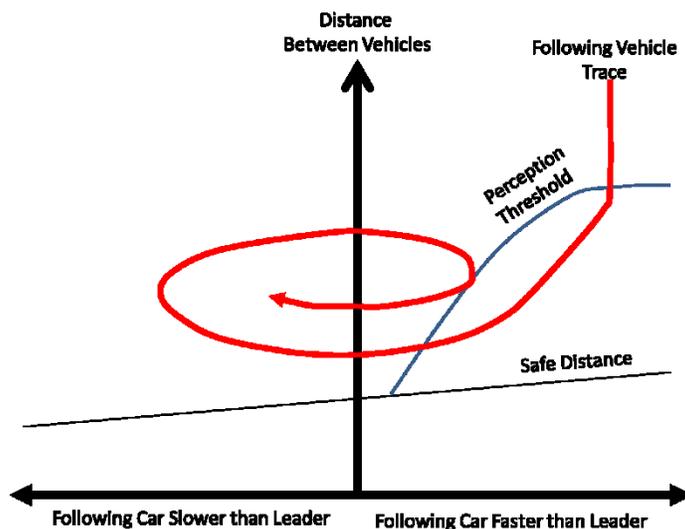
A.2 Customizing Tactical Driving Behavior in VISSIM

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).

A.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 model. 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).

$bx = (bx_add + bx_mult * z) * \text{SQRT}(v)$.

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 12 shows the calibration parameters available for the Wiedemann 74 model. Table 13 shows the calibration parameters for the Wiedemann 99 model.

Table 12. 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 13. 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 $dx_safe = CC0 + CC1 \cdot v$. 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 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.

A.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.

A.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).

A.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).

Appendix B. Mapping of Analysis Scenarios to Hypotheses

Table 14 presents a preliminary mapping of the model scenarios to the hypotheses for the Wyoming site. The notes explain when mapping is not possible for a specific hypothesis. The analysis scenarios are described in Chapter 6 of this AMS plan.

Table 14. Preliminary Mapping of Simulation Analysis Scenarios to Key Hypotheses—Wyoming

Analysis Scenarios	USDOT Hypotheses for Wyoming
See Note 1	1. The pilot deployment will reduce weather-related crashes and incidents (or other safety surrogate measures if crashes are rare) for trucks and other vehicles.
See Note 1	2. The pilot deployment will reduce the number of trucks that are stranded, must backtrack, or otherwise waste time and fuel resulting from road closures or a lack of appropriate parking availability.
See Note 2	3. The pilot deployment will reduce emissions from connected trucks due to reduction in congested travel.
See Note 1	4. The pilot deployment will reduce emissions from connected trucks due to reduced speed variation as a result of weather-responsive variable speed limit.
See Note 1	5. The pilot deployment will reduce emissions for connected trucks approaching a work zone due to work zone warning.
See Note 1	6. The pilot deployment will reduce the incident detection time for connected trucks that send out distress notification.
1—Base 2—Deploy 3—Seven Year 4—Max Deploy	7. The pilot deployment will result in improved public agency efficiency and decision-making by transportation managers.
1—Base 2—Deploy 3—Seven Year 4—Max Deploy	8. As the market penetration of connected trucks and fleet vehicles increases, benefits will increase in terms of reduced emissions and incident detection time.
1—Base 2—Deploy 3—Seven Year 4—Max Deploy	9. As the market penetration of connected trucks and fleet vehicles increases, emissions will reduce for non-equipped vehicles traversing the I-80 corridor.
1—Base 2—Deploy	10. Incremental increases in connected vehicle deployment will result in higher benefit-cost ratio up to a certain deployment cost threshold, after which the

Analysis Scenarios	USDOT Hypotheses for Wyoming
3—Seven Year	benefit-cost ratio will reduce.
4—Max Deploy	
See Note 2	11. The performance of the connected vehicle devices will satisfy end users.
See Note 2	12. The performance of CV applications and the impact of the CV deployment on travel will satisfy end users.
See Note 1	13. The pilot deployment will result in end users taking appropriate action based on alerts/warnings/advisories/traveler information.
See Note 2	14. The pilot deployment will meet the safety, mobility, environmental, and public efficiency (SMEP) goals of the pilot deployers and transportation managers.

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 C. Clustering Data Needs and Potential Sources—Wyoming

Attributes	Captured	Data Set	Potential Data Sets	Notes
Traffic demand or congestion	Partial	<ul style="list-style-type: none"> • WYDOT Traffic Data website • WYDOT Vehicle Miles Book 	None	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 10 out of 50 RWIS on I-80 archiving data • Pikalert System can be used for after data • Weather events and impact cataloged in Tables 6-1 and 6-2 in <i>Initial System Performance Report</i> • MesoWest archive was used to establish baseline • Includes relative humidity, wind speed, road temp, road surface condition, visibility, and storm number 	None	None
Incident conditions (type, duration, severity)	Partial	Road condition reports	None	Incidents include crashes, disabled vehicles, etc.
Work zone conditions (type, duration, severity)	No	Construction Console data includes work zones along I-80 and nearest	None	None

Attributes	Captured	Data Set	Potential Data Sets	Notes
of impacts)		detector		
Special event conditions (type, duration, severity of impacts)	Partial	Not part of Wyoming	None	None
Travel time (system data and CV-specific data)	Partial	Processed speed data from Wavetronix speed records	<ul style="list-style-type: none"> • NPMRDS • CV BSM data 	<ul style="list-style-type: none"> • VSL data could be used as a supplement. • 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	<ul style="list-style-type: none"> • WYDOT Traffic Data website • WYDOT Vehicle Miles Book 	None	None
Road closure conditions	Partial	Road Closure Database maintained by TMC	None	None
Holidays	No	No data set needed	None	None

Attributes	Captured	Data Set	Potential Data Sets	Notes
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
Bottleneck throughput	Partial	Traffic counts at bottlenecks	NPMRDS can confirm bottleneck locations	None

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