FINAL REPORT

PROJECT G3

AUGUST 2022

Utilization of Connectivity & Automation in Support of Transportation Agencies' Decision Making

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
Project G3		

4. Title and Subtitle
Utilization of Connectivity and Automation in Support of Transportation Agencies' Decision Making

5. Report Date
8/2/2022

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.
STRIDE Project G3

9. Performing Organization Name and Address

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10. Work Unit No.

11. Contract or Grant No.

Funding Agreement Number 69A3551747104

12. Sponsoring Agency Name and Address
University of Florida Transportation Institute/ Southeastern Transportation Research, Innovation, Development and Education Center (STRIDE) 365 Weil Hall,
P.O. Box 116580 Gainesville, FL 32611
U.S Department of Transportation/Office of Research, Development & Tech
1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report and Period Covered
1/1/2020 to 8/2/2022

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract - Studies from around the world have started investigating aspects of ATV simulation. However, these efforts are still in their infancy, and are constrained by the limited amount of real-world data to validate and calibrate the developed models. The existence of some work on this subject does not mean that the conducted research up to this point is sufficient. In fact, we expect that ATV modeling and simulation will be an important area of research for many years to come. There is a need to examine existing studies and guidance on the subject, collect information from these studies to inform the developments and guidance of ATV simulation, and provide additional developments and guidance to support ATV simulation. This project makes use of existing information and data to provide guidance and use cases to support agency use of simulations of ATV. Specifically, this project provides: 1) An assessment of the existing research, developments, models, and methods that enable the simulation of ATV; 2) A documentation of state agency needs regarding planning and operations of highways with ATV presence; 3) A modeling framework(s) and guidance for ATV and the associated applications for use by transportation agencies; 4) Demonstration of the use of simulation to use cases that require assessing the highway operations with ATV presence.

17. Key Words	18. Distribution Statement
connected vehicles; automated vehicles; simulation; analysis; modeling	No restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
N/A	N/A	109 pages	N/A

DISCLAIMER

ACKNOWLEDGEMENT OF SPONSORSHIP AND STAKEHOLDERS

This work was sponsored by a contract from the Southeastern Transportation Research, Innovation, Development and Education Center (STRIDE), a Regional University Transportation Center sponsored by a grant from the U.S. Department of Transportation's University Transportation Centers Program.

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LIST OF ACRONYMS

ABM	Activity-Based Modeling
ABS	Antilock Brake System
ACC	American Control Conference
ACES	Automated, Connected, Electric, And Shared
ADS	Automated Driving System
AM	Advanced Merging
AMS	Analysis, Modeling, and Simulation
API	Application Programming Interface
ASCS	Adaptive Signal Control System
ATCMTD	Advanced Transportation Congestion Management Technology Deployment
AV	Autonomous Vehicles
AWS	Amazon Web Services
BSM	Basic Safety Messages
CACC	Cooperative Adaptive Cruise Control
CAV	Connected and Autonomous Vehicle
CDA	Cooperative Driving Automation
CDC	Conference on Decision and Control
CICAS	Cooperative Intersection Collision Avoidance System
CISP-BMEI	Congress on Image and Signal Processing, Biomedical Engineering and Informatics
CISVWS	Cooperative Intersection Signal Violation Warning System
COM	Component Object Model
CROSS	Connected-Vehicle-Based Road Safety Information System
CSW	Curve Speed Warning
CV	Connected Vehicle
D-RIDE	Dynamic Ridesharing
DDT	Dynamic Driving Task
DMA	Dynamic Mobility Applications
DNPW	Do Not Pass Warning
DPW	Do not pass warning
DR-OPT	Drayage Optimization
DRAC	Deceleration Rate To Avoid Crash
DSR	Dynamic Shear Rheometer
DSRC	Dedicated Short-Range Communications
EDM	External Driver Model
EEBL	Emergency Electronic Brake Lights

EPA	Environmental Protection Agency
ERDW	End of Ramp Deceleration Warning
EVAC	Emergency Communications and Evacuation
FCW	Forward Collision Warning
FRATIS	Freight Advanced Traveler Information System
GIS	Geographic Information System
GLOSA	Green Light Optimized Speed Advisory
HPMS	Highway Performance Monitoring System
I-SIG	Intelligent Traffic Signal System
ICAIIC	Artificial Intelligence in Information and Communication
IDM	Intelligent Driver Model
IDTO	Integrated Dynamic Transit Operation
IMA	Intersection Movement Assist
INC-ZONE	Incident Scene Work Zone
INFLO	Intelligent Network Flow Optimization
ITSC	Intelligent Transportation Systems Conference
IV	Intelligent Vehicles
LCW	Lane-Change Warning
LOS	Level of Service
MMITSS	Multimodal Intelligent Traffic Signal System
MOVES	Motor Vehicle Emission Simulator
MPO	Metropolitan Planning Organization
MPR	Market Penetration Rate
MSCR	Multiple Stress Creep Recovery
NCDOT	North Carolina Department of Transportation
OBU	On-Board Unit
ODD	Operational Design Domain
OV	Opposing Vehicle
PCW	Pedestrian Collision Warning
PED-SIG	Pedestrian Signal System
PSCW	Pedestrian In Signalized Crosswalk
Q-WARN	Queue Warning
RCA	Rail Crossing Application
RESP-STG	Staging Guidance For Emergency Responders
RIO	Real-Time Intersection Optimizer
RLVW	Red-Light Violation Warning
RO-MAN	Robot and Human Interactive Communication
RR	Railroad
RSE	Roadside Equipment

RSU	Roadside Units
RSWZW	Reduce Speed/Work Zone Warning
RSZW	Reduced Speed Zone Warning
RT	Reaction Time
RTA	Right-Turn Assist
SAE	Society of Automotive Engineers
SLTA	Signalized Left-Turn Assist
SPAT	Signal Phase and Timing
SPD-HARM	Speed Harmonization
SSAM	Surrogate Safety Assessment Model
SSGA	Stop Sign Gap Assist
STRIDE	Southeastern Transportation Research, Innovation, Development and Education Center
SV	Subject Vehicle
SWIW	Spot Weather Information Warning
SWIW-D	Spot Weather Information Warning–Diversion
T-DISP	Dynamic Transit Operations
TCS	Traction Control System
THEA	Tampa-Hillsborough Expressway Authority
TIM	Traveler Information Messages
TSP	Transit Signal Priority
TSSM	Transportation System Simulation Manual
TTC	Time to Collision
TV	Traditional (human driven) Vehicles
TWSC	Two-Way Stop Controlled [Intersection]
USDOT	U. S. Department of Transportation
USEPA	U. S. Environmental Protection Agency
V2I	Vehicle-to-Infrastructure [Communication]
V2V	Vehicle-to-Vehicle [Communication]
V2X	Vehicle-to-Everything [Communication]
VNC	Vehicular Networking Conference
VNC	Vehicular Networking Conference
VNC	Vehicular Networking Conference
VTRBW	Vehicle turn in front of bus warning
VTRFTV	Vehicle Turning Right in Front of a Transit Vehicle
WWE	Wrong Way Entry

ABSTRACT

State, regional, and local agencies have utilized simulation models to support the decisions associated with various business processes. An increase in the market penetration is expected for vehicles with advanced technologies, referred to in this document as advanced technology vehicles (ATV) and including connected vehicles (CV), automated vehicles (AV), connected and automated vehicles (CAV), and associated applications. Simulation modeling will play a critical role in assessing the performance of the transportation system with these vehicles and supporting the associated decisions.

Studies from around the world have started investigating aspects of ATV simulation. However, these efforts are still in their infancy, and are constrained by the limited amount of real-world data to validate and calibrate the developed models. The existence of some work on this subject does not mean that the conducted research up to this point is sufficient. In fact, we expect that ATV modeling and simulation will be an important area of research for many years to come. There is a need to examine existing studies and guidance on the subject, collect information from these studies to inform the developments and guidance of ATV simulation, and provide additional developments and guidance to support ATV simulation.

This project makes use of existing information and data to provide guidance and use cases to support agency use of simulations of ATV. Specifically, this project provides:

- An assessment of the existing research, developments, models, and methods that enable the simulation of ATV
- A documentation of state agency needs regarding planning and operations of highways with ATV presence
- A modeling framework(s) and guidance for ATV and the associated applications for use by transportation agencies
- Demonstration of the use of simulation to use cases that require assessing the highway operations with ATV presence.

Keywords: Connected vehicles; Automated vehicles; Simulation; Analysis; Modeling

EXECUTIVE SUMMARY

An important challenge that has not been addressed in the existing national and state guidance is the simulation of vehicles with advanced technologies, referred to in this document as advanced technology vehicles (ATV) that includes connected vehicles (CV), automated vehicles, connected and automated vehicles (CAV) and the associated applications. ATV are expected to introduce transformative changes. These changes will impact mobility, safety, sustainability, and equity in addition to impacting agency operations among other impacts. Public agencies need to account for ATV in making various decisions at the strategic, tactical, and operational levels. With the expected increase in the market penetrations of ATV, simulation modeling will play a critical role in assessing the performance of the transportation system with these vehicles and supporting the decisions associated these vehicles and the associated infrastructure support. This use of simulation modeling is particularly critical considering the limited real-world deployments of ATV.

Studies from around the world have started investigating aspects of ATV simulation. However, these efforts are still in their infancy, and are constrained by the limited amount of real-world data to validate and calibrate the developed models. The existence of some work on this subject does not mean that the conducted research up to this point is sufficient. In fact, we expect that ATV modeling and simulation will be an important area of research for many years to come. There is a need to examine existing studies and guidance on the subject, collect information from these studies to inform the developments and guidance of ATV simulation, and provide additional developments and guidance to support ATV simulation.

With the above in mind, this project has been initiated to make use of the existing information and data to provide guidance and use cases to support the agency use of simulations of ATV. The specific objectives are to provide:

- An assessment of the existing research, developments, models, and methods that enable the simulation of ATV
- A documentation of state agency needs regarding planning and operations of highways with ATV presence
- A modeling framework(s) and guidance for ATV and the associated applications for use by transportation agencies
- Demonstration of the use of simulation to use cases that require assessing the highway operations with ATV presence.

E.1 Review of State of Practice

This project conducted an assessment of the existing research, developments, models, and methods that enable the simulation of ATV. This review has revealed different and sometimes contradictory findings on the impact of ATV technologies on transportation system mobility and safety. Those differences can invariably be traced to the use of different assumptions, algorithms, and simulation platforms. A roadmap identifying the various topics covered in the review is shown in Figure E-1. The reviewed studies covered the assessment and simulation of the mobility and safety impacts of ATV on freeways and arterials. A one-page syntheses of the key elements depicted in the roadmap is presented in this document figure as they relate to facility types and mobility or safety themes. The detailed literature is presented under different cover.

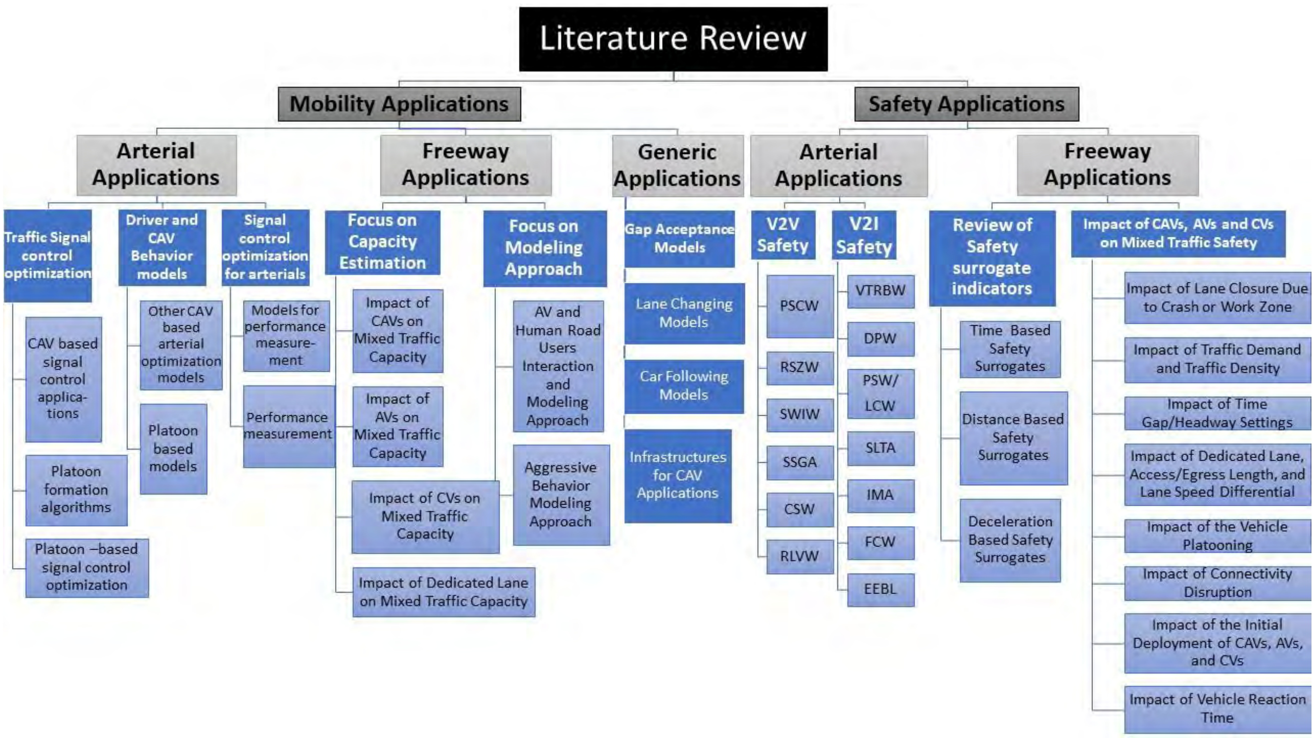


Figure E-1: Roadmap of Key Literature Review Elements

E.2. Identification of Agency's Needs

This project has identified the needs of public agencies in the southeastern United States in modeling by conducting a virtual focus group meeting with the participation of public agency stakeholders. The goal of this meeting was to communicate the project objectives and obtain inputs regarding the ATV modeling needs and priorities. Prior to the meeting, the project team developed interview questions to address topics related to the scope of the study, including the agency's current ATV activities, efforts, plans, barriers, and challenges regarding the adoption, implementation, and impacts of ATV technologies. Some questions were designed to identify the participants' opinions on the modeling aspect of ATV.

The discussion in the workshop indicated that the level of ATV application deployment varied by state, with some states investing significantly, mainly in infrastructure support of CV deployment.

At this point, the consideration of AV and CAV in traffic operations is limited but this can be different with planning agencies that are interested in long-range modeling and planning. Participants in the workshop agreed that there is a need for providing guidance for transportation agencies to account for the impacts of ATVs. Overall, the majority of respondents were not satisfied with the current ability to understand the impact of ATV deployments and utilize this information to guide deployment decisions.

The participants confirmed that one of the biggest barriers to decision making is the lack of knowledge and guidelines regarding ATV technology and the anticipated impacts. This can include difficulty in considering uncertainty in adopting the technology, various types of vehicle fleet considerations, and the impacts on traffic and travel behaviors. Some participants indicated that it is very useful to have analysis examples that could include a set of scenarios and/or sensitivity analysis to demonstrate how analysis can support the decisions. Given the absence of real-world knowledge of ATV impacts, there is a need to identify the input parameters that could be considered when modeling the ATV impacts.

With regard to performance metrics, there is an interest in comparing the performance of the infrastructure support of the technologies in relation to the improvements in performance expected from traditional improvements. One example to consider when identifying the performance measures of ATV analysis is the federal process of approval of traditional improvements such as interchange modification and facility capacity addition. The comparison should include the initial cost as well as the operations and maintenance (O&M) costs because it is important for state DOTs to identify the O&M cost before implementation of a brand-new technology.

The participants noted that, currently, state DOTs work with consultants and researchers to select the type(s) of tools for use in the analysis. There is a feeling that simulation models have the potential to model ATV applications to quantify the impacts on the transportation network. There is also need for extending and/or converting the traditional demand models to allow them to consider ATVs in demand forecasting.

E.3. Modeling Guidance and Framework

The guidance and framework presented in this document are intended to provide information that enables the analysis, modeling, and simulation of ATVs based on the information available at the time of the preparation of the document. It is anticipated that the guidance will be updated and extended as more information and research become available. The guidance presented in this document is not intended to be a standalone guidance but is developed to enhance and fill the gaps of the seven steps of microscopic simulation analysis that are addressed in guidance provided by state departments of transportation (DOT) such as the DOTs of Florida, Iowa, Virginia, Washington State, and Oregon, as well as national guidance such as that produced by the Federal Highway Administration and in the Transportation System Simulation Manual. The following aspects of simulation are addressed.

Project Planning and Scoping

The detailed consideration of ATVs in the project planning and scoping steps is critical to the successful simulation of these technologies.

Analysis Objectives: The analyst needs to clearly understand the project goal and objectives and work with other stakeholders to potentially clarify or even revise the goal and objectives if needed. The study objectives will provide the basis for selecting the evaluated alternatives, formulating the hypotheses to be addressed by the analysis, the performance measures, and the modeling framework.

Overall Modeling Framework: A framework of ATV modeling as proposed by the Federal Highway Administration (FHWA) includes four main dimensions of ATV modeling: Supply Changes, Demand Changes, Performance Changes, and Network Integration. These four dimensions of ATV modeling can be used for the setting of the ATV modeling project level framework. Depending on the analysis, modeling, and simulation (AMS) objectives and scopes, all or a subset of the four dimensions need to be included in the project modeling framework.

Identification of the Technical Approach: The additional complexities associated with ATV modeling should be considered in the early stages of the project to determine the required capability and resources and to confirm that these requirements can be met. The technical approach should be carefully identified in as much detail as possible. It is evident that no single existing AMS tool has the capabilities required to analyze all aspects and applications of ATV. A combination of tools may be needed. In addition, many of the required modeling components for ATVs do not exist in current modeling tools. Thus, additional programming to extend the modeling capabilities of the existing tools is often needed, for example, using the Application Programming Interface (API) of commercially available tools.

Uncertainty Associated with ATV: There are still significant uncertainties associated with ATV deployment and adoption. Scenario planning is a basic method for planning under deep uncertainty and as a step incorporated in performance-based planning at various stages of the process. It is recommended that such an approach should be used in ATV simulation projects, particularly since the timeline for adoption of ATV technology is debatable.

Performance Measure Identification: An important aspect of the hypothesis formulation as part of the ATV analysis is identifying performance measures that are relevant to the project goal and objectives and expected impacts of ATV on different measures. The identification of the performance measures should be based on the project goal and objectives, as well as an understanding of the capabilities and impacts of the wide range of types, levels, and classes of ATV.

Data Requirements and Availability: The identification of the data requirements, availability, and methods for filling the data gaps are critical considerations in the planning and when scoping the project and selecting the modeling approach for the project.

Tool Selection: The next step in the project planning and scoping process is tool selection based on the study scope, constraints, data availability and other factors. The Highway Capacity Manual and simulation tools provide methods and models for evaluating the impact of ATVs. The user should become familiar with those assumptions before selecting the tool for the analysis and relying on results obtained by these tools.

Data Availability and Collection

The availability of real-world data for ATVs operating in mixed traffic conditions remains sparse. The review conducted in this project highlights two real-world datasets for CV and AV, respectively, and one OEM dataset for AVs. However, the review did not find any existing real-world data set for real-world deployment of connected automated vehicles (CAVs)

Using Simulation to Evaluate ATV

When selecting a specific simulation model or external tool the analyst should match the project planning, objectives, identified features, and needed performance metrics identified with the capabilities of the various available models. In the selection of a tool it is important to consider the key ATV features that must be captured by the analysis versus those that are desirable. The selected tools at a minimum should provide the required features. This section discussed the current state of commercial models.

Verification, Calibration and Validation

Verification is the confirmation that a model has been constructed as intended, calibration is the process of adjusting underlying parameters of a verified model to be representative of that in the field and validation confirms that the model accurately represents the given system or field conditions. Each of these tasks must be undertaken to successfully model ATVs.

Alternative Analysis

In alternative analysis the analyst must model the various potential alternatives as well as their associated demand forecasts. The potential for ATVs in any future vehicle stream provides a significant source of additional "driver" behavior uncertainty which must be reflected in a modeling effort.

E.4. Case Studies

This document describes a series of case studies that utilize microscopic simulation models to model various ATV applications. The simulated applications are categorized as arterial safety applications, arterial mobility applications, and freeway mobility applications. The case studies addressed the following applications:

- Red Light Violation Warning
- Unsignalized Intersection Gap Assist
- Signalized Intersection Left-Turn Gap Assist
- Freeway Mobility in Mixed Traffic
- Freeway Mobility with Dedicated Lane
- Freeway Weaving to Optimize Operations
- Modeling Arterial Mobility applications
- Simulating Signal Control Optimization
- Evaluation of Operations and Environmental Quality.

1. INTRODUCTION

Transportation modelers have widely used advanced analysis, modeling, and simulation (AMS) tools to support planning, design, and operations considering the increasing complexity of the transportation system, the interactions of various factors impacting system performance, and the increasingly sophisticated strategies, tactics, and operation plans to mitigate congestion. There has been a recognition that effective utilization of simulation under these complexities requires the development of frameworks, methods, and guidance to support various tasks starting from scoping the project and including data collection, model development, model calibration, and interpretation of the results. The Federal Highway Administration, as well as states from around the nation have developed guidance to be used in transportation system AMS efforts. In addition, the first edition of the *Transportation System Simulation Manual* (TSSM) has recently been developed to provide guidance and methods for using simulation with the recognition that there are many challenges that still need to be addressed by research and that the initial version of the TSSM is a starting point that will motivate further development.

An important challenge that has not been addressed in the existing national and state guidance is the simulation of the emerging connected and automated vehicles (CAV) technologies. Vehicles with advanced technologies are referred to in this document as advanced technology vehicles (ATV) and include connected vehicles (CV), automated vehicles, CAVs, and associated applications. All of these are expected to introduce transformative changes. Public agencies will need to account for the impact of ATVs in making various decisions at the strategic, tactical, and operational levels. With the expected increase in the market penetration of ATVs, simulation modeling will play a critical role in assessing the performance of the transportation system with these vehicles and supporting the decisions associated with these vehicles and associated infrastructure support. This use of simulation modeling is particularly critical considering the limited real-world deployments of CAVs.

Studies from around the world have started investigating aspects of CAV simulation. However, these efforts are still in their infancy and are constrained by the limited amount of real-world data to validate and calibrate the developed models. The existence of some work on this subject does not mean that the conducted research up to this point is sufficient. In fact, we expect that CAV modeling and simulation will be an important area of research for many years to come. There is a need to examine existing studies and guidance on the subject, collect information from these studies to inform the developments and guidance of CAV simulation, and provide additional developments and guidance.to support CAV simulation.

1.1. Project Objectives

The goal of this project is to provide guidance and use cases to support simulation of ATVs. The specific objectives are:

- Assessment of the existing research, developments, models, and methods that enable the simulation of ATV
- Documentation of state agency needs regarding planning and operations of highways with ATV presence
- Identification of a modeling framework(s) and guidance for ATVs and the associated applications for use by transportation agencies
- Demonstration of the use of simulation to use cases that require assessing the highway operations with ATV presence.

1.2. AMS of ATV in Supporting Agency Business Processes

State, regional, and local agencies have utilized AMS to support the decisions associated with various business processes. Hadi et al. (2017) identified the business processes of state, regional and local agencies that can be supported by AMS, as shown in Table 1-1. It is expected that ATV analysis will be incorporated and become an important part of the analysis to support the various business processes described in Table 1-1.

Table 1-1. Potential Support of ATV AMS of Agency Business Processes (Source: Hadi et al., 2017)

Business Process		Potential AMS Support
Planning Office	State Transportation Plan	• Assess the performance metrics that correspond to each goal for existing conditions based on real-world data, travel demand model, or other modeling methods and tools • Compare alternative improvements and prioritize projects
	Strategic Intermodal System	• Estimate the impacts of alternative improvement and prioritize projects
	Planning Studies	• Estimate the impacts of alternative improvements and prioritize projects
	Interchange Access Request	• Estimate the impacts of alternative improvements and prioritize projects
	Highway Capacity and Level of Service (LOS)	• Calculate LOS • Estimate the impacts of highway capacity improvement and advanced strategies and technologies

Business Process		Potential AMS Support
	Statistics, Measures, and Trends	• Produce data-based statistics, measures, and forecasting
	Performance Measures	• Produce data-based and model-based performance measures that are required by MAP-21, FAST Act, and state rules
Metropolitan Planning Organizations (MPOs)	Long-range Transportation Plan	• Calculate performance measures that correspond to each goal for existing conditions based on data and travel demand model • Compare alternative improvements and prioritize projects
	Transportation Improvement Program	• Compare alternative improvements and prioritize projects
	Unified Planning Work Program	• Calculate performance metrics for complete and ongoing projects • Compare alternative improvements and prioritize projects
	Congestion Management Process	• Assess the benefits and costs of congestion management strategies
	Bicycle/Pedestrian Program	• Evaluate the benefits and costs of bicycle/pedestrian projects
	Freight Program	• Evaluate freight-related improvements
	Transportation Alternative Program	• Compare alternative improvements and prioritize projects
	Connected and Autonomous Vehicle Program	• Assess ATV and shared mobility impacts
	Performance Measurement Program	• Produce performance measures
	Transportation Disadvantaged Program	• Evaluate the benefits and costs of transportation disadvantaged projects
Planning, Design, and Engineering (PD&E) Studies		• Incorporate emission estimation for alternative projects • Compare alternative improvements and prioritize projects based on more detailed analysis such as Highway Capacity Manual procedures or simulation.
Traffic Engineering and	Traffic Service	• Estimate the impacts of alternative improvements • Compare intersection control strategies

Business Process		**Potential AMS Support**
Operations (Focusing on planning for operations)	Transportation System Management and operations (TSM&O)	• Assess the benefits and costs of TSM&O strategies by adding additional evaluation modules
	Traffic Incident Management/Commercial Vehicle Operations	• Update the parameters for incident management evaluation module based on latest data

1.3. Connected Vehicle Applications

Connected vehicle (CV) technologies are expected to provide significant improvements in system performance. In order to evaluate CV impacts, an analyst should be familiar with connected vehicle technologies and associated applications. The USDOT identified a large number of CV applications classified as mobility, safety, and environmental applications. USDOT's Dynamic Mobility Applications (DMA) Program identified several high-priority mobility applications (USDOT, 2018b). Table 1-2 summarizes many of the high-priority mobility applications that use vehicle-to-infrastructure (V2I) and/or vehicle-to-vehicle (V2V) technology.

Table 1-2. USDOT Program DMA Bundles and Applications (USDOT, 2018b)

Bundle	Applications
Freight Advanced Traveler Information System (FRATIS)	Freight Specific Dynamic Travel Planning and Performance, Drayage Optimization (DR-OPT)
Integrated Dynamic Transit Operation (IDTO)	Connection Protection (T-Connect), Dynamic Transit Operations (T-DISP), Dynamic Ridesharing (D-RIDE)
Response, Emergency Staging and Commutations, Uniform Management, and Evacuation (R.E.S.C.U.M.E.)	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG), Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE), Emergency Communications and Evacuation (EVAC)
Multimodal Intelligent Traffic Signal System (MMITSS)	Intelligent Traffic Signal System (I-SIG), Transit and Freight Signal Priority (TSP and FSP), Emergency Vehicle Preemption (PREEMPT)
Intelligent Network Flow Optimization (INFLO)	Dynamic Speed Harmonization (SPD-HARM), Queue Warning (Q-WARN), Cooperative Adaptive Cruise Control (CACC)
Enable Advanced Traveler Information Systems (Enable ATIS)	EnableATIS (Advanced Traveler Information System 2.0)

In addition to the applications in Table 1-2, there is also a large number of potential V2I, V2V, and vehicle-to-vulnerable-user safety applications (USDOT, 2018C; Richard et al., 2015a). Some of the applications that use V2I communications are listed below.

- Applications enabled by Signal Phase and Timing (SPaT), MAP (intersection geometric description), and GPS correction data messages sent from Roadside Units (RSU). These applications include:
  - **Signalized Left-Turn Assist (SLTA):** The SLTA system supports drivers who make permissive left turns at signalized intersections. This system identifies the location and speed of vehicles traveling on the opposing thru movement and provides the driver making a left turn with information to assist in selecting an adequate gap when turning. The objective of this system is to help reduce driver errors related to detecting traffic and judging gaps.
  - **Red-Light Violation Warning (RLVW):** This system provides a warning to drivers who may potentially enter the intersection in violation of the signal control. The objective of this system is to reduce the frequency of red-light violations.
  - **Right-Turn Assist (RTA):** This application is similar to SLTA but warns drivers making a right turn on red of the potential for a collision.
  - **Pedestrian in Signalized Crosswalk (PSCW):** An application that warns vehicles of a potential conflict with pedestrians that are within the crosswalk of a signalized intersection.
  - **Mobile Accessible Pedestrian Signal System (PED-SIG):** This application provides pedestrian information about crossing signal timing and improves safety for visually impaired pedestrians.

- **Stop Sign Gap Assist (SSGA)**: This is a system that supports drivers on minor roads who are attempting to either cross or enter the intersecting major road. SSGA provides drivers with information about oncoming vehicles traveling on the major road. The objective of this system is to help drivers safely travel through or turn onto a highway from a stop-controlled intersection.

- **Reduce Speed/Work Zone Warning (RSWZW)** and Road Hazard Warning: Information is provided to the vehicle to enable alerts or warnings relating to a specific situation, such as warning drivers to reduce speed, change lanes, or come to a stop within or approaching work zones and other hazards. The data can be obtained from multiple sources, including vehicles, field devices, management and information centers, and third-party data sources.

- **Curve Speed Warning (CSW):** The CSW application supports motorists when driving through a roadway curve at a safe speed. The system provides an alert or warning to drivers if their current travel speeds exceed a safe or advisory speed for the curve. In arterial environments, this application is similar to a ramp curve warning.

- **Rail Crossing Application (RCA):** This application includes equipping railroad (RR) grade crossings with roadside equipment (RSE) that provides warnings to vehicles about approaching and crossing railroad tracks. The warning range of communication technologies, such as dedicated short-range communications (DSRC) is greater than conventional equipment. The data can be obtained from multiple sources, including vehicles, management and information centers, field devices, and third-party data sources.

- **Spot Weather Information Warning (SWIW)**: This system provides drivers with information about potential weather-related hazards and appropriate precautions, such as reduced travel speed. The data can be obtained from multiple sources, including vehicles, management and information centers, field devices, and third-party data sources.

1.4. Levels of Automation and Cooperative Driving Automation

Transportation agencies should also become familiar with the six levels of automation and the four classes of cooperation. The six levels of automation are defined in the Society of Automotive Engineers (SAE) J3016 standards, *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicles* (SAE 2018). The levels of automation are based on whether the automated system can handle lateral and/or longitudinal control individually or in combination, whether the system can handle emergency situations by itself or needs a driver to be attentive to take control during emergencies, and whether the system performs in all scenarios and all conditions or it has a limited operational design domain (ODD), which is a set of operating conditions that it can handle safely. The six levels of automation are:

- No automation (Level 0): Driver manually executes all driving functions such as brake, steering, car following, etc.

- Driver Assistance – Function-specific automation (Level 1): ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask (but not both simultaneously) with the expectation that the driver performs the remainder of the driving tasks.

- Partial Driving Automation (Level 2): The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control but the driver has to constantly monitor the roadway while driving and be ready to take over these controls in a short time.

- Conditional driving automation (Level 3): The sustained and ODD-specific performance by system of all driving tasks with the expectation that the system can issue requests to intervene.

- High Driving Automation (Level 4): The sustained and ODD-specific performance by an automated driving system (ADS) of the entire Dynamic Driving Task (DDT) without any expectation that a user will respond to a request to intervene.

- Full driving automation (Level 5): The sustained and unconditional (i.e., not ODD-specific) performance by the system of all driving tasks without any expectation that a user will respond to a request to intervene.

The classes of cooperative driving automation are defined in SAE J3216 standards (SAE, 2020), which also identifies the relationships between the classes and levels of automation previously defined in SAE J3016 (SAE, 2018). SAE J3216 classifies the cooperative driving automation (CDA) into four classes according to the capability of sharing state information (e.g., vehicle position, signal phasing and timing); sharing of intent (e.g., planned vehicle trajectory, changes to signal timing); and ability to seek agreement on a plan such as coordinated merge, lane change, or platooning. The nature of the cooperation differs based on the level of driving automation. For driver support features (SAE driving automation Levels 1 and 2), only limited cooperation may be achieved because these levels rely on the human driver to do at least some of these functions. For Levels 3 through 5 automation, more substantial cooperation may be achieved. Table 1-3 describes the relationship between cooperation and automation as presented in the SAE J3216 standards.

Table 1-3. Relationship between Classes of CDA Cooperation and Levels of Automation, as Presented in SAE J3216 Standards (SAE, 2020)

	SAE Driving Automation Levels					
	No Automation	**Driving Automation System**		**Automated Driving System (ADS)**		
CDA Cooperation Classes	**Level 0** *No Driving Automation (human does all driving)*	**Level 1** *Driver Assistance (longitudinal OR lateral vehicle motion control)*	**Level 2** *Partial Driving Automation (longitudinal AND lateral vehicle motion control)*	**Level 3** *Conditional Driving Automation*	**Level 4** *High Driving Automation*	**Level 5** *Full Driving Automation*
No cooperative automation	(e.g., Signage, TCD)	Relies on driver to complete the DDT and to supervise feature performance in real-time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
Class A: Status-sharing *Here I am and what I see*	(e.g., Brake Lights, Traffic Signal)	Limited cooperation: Human is driving and must supervise CDA features (and may intervene at any time), and sensing capabilities may be limited compared to C-ADS		C-ADS has full authority to decide actions Improved C-ADS situational awareness beyond on-board sensing capabilities and increased awareness of C-ADS state by surrounding road users and road operators		
Class B: Intent-sharing *This is what I plan to do*	(e.g., Turn Signal, Merge)	Limited cooperation (only longitudinal OR lateral intent that may be overridden by human)	Limited cooperation (both longitudinal AND lateral intent that may be overridden by human)	C-ADS has full authority to decide actions Improved C-ADS situational awareness through increased prediction reliability, and increased awareness of C-ADS plans by surrounding road users and road operators		
Class C: Agreement-seeking *Let's do this together*	(e.g., Hand Signals, Merge)	N/A	N/A	C-ADS has full authority to decide actions Improved ability of C-ADS and transportation system to attain mutual goals by accepting or suggesting actions in coordination with surrounding road users and road operators		
Class D: Prescriptive *I will do as directed*	(e.g., Hand Signals, Lane Assignment by Officials)	N/A	N/A	C-ADS has full authority to decide actions, except for very specific circumstances in which it is designed to accept and adhere to a prescriptive communication		

1.4.1. Vehicle Definitions and Vehicle Characteristics

In this document, we define the vehicles based simply on the presence of automation and connectivity. We define CAVs as automated vehicles with different levels of vehicle automation according to SAE J3016 standards that are supported by communications and collaboration with other vehicles and infrastructure, as well as vehicle sensors. Autonomous vehicles (AVs) can also be categorized as one of the SAE J3016 levels but do not communicate with other vehicles and will generally maintain longer headways with leading vehicles for crash avoidance purposes. Connected vehicles (CVs) are human driven but can communicate with other such vehicles through V2V communications and/or with the infrastructure (V2I). Finally, traditional vehicles (TVs) represent human-driven vehicles, for which ample simulation experience has been gained over the decades.

There is much uncertainty regarding the operational modes of AVs and CAVs given the proprietary nature and frequent updating of the algorithms controlling their longitudinal and lateral spacing with other vehicles. There are also potential variations in the delivered customer options (e.g., settings for aggressive vs. conservative driving modes or space headway options). Those trends will result in even higher variability in performance across AV and CAV operating modes. Simplifying assumptions must be made when exercising any simulation environment to gain an overall perspective of the system performance under various scenarios; for example, the literature generally assumes that AVs will maintain, on average, longer headways with leading vehicles than drivers of TVs do, mostly for safety reasons, at the expense of more efficient mobility. On the other hand, CAV headways should be modeled as dependent on whether CAVs are following other CAVs or not. In other words, the same vehicle can operate under two different car-following modes in simulation, depending on its lead vehicle type. Figure 1-1 below summarizes the classification of different vehicle types based on automation and connectivity.

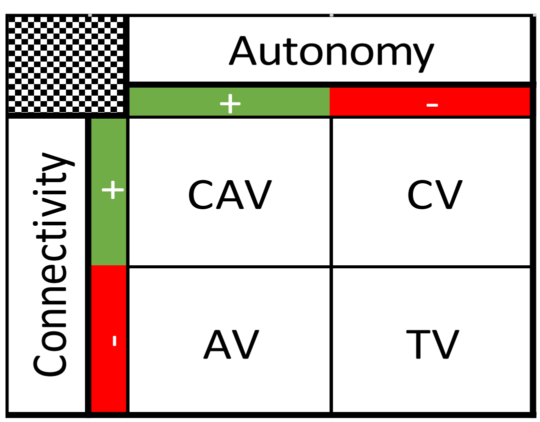


Figure 1-1: Classification of vehicles based on connectivity and automation

1.4.2. Considerations of ATV Market Penetration

We define a mixed traffic environment where the traffic stream consists of a mixture of different vehicle types (e.g., CAV, AV, CV, and TV) operating in the same right of way. Because traffic dynamics are significantly different for CAVs, AVs, CVs, and TVs, the introduction and mixing of these vehicles will have drastic impacts on the driving environment and the associated driver-vehicle behavior. Todd Littman (2019) has generated a series of future market penetration rate (MPR) scenarios, indicating that AVs would be available at least in lower market penetrations in the not-too-distant future, as shown in Figure 1-2 below. In that figure, sales refer to the fraction of all vehicle sales that are AVs, fleet represents the fraction of the on-road vehicles that are AVs, while travel refers to the fraction of VMTs generated by those vehicles

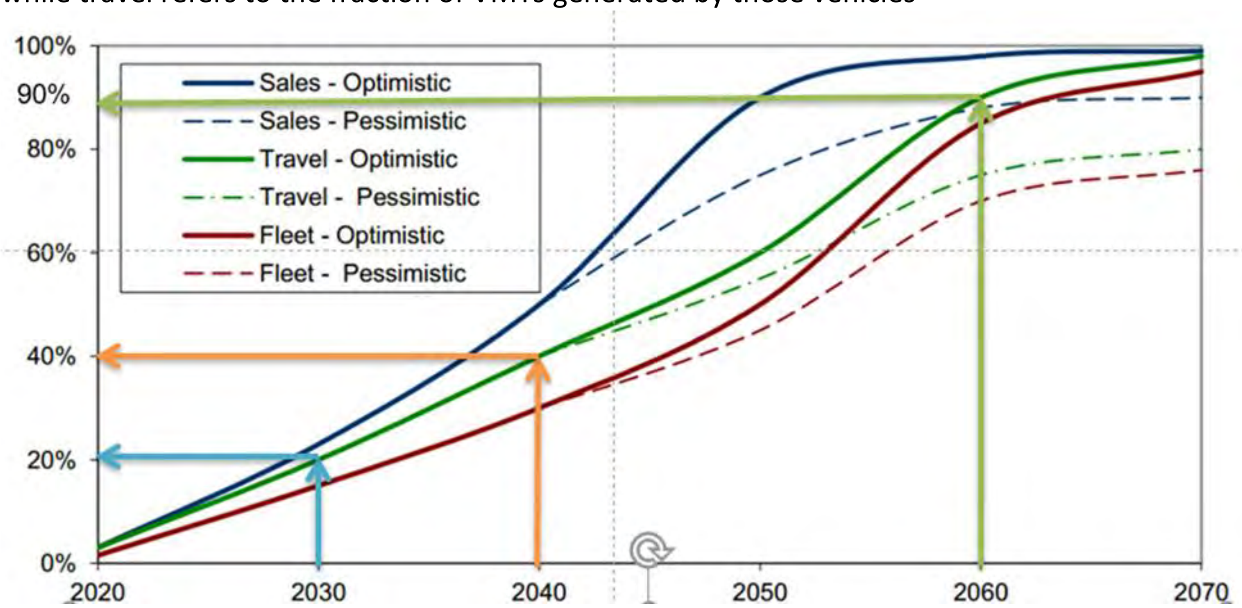


Figure 1-2: Prediction of CAV and AV introduction timeline (Littman 2019)

It is evident from these projections that reaching a 100% MPR of AVs is likely to be far away into the future. Within this interim period, roads will be servicing a mixture of the four classes of vehicles mentioned earlier in this section. Thus, the impact of vehicle class interaction on both mobility and safety will continue to be a significant research question to be addressed well into the next decade or longer. It is recommended when modeling future year traffic scenarios that the analyst perform sensitivity analysis by varying the proportions of the different vehicle types and producing the results based on the sensitivity analysis.

1.5. Document Organization

The remaining chapters of this document are as follows. Chapter 2 provides a review of the state of practice in ATV modeling organized in several modules that span mobility and safety applications. This material is followed by a series of one-page summary reviews of various studies on the effect of automation and connectivity on mobility and safety. A comprehensive and detailed literature review is provided in Appendix A of this report, under separate cover.

Chapter 3 identifies the needs of transportation agencies in modeling ATVs based on the inputs received in a virtual focus group meeting with the participation of state and local agency stakeholders. Chapter 4 presents the guidance and framework developed in this study to enable the AMS of ATV. The guidance presented in this document is not intended to be standalone but rather is developed to enhance microscopic simulation analysis guidance at the national level (Wunderlich et al., 2019) and state departments of transportation such as those of the FDOT (FDOT, 2014), Iowa DOT (IDOT, 2018), Virginia DOT (VDOT, 2020), Washington State DOT (WSDOT, 2014), and Oregon DOT (ODOT, 2011). Chapter 5 includes case studies of utilizing microscopic simulation models to model ATV applications conducted in this project.

2. REVIEW OF STATE OF PRACTICE

2.1. Introduction

Connectivity and autonomy are two innovative technologies expected to benefit travel efficiency, throughput, reliability, and safety. Studies on the impact of integrating vehicle connectivity and autonomy have been predominantly conducted using simulation. Such studies' outcomes strongly depend on the methodological framework, algorithms and models, assumptions, and simulation platform employed. This review has revealed different and sometimes contradictory findings on the impact of these technologies on transportation system mobility and safety. Those differences can invariably be traced to the use of different assumptions, algorithms, and simulation platforms. A roadmap identifying the various topics covered in the detailed literature review included in Appendix A and shown in Figure 2-1. In this chapter, we provide one-page syntheses of the key elements depicted in the roadmap figure as they relate to facility types and mobility or safety themes. A reference is given to the page in Appendix A where the details of the reviewed element can be found. All references cited herein are provided in Appendix A.

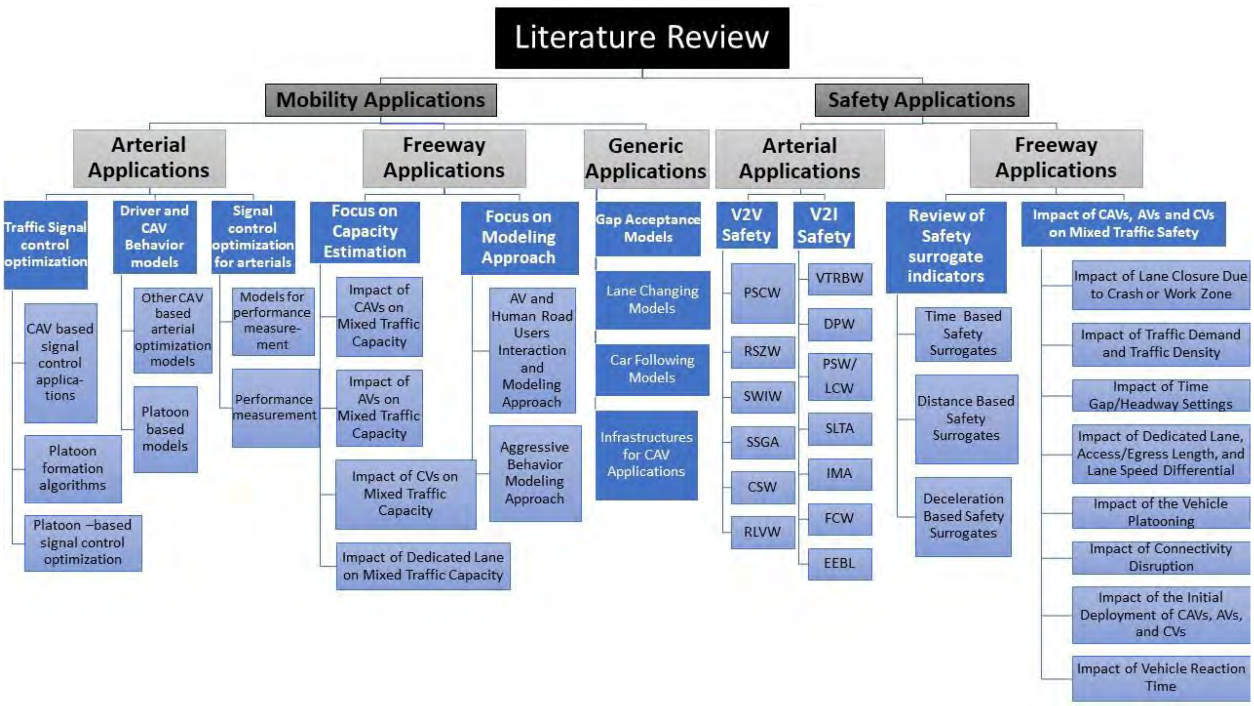


Figure 2-1: Roadmap of key literature review elements

2.2. Literature Review Synthesis

2.2.1. Mobility

Freeway Applications (see also Appendix A, pages 7-29)

Key Findings: There is an extensive body of literature covering the mobility impacts of AVs, CVs, and CAVs on capacity and travel time on freeway segments and facilities. The reviewed studies have used a variety analytical and macroscopic traffic models; however, microscopic simulation is primarily utilized in assessing the mobility impacts on freeways. The findings of those studies are very much dependent on the assumptions made in the simulation or other models. Specifically, the specification of time gaps for different vehicle pairs are the strongest determinant of capacity effects. Typical modeling of CAVs uses the Cooperative Automated Cruise Control Algorithm (CACC) for longitudinal control. In general, the literature has shown that CAV introduction with V2V connectivity into the vehicle mix has a positive impact on capacity as it is assumed that they can generally operate on shorter headways than human-driven vehicles, but positive impact on capacity is less certain with AV that do not have V2V communications. This CAV benefit is most likely true if those vehicles operate in a dedicated lane where they can maintain short headways in platoons. However, until a meaningful percentage of CAVs are operating on the roadway system; it will not be known with certainty if this underlying assumption holds.

One study ventured to state that a per lane capacity of near 6,000 CAVs per hour can be achieved under ideal conditions and very long platoons. The literature suggests that lane dedication is optimal at a CAV market penetration rate (MPR) of 30%–50%. At higher or lower MPRs, congestion is likely to occur either in the dedicated or general-purpose lanes. Regarding AVs, the verdict is mixed and, as mentioned earlier, is highly dependent on the time gap setting used in simulation. Some studies have shown that AVs will increase capacity if the gap setting is within 0.8–1.2 seconds, while others have actually shown a drop in capacity with their introduction. Finally, regarding CVs with capabilities for V2V and V2I communications, some of their mobility effects lie at the strategic rather than operational level. This includes the ability to bypass incident locations, avoid traveling on a lane to be closed downstream, and other route guidance information. One study stipulated that driver reaction time could be reduced and that acceleration for those vehicles can be modeled using the Intelligent Driver Model (IDM). Applications of CV speed-flow relationships at the network level using mesoscopic models have shown the potential for capacity improvements especially at medium or high demand levels.

Key Gaps Identified: The reviewed past studies on vehicle automation and connectivity have generally lacked strong empirical evidence on the longitudinal and lateral behavior of CVs, AVs and CAVs in real-world settings. Much of the underlying empirical data are limited to a few vehicles in pilot studies, and key OEM data are often inaccessible to researchers. Furthermore, it appears that current OEM efforts regarding vehicle automation are geared primarily towards crash avoidance and improved navigation, rather than mobility efficiency, leaving the field lacking some important mobility parameters.

A second gap identified in the review pertains to assumptions regarding drivers' reaction to the presence of automation. There is a need for a well-designed study to investigate driver behavior in the presence of automated vehicles.

Please, note that an important area of research is the simulation of freight ATVs such as truck platooning. However, this area of research is not addressed in this review of literature and the research in this phase of the project.

Arterial Applications (Also see Appendix A, pages 29-31)

Key Findings: This part of the literature review summarizes research related to the use of CAV technologies to improve operations at signalized intersections, arterials, and networks. Regarding signalized intersections, several research efforts have developed vehicular trajectory control and intersection controller optimization based on CAV technologies. These two approaches can also be integrated into a single process such that both aspects can be optimized simultaneously to achieve maximum benefits. Some of these studies are based on platoon-based signal control optimization and approach the problem from the control theory perspective. They treat each vehicle in the platoon as an individual agent and design control algorithms involving the inter-vehicle gap and velocity to reach stability, or a "consensus state", i.e., position and velocity consensus with respect to the leader and the follower. This approach seems to work for simplified phasing at the intersection and does not seem straightforward to extend for right- and left-turning movements which require lower speeds when approaching the stop bar and making turns.

Several simulation-based studies of jointly optimized signal control and trajectories have shown that this approach can improve intersection performance particularly for higher demand levels. However, it is not clear how human drivers (for connected vehicles) would react to recommendations of optimal trajectories through an intersection. Field experiments at a closed-course signalized intersection have illustrated the complexity of field implementation of such systems. While the technology is certainly improving, there remain significant gaps in the sensing ability and communication speed required to make such systems a reality. There have been limited efforts for optimizing signal control through arterials and networks, and those have used extensive simplifying assumptions.

Key Gaps Identified: First, most of the existing studies are based on a number of assumptions, such as intersections with no left turns. In order to move these technologies from simulation to implementation, the existing models must be enhanced to be as realistic as possible. Second, most efforts to leverage CAV technologies for signal control have focused on isolated signalized intersections. Given that most of the congestion issues occur along urban streets with coordinated intersections, rather than isolated intersections, new methods should be developed to leverage CAV technologies such that arterial and network operations can be improved. Third, many of the simulations conducted have been based on the researchers' own tools. These are generally not available to others such that they can be thoroughly vetted. Therefore, it is difficult to assess the effectiveness of the solutions proposed and to compare different types of solutions. Fourth, most of the research conducted is simulation based. As the technologies mature, it is important to conduct field experiments, which are generally more complex but essential in order to successfully implement these technologies. There are significant complexities, primarily related to sensing, communications, and human factors, that are not effectively addressed in simulation studies.

Please, note that an important area of research is the simulation of the interaction of ATVs with other modes such as pedestrians and bicycles. However, this area of research is not addressed in this review of literature and the research in this phase of the project.

2.2.2. Safety

Freeway Applications: Surrogate Safety Measures (See also Appendix A, pages 39-54)

Key Findings: Safety surrogate measures (SSMs) have been used for a long time in highway safety research, dating back to the mid-1970s. They have received more prominence in automation and connectivity research as a result of the extensive use of simulation modeling for the analysis of mobility impacts of CAV and AV introduction into the traffic stream. Original research regarding SSMs focused on three primary measures: time-to-collision (TTC), reaction time (RT), and deceleration rate to avoid crash (DRAC). Severity thresholds for both measures are reported in the literature and have varied considerably over time and vehicle class. The original SSM measures were incorporated in the most widely used supplemental algorithm called SSAM, which tracks vehicle trajectories in simulation platforms and reports on the values of SSMs associated with various scenarios. Since this original work, there has been a significant expansion in defining new SSMs to account for three characteristics: frequency, severity, and duration. This review indicated a wide range of reported thresholds for many of the measures; TTC varied from a low value of 0.50 seconds in some studies up to 5 seconds in other studies. One study used different TTC thresholds depending on the type of following vehicle (0.75–1.0 if the following vehicle is a CAV, and 1.5 if it is a TV). Other studies have focused on a reduced reaction time for non-TV vehicles, bringing the value down to 0.1 seconds for CAVs. Other studies performed a sensitivity analysis of the various thresholds and reported their findings. More sophisticated measures that combined several characteristics such as TET (time-exposed time-to-collision, or the number of seconds time headway is below the TTC threshold) and TIT (time-integrated time-to-collision, which also includes how much lower than the TTC threshold is experienced) offer a more comprehensive account of attributes beyond exposure time to high-risk conditions.

Key Gaps Identified: Similar to the use of "time gap" assumptions in the mobility reviews, the same limitations apply to SSMs. The literature reviewed appears to be lacking a rigorous theoretical basis for determining the appropriate SSM thresholds to be applied to vehicles with automation and/or connectivity features. In the same vein, there is even less empirical data available regarding the thresholds that OEMs use, for example, to trigger an emergency deceleration to a stop. We recognize that those safety algorithms are currently being implemented in CVs, AVs, and CAVs as automated crash avoidance features, but are considered to be proprietary by the various manufacturers. An important gap is the impact of the use of car-following models on the resulting SSM frequency and severity, keeping thresholds at fixed values. For example, in VISSIM or in SUMO, one may use the Wiedemann 99 car-following model for TVs, an Adaptive Cruise Control (ACC) car-following algorithm for AVs and a Cooperative Adaptive Cruise Control (CACC) car-following algorithm for CAVs. To what extent the selected models influence the patterns of SSMs is not known.

A third gap in this domain is the lack of open source, empirical datasets of mixed CVs, AVs, TVs, and CAVs in the traffic stream. Specifically, there is a need to observe mixed flow platoons in a car-following mode, under various initial conditions, to enable researchers to contrast the SSM patterns across vehicle types, spacing, and initial speed. The research team has been able to download a TV+AV open-source dataset in Europe called "OpenACC" which may allow us to generate a limited set of SSMs for at least these two classes of vehicles in car-following mode. Finally, SSM-based research focused on trucks in platoons appears to be generally lacking in the literature.

Freeway Applications: Mixed Traffic Safety Impacts (See also Appendix A, pages 52-58)

Key Findings: This review focuses on studies that examined the effect of automation and connectivity on safety, assessed mostly using surrogate safety measures based on simulation model results. The review indicates that applications based on connectivity can reduce the response time to events decreasing the likelihood of conflicts. A study found that a dedicated CV lane reduced conflicts by 58% and that lane dedication is optimal at a CV market penetration rate (MPR) between 10% and 30%. However, at higher MPRs it would be best to also allow CVs on the general purpose (GP) lanes. A driving simulator study revealed that combining information from an onboard unit and variable message signing reduced conflicts significantly for CVs.

The majority of the reviewed studies focused on CAV impacts across scenarios. Because CAVs tend to operate at nearly constant speed, a study found that irrespective of the time gaps, an increase in CAV market penetration was consistent with an overall speed variation reduction and associated reduction in rear end conflicts. Another study investigated the effect of connectivity levels on conflicts. In other words, it explored the effect of feedback received from one to multiple leading vehicles. The study found that a significant reduction in conflicts occurred as the level of feedback increased. In general, at low CAV market penetration, connectivity is not pervasive, and therefore, CAV safety benefits are not significant. Safety benefits only become significant when a pre-specified threshold is reached (for example a time to collision or TTC of 1.5 is reached). Surprisingly, there were fewer studies focused on the effect of AVs on safety. A mixed traffic analysis study showed that at low MPRs, AVs actually resulted in an increase in conflicts, as measured by the driving volatility surrogate measure. Another study, one year earlier, gave the opposite results, indicating that at MPRs of 15%–25%, AVs reduced the number of forced stops and improved traffic harmonization.

Key Gaps Identified: Similar to mobility, most of the studies reviewed assume a monolithic set of safety-related parameters for specific vehicle types. While they may vary across scenarios, they are fixed within a scenario. As mentioned earlier, it is likely that OEMs will enable the AV user to select desired gap, desired speed, and desired lane settings. Potentially, these settings may mirror TV drivers' typical driving behavior. In other words, the implemented mix of AV, TV, and CV vehicles will likely be significantly more heterogeneous than that assumed by many of the reviewed studies.

Secondly, the lack of empirical evidence on the impact of vehicle types on observed safety via crash statistics represents a gap regarding the validity of the reviewed studies' results. And as mentioned earlier, human drivers' response to the presence of connected or automated vehicles in the traffic stream has not been studied sufficiently in the literature, although driver simulator studies may be able to shed light on those effects and potential spillover on safety measures. Finally, additional research regarding lateral safety issues is required. This is especially critical in the presence of extensive weaving due to either the presence of multiple interchanges and/or dedicated AV or CAV lane access and egress. Most studies seem to focus predominantly on longitudinal controls.

Arterial Applications (See also Appendix A, pages 57-67)

Key Findings: Safety applications on arterials can be categorized as V2I, V2V, and vehicle-to-vulnerable-user. The V2I safety applications include Red Light Violation Warning (RLVW), Curve Speed Warning (CSW), Stop Sign Gap Assist (SSGA), Spot Weather Impact Warning (SWIW), Reduced Speed Zone Warning (RSZW), and Pedestrian in Signalized Crosswalk (PSCW). V2V safety applications include Emergency Electronic Brake Lights (EEBL), Forward Collision Warning (FCW), Intersection Movement Assist (IMA), Signalized Left-Turn Assist (SLTA), Blind Spot/Lane Change Warning (BSW/LCW), Do Not Pass Warning (DNPW), and Vehicle Turn Right in Front of Bus Warning (VTRIFB). These applications mostly aim to assist drivers in avoiding crashes by sending warning messages or information that can be used by the on-board units (OBU) to generate warnings. Regarding the platform used in quantifying the safety performance, the reviewed studies used driving simulators, field tests, and microscopic traffic simulations.

A study done by Najm et al. (2010) estimated the safety benefits of CV-based applications in reducing the annual crash rates at signalized intersections. The findings showed that these applications could address about 26% of all related vehicle crashes. A study conducted by Ahmadi and Machiani (2019) examined the drivers' performance when subject to a personalized adaptive CSW compared with conventional CSW. They suggested that CSW should be flexible in considering different driver behaviors. Banerjee et al. (2020) investigated the effect of RLVW application on driver's braking behavior using a driving simulator. The results showed that participants react more quickly to the change in the signal indication in the presence of RLVW. Another study by Jang et al. (2011) developed an RLVW that consists of a prediction model and a warning algorithm. The prediction model was tested using a microscopic simulation model. Overall, all CV-based safety applications have shown positive safety benefits that increase as the CV market penetration rate increases.

Key Gaps Identified: The key factors to be considered when using a traffic simulation in modeling CV-based safety applications is the calibration of parameters that influence the modeling of CV and the associated applications. Special consideration should be given to fine-tuning these parameters depending on the modeled application considering that these parameters may not be adequately fine-tuned in "general-purpose" calibration of the simulation models. For example, when modeling an application that supports the cooperative permissive left turn of automated vehicles, specifying gap acceptance parameters that accurately represent the real-world drivers' behavior is crucial to the application modeling and assessing the resulting safety benefits. Therefore, gap acceptance parameters in the form of a probability distribution should be used in the simulation. Modeling the RLVW application also requires the calibration of drivers' behavior at the onset of the yellow indication. For example, the microscopic simulation tool VISSIM uses a logit model to determine the probability of stopping of each vehicle at the point in time when the yellow is indicated. Therefore, the parameters in the logit model should be calibrated such that the number of vehicles that stop at the intersection and red-light violators approximate real-world data. It is also observed that a number of studies that used traffic simulation assumed that there was communication latency from between vehicles or between vehicles and the infrastructure, which may affect the simulation results.

3. IDENTIFICATION OF AGENCY NEEDS

This chapter summarizes the needs of public agencies in the southeastern United States in modeling ATVs. For the purpose of this identification, this study conducted a virtual focus group meeting on November 5, 2020, with the participation of public agency stakeholders. The goal of this meeting was to communicate the project objectives and obtain inputs regarding the CAV modeling needs and priorities. Prior to the meeting, the project team developed interview questions to address topics related to the scope of the study including the agency's current CAV activities, efforts, plans, barriers, and challenges regarding the adoption, implementation, and impacts of CAV technologies. Some questions were designed to identify the participants' opinions on the modeling aspect of CAVs. For example, the participants were asked to describe the tools and performance metrics they use to analyze the impacts of CAVs. In addition, the participants were asked to provide the key questions they have and critical understandings they seek with the simulation of CAVs. In this discussion with the stakeholders, the term CAVs often refer to all types of automated and/or connected vehicles.

3.1. Interview Questions

The list of questions used during the focus group is provided below:

- What are your agency's current CAV activities regarding CAV adoption?
- What are the major issues and questions your agency has regarding the adoption and impacts of CAV?
- Are there specific performance metrics related to CAV that your agency is interested in?
- Does your agency have a roadmap or plan for future CAV efforts, projects, implementation, etc.?
- How does your agency address the CAV plan organizationally?
- Who currently undertakes modeling or analysis for CAVs for projects? Can you give an example?
- What tools, that is, analytical models, simulations, custom-made spreadsheets, regional travel demand models, etc., are your agency currently using to model CAVs?
- When thinking about agency decision-making regarding CAV, what are the key questions your agency hopes to answer or critical understandings your agency needs that you seek to achieve through CAV modeling?
- What are the main concerns and barriers to your agency's current approach in CAV modeling?

- What collaborations are needed with other departments in your organization and agencies in your region?
- Is there anything else about CAV modeling within your agency, your modeling needs, or other issues that we did not ask you that you would like to tell us about? That is, what did we miss?

3.2. Interview Findings and Discussion

Participants in the workshop agreed that there is a need to provide a formal taxonomy of CAV systems and practical and realistic guidance for transportation agencies to account for the impacts of CAV. It was noted that there has been significant progress made by the DOTs to build CAV infrastructure. Additional thoughts were given regarding the readiness of the physical and digital infrastructures for CAV deployment. Overall, the majority of respondents were not satisfied with the current ability to understand the impact of CAV deployments and utilize this information to guide deployment decisions.

3.2.1. Current Deployments

The participants from Georgia DOT reported their agency's current CAV activities regarding CAV adoption. Some of the activities included deploying CV RSU on urban arterials. In addition, Georgia DOT, in coordination with the Atlanta Metropolitan Planning Organization (MPO), is deploying CV-based vehicle-to-everything (V2X) applications across the region on a broad scale. Another project was conducted on segments of I-95 to demonstrate the impacts of CAV applications such as queue warnings, crash warnings, and other applications in a rural network setting, in partnership with private sector companies. Additional pilot projects included transit signal priority applications and preemption applications with partners such as the toll authority and Georgia Regional Transportation Authority.

The participants from Florida DOT reported that they have established a $120 million CAV program over a five-year period. This program includes a total of 25 different implementation projects. One of the first projects was conducted in response to the AASHTO SPaT Challenge and was completed in two and a half years in Tallahassee, FL. The second project was the Gainesville SPaT project that included CV-based applications such as pedestrian collision warning systems, transit signal priority, and emergency vehicle preemption systems. The third SPaT project was developed in the City of Tampa. A fourth important effort is the I-75 FRAME megaproject that was supported in part by the Advanced Transportation Congestion Management Technology (ATCMTD) initiatives funded by the USDOT.

The participants from North Carolina DOT (NCDOT) reported that they completed a number of SPaT projects. It was mentioned that NCDOT is seeking to ensure that traffic signal system infrastructure is capable of handling the CAV deployments. Finally, the participants from South

Carolina and Mississippi DOTs reported that they did not have many CAV implementation projects to report. Detailed minutes of this discussion on this topic can be found in Appendix B (under separate cover).

3.2.2. Issues and Concerns

The next questions focused on the major issues and concerns that the participants had regarding the adoption of CAV technologies and the assessment of the associated impacts. Most of the responses confirmed that one of the biggest barriers is the lack of knowledge and guidelines regarding CV and CAV technology and the anticipated impacts. A participant mentioned the difficulty in considering the uncertainty in adopting the technology, vehicle fleet type considerations, and the impacts on traffic travel behaviors. Some participants suggested that it would be very useful to have analysis examples that could include a set of scenarios and/or sensitivity analysis to demonstrate how analysis can support the decisions. In the absence of real-world knowledge of CAV impacts on the transportation system, a participant pointed out the need of identifying the input parameters that could be used when modeling the CAV impacts. For example, there is a need for identifying the proportions of vehicles with different levels of automation and connectivity when modeling future year conditions. In addition, the participants discussed the need for "guidance" on how to model CAV and how to use of the results of the modeling in the decision-making process.

The issues of "value proposition" arose several times during the focus group meeting. The participants discussed safety impacts among other impacts in determining the return on investment.

3.2.3. Performance Metrics

The next set of questions focused on the performance metrics that agencies are interested in when assessing CAV impacts. A participant answered this question from a higher-level point of view and mentioned that their DOT will be interested in comparing the performance of the infrastructure support of the technologies in relation to the improvements expected from traditional improvements. The participants emphasized the importance of assessing both the safety and mobility impacts. A participant said, If you have a proliferation of CAV technologies, for example, the SPaT applications where drivers are aware of the signal status that is about to turn green and so on, we will be looking at the operational performance, improvements in reliability across the network; these are on the operation side. On the safety side, it is as simple as crash reductions, serious injuries, and fatalities.

Another participant from the FHWA added that one example to consider when identifying the performance measures of CAV analysis is the federal process of approval of traditional improvements such as interchanges modification and facility capacity addition.

The comparison should include the initial cost as well as the operations and maintenance (O&M) costs because it is important for state DOTs to identify the O&M cost before implementation of a brand-new technology. The participant said, "*No consensus on what it takes to maintain an RSU. I got a range from $300–$2800 per unit. Do we have a good understanding of the O&Ms? Before recommending adding these technologies, we need to have detailed O&M costs. MPOs are thinking about how to incorporate this; they should be able to determine the qualitative and quantitative benefits.*"

3.2.4. Modeling Tools

The next questions focused on the CAV modeling tools including analytical tools, simulation tools, custom-made spreadsheets, regional travel demand models, and so on. The participants noted that currently state DOTs work with consultants and researchers to select the type(s) of tools and to use the tool(s) in the analysis. There is a feeling that simulation models have the potential to model CAV applications to quantify the impacts on the transportation network. Some participants pointed out that most of the projects that focus on CAV deployment are not based on the operational evaluation of the applications. The participants further mentioned that the modeling of operational strategies to determine their mobility and safety impacts have been very limited.

Some participants reported specific challenges that they currently face. For example, one participant mentioned a barrier at the MPO level related to demand forecasting model development. There is a need for extending and/or converting the traditional demand models to allow them to consider CAVs in demand forecasting.

3.3. Summary

The discussion in the workshop indicates that the level of CAV application deployment varies by state, with some states investing significantly mainly in infrastructure support of CV deployment. At this point, the consideration of AV and CAV in traffic operations is limited, but this can be different with planning agencies that are interested in long-range modeling and planning. Participants in the workshop agreed that there is a need to provide guidance for transportation agencies to account for the impacts of CAVs. Overall, the majority of respondents were not satisfied with the current ability to understand the impact of CAV deployments and utilize this information to guide deployment decisions.

The participants confirmed that one of the biggest barriers to decision making is the lack of knowledge and guidelines regarding CAV technology and the anticipated impacts. This can include the difficulty in considering the uncertainty in adoption of the technology, various types of vehicle fleet considerations, and the impacts on traffic and travel behaviors. Some participants indicated that it is very useful to have analysis examples that could include a set of scenarios and/or sensitivity analysis to demonstrate how analysis can support the decisions. Given the absence of real-world knowledge of CAV impacts, there is a need to identify the input parameters that could be considered when modeling the CAV impacts.

With regard to performance metrics, there is an interest in comparing the performance of the infrastructure support of the technologies in relation to the improvements in performance expected from traditional improvements. One example to consider when identifying the performance measures of CAV analysis is the federal process of approval of traditional improvements such as interchanges modification and facility capacity addition. The comparison should include the initial cost as well as the operations and maintenance (O&M) costs because it is important for state DOTs identify the O&M cost before implementation of a brand-new technology to.

The participants noted that currently state DOTs work with consultants and researchers to select the type(s) of tools to use in the analysis. There is a feeling that simulation models have the potential to model CAV applications to quantify the impacts on the transportation network. There is also need for extending and/or converting the traditional demand models to allow them to consider CAVs in demand forecasting.

4. ATV MODELING FRAMEWORK AND GUIDANCE

The guidance and framework presented in this chapter are intended to provide information that enables the analysis, modeling, and simulation of ATVs based on the information available at the time of the preparation of the document. The ATV field and ATV AMS modeling and simulation are still in the early stages. Thus, it is anticipated that the guidance will be updated and extended as more information and research become available. The guidance presented in this document is not intended to be a standalone guidance but is developed to enhance and fill the gaps of the seven steps of microsimulation analysis that are addressed in guidance provided by states such as by FDOT (FDOT 2014), Iowa DOT (IDOT 2018), Virginia DOT (VDOT 2020), Washington State DOT (WSDOT 2014), and Oregon DOT (ODOT 2011) as well as national guidance such as the *Traffic Analysis Toolbox Volume 3* (Wunderlich et al., 2019), the "Scoping and Conducting Data-Driven 21st Century Transportation System Analyses" document (Wunderlich et al., 2017), and the *Transportation System Simulation Manual* (TRB, forthcoming). The flow chart in Figure 4-1 shows the seven steps as presented in the *Traffic Analysis Toolbox Volume 3* (Wunderlich et al., 2019). This chapter presents ATV-related AMS guidance for each of these seven steps.

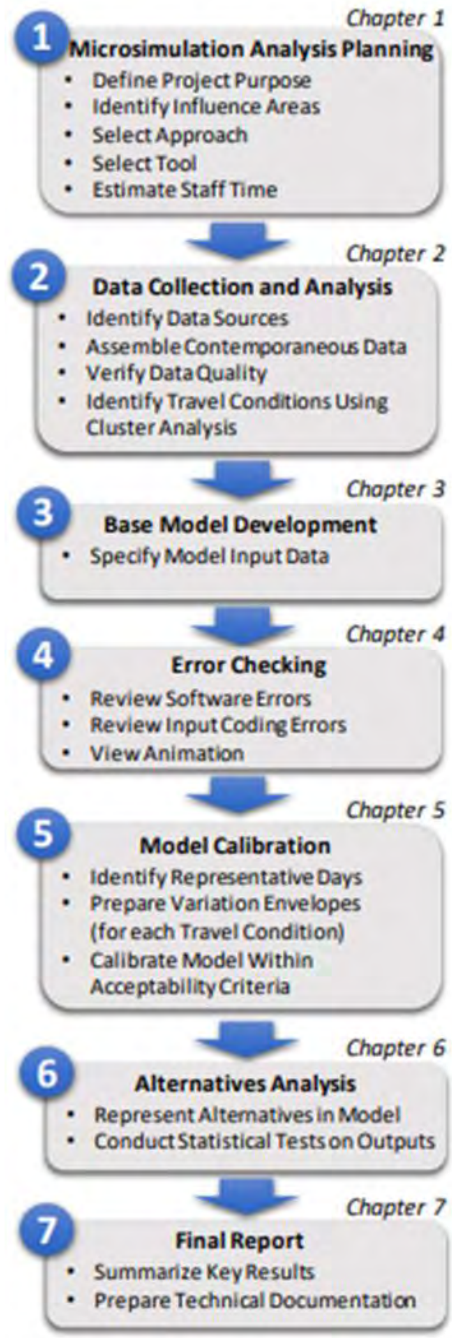


Figure 4-1: Traffic simulation analysis steps (Wunderlich et al., 2019)

4.1. Project Planning and Scoping

The planning of a simulation project involves the identification of the objectives, hypotheses, data needs, data quality requirements, performance measures, responsible parties for various parts of the project, geographic and temporal scopes, studied alternatives, technical approach, appropriate analysis tools, and estimation of the required resource estimates.

4.1.1. Analysis Objectives

The analyst needs to clearly understand the project goal and objectives and work with other stakeholders to potentially clarify or even revise the goal and objectives, if needed. The study objectives will provide the basis for selecting the evaluated alternatives, formulating the hypotheses to be addressed by the analysis, the performance measures, and the modeling framework.

As stated earlier in this document, there is a wide variation of the types of connected, automated, and cooperative applications. Only a subset (can be a small subset) of these types and applications will likely need to be modeled in a given project. The modeling of ATV will increase the complexity and uncertainty associated with the AMS tasks and thus the required resources. The CV AMS effort should focus on the needs of the project and model only the subset of ATVs and applications that needs to be modeled.

4.1.2. Overall Modeling Framework

Although this document mainly focuses on microscopic simulation of ATV, the analyst needs to understand that in many projects, microscopic simulation is a component of a larger AMS effort that involves other analysis types, including demand forecasting tools, mesoscopic simulation-based dynamic traffic assignment, other behavioral modeling tools and algorithms, and highway capacity analysis tools. In addition, the analyst should consider the need to model ATV as part of a more comprehensive assessment of emerging technologies and strategies, including automated, connected, electric, and shared (ACES) vehicles and transportation system management and operations (TSM&O).

The FHWA developed a comprehensive ATV AMS framework (Mahmassani et al., 2018). Although the framework was produced to inform ATV AMS model development effort, it can be used as a basis for a project-level AMS framework by the analysis team. The framework includes four main dimensions of ATV modeling: supply changes, demand changes, performance changes, and network integration. It should be noted that depending on the AMS objectives and scopes, all or a subset of the four dimensions need to be included in the project modeling framework.

- ***Supply Changes:*** The increase in the market penetration of the ATVs will be accompanied by changes to the physical and digital infrastructure, including those that enable V2I connectivity, in addition to enabling new mobility options such as mobility as a service, shared fleet utilization, last-mile automation, and automated trucks. The assumptions about supply changes and the associated performance are important parts of the ATV modeling process.

- ***Demand Changes:*** ATV is expected to have significant impacts on activity and travel choices. It is expected that there will be major impacts due to the changes in the value-of-time due to multitasking and changes in various performance metrics of traveling. At high levels of automation (Levels 4 and above according to SAE J3106 standards), the reduction in the stress of travel and the ability to perform other tasks while in the vehicle are expected to reduce the value of travel time, potentially increasing the number of trips and vehicle miles travelled. Shared mobility enabled by ATVs will also have significant impacts on demand generation and associated activities and the decision to own a vehicle. In addition to trip generation, it is expected that ATVs will impact other travel activities such as mode choice, route choice, and departure time, among others. The number of trips by people that do not have cars, who are seniors, or are differently abled will also increase. Estimation of the demand changes requires enhanced demand forecasting models that can effectively determine the impacts of ATVs on trip generation, distribution, mode choice, trip time, route choice, and even land use. This demand forecasting component is beyond the scope of this document.

- ***Operational Performance:*** ATVs will have significant impacts on capacity and stability of the traffic stream. Thus, there is a potential for significant improvements in travel time and travel time reliability, if these technologies are developed and utilized. ATVs will also have significant impacts on other measures such as safety, environmental impacts, equity, and resilience measures, among others. The assessment of the operational performance and impacts of ATV using microscopic simulation is the major focus of this project. ATV AMS should be able to capture the interactions between the vehicles, infrastructure, and others such as pedestrians and bicycles considering a heterogeneous mix of traffic including manual drivers, different levels of automated vehicles with and without connectivity, and vehicles with different classes of collaboration. These vehicles will have different reaction times, driving errors, acceleration/deceleration, car-following headways, gap acceptance, lane-changing, speed-setting, merging, and weaving behaviors. It is recognized that these behaviors are expected to vary depending on the equipped sensors, wireless communications, and the control algorithms installed by different car manufacturers. However, it is also recognized that an abstraction of the resulting behaviors is acceptable for many CV AMS applications in the absence of more detailed information about the performance of the implementations of these manufacturers.

- ***Network Integration:*** The ATV modeling may include multiple tools, tool extensions, algorithms, and preprocessing and post-processing tools. There is a need to integrate the tools to capture the ACES interactions at the network level.

4.1.3. Identification of the Technical Approach

The additional complexities associated with ATV modeling should be considered in the early stages of the project to determine the required capability and resources and to confirm that these requirements can be met. The technical approach should be carefully identified in as much detail as possible. It is evident that no single existing AMS tool has the capabilities required to analyze all aspects and applications of ATVs. A combination of tools may be needed. In addition, many of the required modeling components for ATVs do not exist in current modeling tools. Thus, additional programming to extend the modeling capabilities of the existing tools is often needed, for example, using the application programming interface (API) of commercially available tools.

A recent FHWA project (Abbas et al., 2020) identified the steps required to select the analysis approach as follows: scope definition; questions to be answered by modeling; a list of needs and requirements to answer the questions; and ranking and prioritization of the list. Based on the above, the analyst will identify the approach considering the available tools' capabilities and determining the level of customization needed. The project team should then define and evaluate the tasks, determine whether the analysis can be done given the resources, and weigh the number of questions that can be answered considering the resources. This process will also identify the data needs and availability (further discussion of this is presented in a separate subsection). The above-mentioned FHWA study recommended using what is referred to as the Pillar Diagram that is intended to facilitate the brainstorming process recommended to select the modeling approach. The Pillar Diagram includes three pillars (components) that addresses four possible levels of analysis details within each pillar: (1) activity-based modeling (ABM) and origin-destination analysis; (2) microscopic analysis; and (3) macroscopic analysis. For each of the components, the authors identified four possible types of analysis:

- Standard features in existing AMS tools
- Capabilities obtained through scripting or application programming interface (API).
- Capabilities that can only be obtained through tools developed outside the available AMS tools.
- Capabilities that can only be obtained through development of new tools or frameworks.

It is recommended that the ATV analyst review the deliverables from the above-mentioned FHWA study and utilize the methodology proposed in that project in selecting the analysis approach. Once the approach is selected, then specific tool(s) to be used in the analysis will have to be selected. Further discussion of the selection of the tool(s) is presented later in this section.

4.1.4. Uncertainties Associated with ATVs

AMS can be conducted to assess the impacts of ATV in various time periods in the future, ranging from short term to long term. When simulating ATVs, it is important to estimate the ATV adoption because the market penetrations of different levels and classes of ATVs in the traffic stream will determine the system performance. Studies have been conducted to provide information regarding the increase in the market penetrations of the ATV. Section 1.4.2 shows an example of the results from one of these studies (Littman, 2019). However, there are still significant uncertainties with ATV adoption. There are many issues that will impact the rates of the adoption of various types of ATVs, depending on the specific connectivity, automation, and cooperation capabilities. These issues include the cost of the technology, whether the technology is used in private or shared vehicles, the provision of the required infrastructure support, various policy and legal issues, and technology progress and issues. The analysts of ATVs should review any updated information that can provide the best estimates at the time of the study of ATV adoption in the analyzed future year.

The uncertainty described above will have to be considered in ATV AMS projects. Previous studies have described scenario planning as the basic method for planning under deep uncertainty and as a step incorporated in performance-based planning at various stages of the process (Twaddell et al., 2016). It is recommended that such an approach should be used in ATV AMS because the timeline for adoption of ATV technology is debatable. In setting the parameters for scenario-based planning, the analysts should review the recent studies on the subject of ATV adoption and assess the confidence levels in these studies. The project should also reach consent among stakeholders about the potential timing of deployment to support the process of scenario development. There is also a need for understanding how to communicate the results under uncertainty; this is fundamental to a conceptual framework for planning and modeling ATVs. A useful resource for scenario-based planning is the scenario-planning guidebook developed by the FHWA (Ange et al., 2017).

4.1.5. Performance Measure Identification

An important aspect of the hypothesis formulation is to identify performance measures that are relevant to the project goal and objectives and expected impacts of ATV on different measures. Thus, in addition to realizing the project goal and objectives, it is important that the analysts understand the wide range of ATV levels and classes and associated applications and use cases. Such impacts are dependent on the market penetration of the technologies as discussed further later in this chapter.

ATV applications are expected to improve mobility measures by increasing throughput, probability of breakdown, and stability. The upcoming release of the next update to the Highway Capacity Manual (HCM) will include ATV-specific sections that recommend capacity modification factors for freeway segments considering different market penetrations of vehicles equipped with CACC operations and dynamic merge operations (Adebisi et al., 2020). In addition, it provides capacity modification factors for protected through, protected left, and permissive left turn movements at signalized intersections. AMS can be used to quantify ATV impact on traffic flow breakdown measures such as the occurrence, severity, duration, and intensity of the bottleneck, and formed shockwaves. The above improvements are expected to improve other key performance indicators such as travel time, travel time reliability, delay, number of stops, percentage time in congestion, travel time reliability indices, and so on.

It is recognized that safety is an important factor in evaluating the impacts of ATV, considering that these technologies will be able to reduce or eliminate crashes that are due to human error, depending on the levels of automation. These measures are the most difficult to estimate using simulation, considering that in microscopic simulation, the analyst usually assumes that drivers are "safe" drivers and that they conduct various activities such as car following, lane changing, merging, and gap acceptance in a safe manner. However, in many cases, the analyst can assess the impacts of ATVs and associated applications using surrogate measures based on the trajectories produced by microscopic simulation models. Further discussion of safety assessment is presented when discussing the Alternative Analysis step in this document.

Sustainability is also an important consideration when setting the measures to assess the environmental impacts of ATVs, considering the smoother operations associated with ATVs. The estimation of the changes in pollutant emission can be estimated by providing inputs to models like the MOVES model developed by the Environmental Protection Agency (EPA), based on processing the trajectories of the simulated vehicles are estimated. It should be mentioned that the sustainability metrics will be also significantly impacted by electric vehicles that are expected to increase their market penetrations in the next few years.

4.1.6. Data Requirements and Availability

The identification of the data requirements, availability, and methods for filling the data gaps are critical considerations in the planning and when scoping the project and selecting the modeling approach for the project (Wunderlich et al., 2017). As will be discussed later in a separate section of this document, various additional types of data are needed for design, calibration, and analysis of ATVs. Analysts need to examine the data requirements and availability at the scoping stage to reduce the risks associated with ATV modeling. This is consistent with the data-driven analytic project scoping process recommended in "Scoping and Conducting Data-Driven 21st Century Transportation System Analyses" (Wunderlich et al., 2017).

The development of parameters for modeling ATV requires *trajectory level* data (high resolution data) for traditional vehicles (TVs) as well as ATVs. Parameter calibration may undertaken directly by the analyst or utilizing parameters developed by others. In this regard, the analyst needs to examine the default microscopic traffic parameters in the utilized tools and models and how these parameters were derived. In some cases, the parameters have been selected based on real-world data collected from field deployment or observing ATVs on test tracks. Abbas et al. (2020) refer to this type of data as encapsulated data. For example, the VISSIM microscopic simulation tool provides default car-following parameters of ATVs based on the CoEXist project in Europe. The analyst needs to examine any encapsulated data in the model and determine if it is adequate for the analysis. When the encapsulated data are not available or not adequate, then the analyst needs to borrow the traffic flow parameters from previous studies, utilize data collected and archived by others, and/or collect data based on a data collection plan. Further discussion of data collection is presented later in Section 4.2. and calibration is presented in section 4.4.

4.1.7. Tool Selection

The next step in the process is tool selection based on the study scope, constraints, data availability, and other factors discussed earlier.

At a macroscopic level, the HCM6.1 provides tools for evaluating the impact of ATVs on various facilities as a function of ATV market penetration and anticipated behavior (Adebisi et al., 2020). These tools were developed using data obtained based on simulation modeling using the VISSIM microscopic simulation tool, with specific assumptions regarding the behavior of ATVs. The user should become familiar with those assumptions before relying on results obtained by these tools. The tools are developed for freeways (basic freeway segments, merge segments, and weaving segments) and intersections. Most importantly, the simulations developed in VISSIM consider two specific types of ATV technologies: Cooperative Adaptive Cruise Control (CACC) and Advanced Merging (AM). CACC simulation was based on a previously developed model and platoon formation rules and assumptions. AM was simulated based on VISSIM's logic, which relies on the creation of gaps on the mainline to accommodate the merging vehicles.

Based on several scenarios implemented in VISSIM, the researchers provide tables of capacity adjustment factors and the corresponding regression models that can be used for an HCM analysis. As indicated earlier, these tables and the respective tools provided by the HCM can be used if the assumptions used in their development (CACC and AM) are compatible with the objectives of the study. However, it is not clear whether real-world ATVs will follow the CACC and AM rules assumed in this analysis.

If the assumptions used in the HCM are not compatible with the objectives of the study, it is recommended that microscopic simulation tools be used directly, and adapted accordingly. Further detail on the use of microscopic simulators may be found in section 4.3.

4.2. Data Availability and Collection

4.2.1. Data for Mixed Traffic

The availability of real-world data for CAVs, AVs, and CVs operating in mixed traffic conditions remains sparse. Our review highlights two real-world datasets for CVs and AVs and one OEM dataset for AVs. However, the review did not find any existing real-world data set for real-world deployment of ATVs. This section briefly describes the available datasets containing information about AVs or CVs operating with TVs.

CV Pilot Data

Connected vehicles provide important information to support real-time management of traffic operation and also for off-line analysis of traffic operations. CV data generated from vehicles are transmitted using messages communicated utilizing cellular communication (C-V2X) or dedicated short-range communication (DSRC). The CV message formats are specified in the Society of Automotive Engineers (SAE) J2735 standards (SAE International, 2016) and various SAE J2945 standards. The basic safety message (BSM), specified in J2735, which contains vehicle safety-related information, is broadcasted to surrounding vehicles, but can be also captured by the infrastructure. The BSM, as defined in the J2735 standards, consists of two parts. Part 1 is sent in every BSM message broadcasted 10 times per second. It contains core data elements, including vehicle position, heading, speed, acceleration, steering wheel angle, and vehicle size. BSM Part 2 consists of a large set of optional elements such as precipitation, air temperature, wiper status, light status, road coefficient of friction, Antilock Brake System (ABS) activation, Traction Control System (TCS) activation, and vehicle type. However, a large proportion of these parameters are currently unavailable from many vehicles, and they are not expected to be available in the near future. Connected vehicle data can be captured by a roadside unit or can be sent to the cloud for processing and use.

There has been limited use of data from large-scale CV deployments in estimating and predicting performance measures. Many of the existing studies use simulation outputs to examine the use of CV to examine this estimation and prediction. Recently, CV data became available from the Connected Vehicle Pilot Deployment Program sponsored by the USDOT, which is a national effort to deploy, test, and operationalize CV applications (USDOT, 2019). The USDOT selected three sites for the pilot CV deployment. These sites are New York City, New York; Wyoming; and Tampa-Hillsborough Expressway Authority (THEA), Florida.

TAMPA CV Pilot

Starting in September 2015, THEA and the USDOT implemented the THEA-connected vehicle pilot program in downtown Tampa (including the adjacent segment of Selmon Expy) as a case study.

Figure 4-2 shows the THEA pilot location. This pilot has equipped buses, streetcars, and privately-owned vehicles with CV technology to enable them to communicate information with each other, as well as with the infrastructure and pedestrians who use an associated smartphone app (Vadakpat, 2018; USDOT, 2017). The pilot aimed at deploying onboard CV units on 1,600 privately owned vehicles, 10 buses, and 10 streetcars. Forty roadside units were installed at the busiest intersections. As shown in Table 4-2, the THEA Pilot includes the implementation of multiple applications with the aim to relieve congestion and reduce collisions. The THEA Pilot employs Dedicated Short-Range Communication (DSRC) to enable data transmissions among a variety of CV devices (See Table 4-2).

Figure 4-2: Connected vehicle pilot deployment in downtown Tampa (USDOT)

Table 4-1. THEA Pilot Site CV Devices

Tampa (THEA) – Devices	**Estimated Number**
RSU	47
Vehicle Equipped with OBU	~1,000
HART Transit Bus Equipped with OBU	10
TECO Line Street Car Equipped with OBU	8
Total Equipped Vehicles	~1,018

Source: USDOT

The THEA pilot includes the deployment of several V2V and V2I applications to enhance mobility and safety (see Table 4-3).

Table 4-2. THEA Pilot Site CV Applications

Category	THEA – CV Application
V2I Safety	End of Ramp Deceleration Warning (ERDW)
	Wrong Way Entry (WWE)
	Pedestrian Collision Warning (PCW)
V2V Safety	Emergency Electronic Brake Lights (EEBL)
	Forward Collision Warning (FCW)
	Intersection Movement Assist (IMA)
	Vehicle Turning Right in Front of a Transit Vehicle (VTRFTV)
Mobility	Intelligent Traffic Signal System (I-SIG)
	Transit Signal Priority (TSP)

Source: USDOT

4.2.2. Data Description

The available CV devices allow the generation and collection of data that consist of records with a resolution of 10 Hz. The generated data include the Basic Safety Message (BSM), Signal Phasing and Timing Messages (SPaT), and Traveler Information Messages (TIM) which are available via either the web interface to download individual batched data files or, by using the ITS data Sandbox Tool. The ITS data Sandbox have the data stored in the cloud in a structure that simplifies the accessibility to the data. An example of the hierarchy assigned to the data is shown below.

{Source_Name}/{Data_Type}/{Year}/{Month}/{Day}/{Hour}

- {Source_Name}: The data producer of the pilot. e.g., THEA.
- {Data_Type}: The message type of the data. Acceptable values: BSM, TIM, SPAT.
- {Year}: Four-digit year value based on the metadata.recordGeneratedAt field in the record (e.g., 2019). Based on UTC time.
- {Month}, {Day}, {Hour}: Two-digit month/day/hour value based on the metadata.recordGeneratedAt field in the record (e.g., 01). Based on UTC military time.

The data available in the ITS data Sandbox tool can be obtained in the form of a JSON file containing multiple messages together in one file. The message types available in the THEA CV Pilot are compliant with the Society of Automotive Engineers (SAE) J2735 and J2945/1 standards. These messages are detailed in the following subsections.

Basic Safety Messages (BSM)

The main purpose of the basic safety messages is to generate and exchange data of the vehicle current attributes. The BSMs are generated by the OBU and transmitted to the RSU. These roadside units are located throughout the study area of the Tampa CV Pilot. A summary of available fields on the BSM files is shown in Table C-1 in Appendix C (under separate cover).

Signal Phasing and Timing (SPaT) messages

SPaT messages are generated by roadside equipment at signalized intersections to be received by CVs. They are used to communicate the current status at signalized intersections. SPaT messages are transmitted by the RSUs. The fields in the SPaT messages are compliant with the SAE J2735 standard and include information such as the timestamp, intersection ID, controller status, current signal phase, and lane identification. A description of the fields available in the SPaT files is shown in Table D-1 in Appendix D (under separate cover).

Traveler Information Messages (TIM)

TIM messages consist of packets of data that are transmitted from the RSUs to be received by vehicles equipped with OBUs. The purpose of the TIM messages is to transmit relevant traffic information by providing situational awareness and warnings to the drivers. The fields available in the TIM messages follow the SAE J2735 standard. Some of the relevant fields include roadside unit ID, timestamp, message count, traveler location, speed limit cautions, messages related to work zone signs and directions, and speed recommendations. A summary of the available fields is shown in Table E-1 in Appendix E (under separate cover).

4.2.3. OpenACC Database

OpenACC is an open-access database of different car-following experiments involving 28 vehicles, 22 of which were equipped with state-of-the-art commercial ACC systems. Experiments were carried out in the framework of four test campaigns. The campaigns have been designed to study, among other things, vehicle dynamics in real-world conditions, the behavior of ACC systems, and car-following patterns under different driving conditions. This effort implements a common data structure across the four different tests locations in order to facilitate comparison between the different campaigns, vehicles, systems, and specifications. The complete data are published as an open-access database (OpenACC) available to the research community. As more test campaigns are carried out, the OpenACC will evolve accordingly. The activity is performed in the framework of the OpenData policy of the European Commission Joint Research Centre with the objective to engage the whole scientific community towards a better understanding of the properties of ACC vehicles in view of anticipating their possible impacts on traffic flow and preventing possible problems connected to their widespread introduction. In this light, OpenACC, over time, also aims at becoming a reference point to study if and how the parameters of such systems need to be regulated, how homogeneously they behave, how new ACC car-following models should be designed for traffic microsimulation purposes, and what are the key differences between ACC systems and human drivers. The vehicles involved in the OpenACC experiment are described in Table 4-4. The test sites used to conduct the experiment are shown in Figure 4-4. As mentioned earlier, the dataset has a 10-Hz resolution of real-world AV trajectory data. An example of the columns contained in the .csv files of the openACC database is given in Table 4-5.

Table 4-3. The Main Specifications of the Vehicles Involved in the OpenACC Experiments

Vehicles	Max power (kW)	Drive-Fuel	Engine displacement (cc)	Battery capacity (kWh)	Propulsion type	Top speed (km/h)	Model year
(L) Fiat (500X)	103	diesel	1956	–	ICE	190	2016
Volvo (XC40)	140	diesel	1969	–	ICE	210	2018
(L) VW (Polo)	63	Gasoline and liquid propane gas	1390	–	ICE	177	2010
Hyundai (Ioniq hybrid)	104	gasoline	1580	1.56	HEV	185	2018
(L) Mitsubishi (SpaceStar)	59	gasoline	1193	–	ICE	173	2018
KIA (Niro)	77.2	gasoline	1580	8.9	PHEV	172	2019
Mitsubishi (Outlander PHEV)	99	gasoline	2360	12	PHEV	170	2018
Peugeot (5008 GT Line)	130	diesel	1997	–	ICE	208	2018
VW (Golf E)	100	electricity	–	35.8	BEV	150	2018
Mini (Cooper)	100	gasoline	1499	–	ICE	210	2018
Ford (S-Max)	110	diesel	1997	–	ICE	196	2018
(L) Audi (A8)	210	diesel	2967	–	ICE	250	2018
Tesla (Model 3)	150	electricity	–	79	BEV	210	2019
BMW (X5)	195	diesel	2993		ICE	230	2018
Mercedes (A Class)	165	gasoline	1991	–	ICE	250	2019
Audi (A6)	150	diesel	1968	–	ICE	246	2018
(L) Smart (BME Addv)	–	–	–	–	–	–	–
(L) Skoda (Octavia RS)	180	gasoline	1984	–	ICE	250	2019
Tesla (model X)	386	electricity	–	90	BEV	250	2016
Tesla (model 3)	250	electricity	–	79	BEV	250	2019
Tesla (model S)	244	electricity	–	75	BEV	225	2018
Mercedes-Benz (GLE 450 4Matic)	270	gasoline	2999	31.2	HEV	250	2019
Jaguar (I-Pace)	294	electricity	–	90	BEV	200	2019
BMW (I3 s)	135	gasoline	647	33.2	HEV	160	2018
Audi (E-tron)	300	electricity	–	83.6	BEV	200	2019
Toyota (Rav 4)	115	gasoline	2487	41.8	HEV	180	2019
Mazda (3)	96	gasoline	1998	–	ICE	197	2019
Audi (A4 Avant)	140	gasoline	1984	0.69	HEV	238	2019

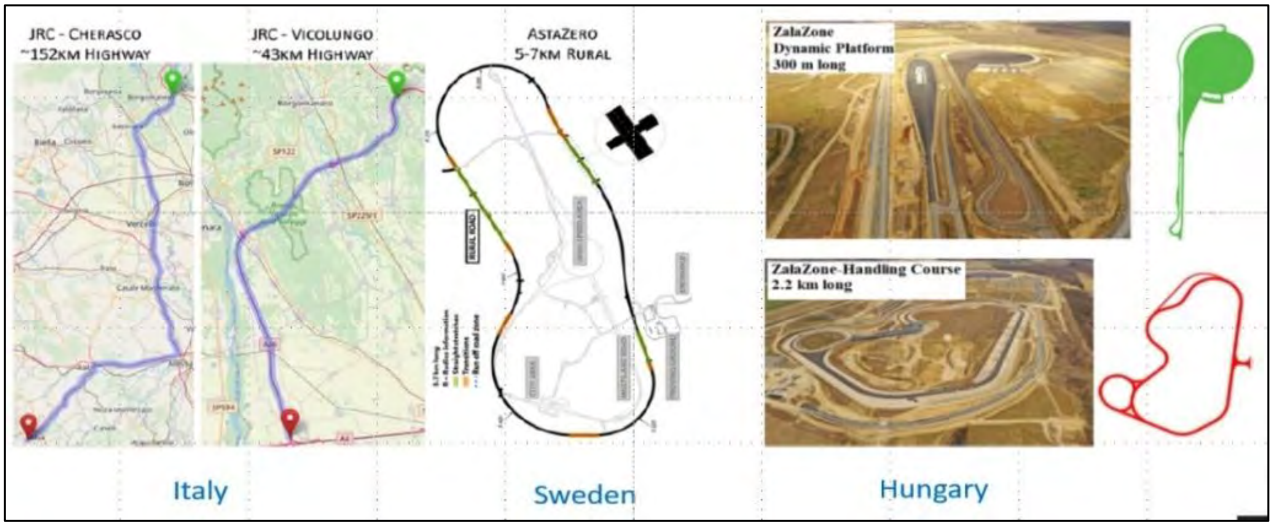


Figure 4-3: **Test sites** for the **OpenACC** experiments (Makridis et al., 2021)

Table 4-4. Dataset Column Description (Makridis et al., 2021)

Column ID	Description	Units
Time	Common time frame for all vehicles	*s*
Speed	Raw Speed (Doppler)	*m/s*
Lat	Latitude	*rad*
Lon	Longitude	*rad*
Alt	Altitude	*m*
E	East (x) coordinate in the local ENU plane (common center for all vehicles)	*m*
N	North (y) coordinate in the local ENU plane (common center for all vehicles)	*m*
U	Up (z) coordinate in the local ENU plane (common center for all vehicles)	*m*
VE	Speed in the East direction of the local ENU plane	*m/s*
VN	Speed in the North direction of the local ENU plane	*m/s*
VU	Speed in the Up direction of the local ENU plane	*m/s*
IVS	IVS computed from raw GNSS data after bumper to bumper correction.	*m*

4.2.4. Cited OEM Parameters for Automated Vehicles

The automobile industry is making substantial progress in terms of launching AVs. Table 4-6 lists a sample of the automobiles' manufacturer settings that are related to automated driving features. The first column shows the brand or manufacturer. The "Distance Levels" attribute refers to the options that the manufacturers are providing to the users regarding following distance (or time) from a lead vehicle. It is unclear whether distance or time are meant in this column. It may be a simple grading from very aggressive to very conservative. For example, General Motors is providing four distance options for its users. If the user choses distance level 1 that means that the vehicle will follow the lead vehicle with the minimum time gap option available. However, if the user chooses distance level 4, the car will follow the lead vehicle with the maximum time gap option available. The next column shows the "Range" attribute of the available *time gap* options. The "Minimum Speed" attribute in the next column indicates the required minimum speed above which the vehicle's automated driving features can be engaged. The technology column shows the car-following that is used for automated driving. It is clear that there are multiple variations both in the technology, when it is engaged, and the level of car-following schemes that will be available to the consumer. As related to model and simulation, what this implies is a high level of heterogeneity across vehicles of the same class (in this case AVs) that must be represented in the model as well.

In summary, real-world data exist that can support simulation model development and validation, although large scale CAV (in platoons) data in the US is generally lacking. Between the pilot CV data, the mixed AV and TV car following field tests, and the range of AV parameters contemplated by the various OEMs, the research team expects to be able to use those datasets for improved ATV modeling in microsimulation in phase 2 of this research.

Table 4-5. OEM Parameters for AVs

Make/Model	Optional Distance Levels	Gap Range	Minimum speed to Activate	Technology
Volvo (Volvo, 2020)	1 to 5	1-2.5 sec	20 mph	Adaptive cruise control
Tesla (Tesla, 2020)	1 to 7	Not reported	45 mph	Traffic aware cruise control
Honda	1 to 4	1.1–2.9 sec	25 mph	Adaptive cruise control
Mercedes (Mercedes, 2020)	1 to 5	Not reported	15 mph	Dystonic plus
BMW (BMW, 2020)	1 to 4	Not reported	20 mph	Active cruise control
Hyundai	1 to 4	82–172 feet at 60 mph	0 mph	Smart cruise control
General Motors	1 to 3	Not reported	Not reported	Adaptive cruise control
Ford	1 to 4	82 to 150 ft at 62 mph	20 mph	Advanced driving assistance system
Cadillac (Cadillac, 2020)	1 to 3	1.1 to 2.5 sec	Not reported	Adaptive cruise control

Make/Model	Optional Distance Levels	Gap Range	Minimum speed to Activate	Technology
Chevrolet	1 to 3	Not reported	25 mph	Adaptive cruise control
Chrysler (Chrysler, 2020)	1 to 4	Not reported	25 mph	Adaptive cruise control

4.3. USING SIMULATION TO EVALUATE ATVS

When considering microscopic simulation for the evaluation of ATVs, most analysists will utilize commercially available software. In general, the analyst has the following four options when using a commercially available microscopic simulator:

- Adjust the existing models through changing specific simulation parameters (this is the approach followed to replicate CACC and develop the HCM models)
- Use new CV models (developed by the vendor) that are internal to the model (this is the approach followed to replicate AM using VISSIM's existing algorithms to develop HCM models)
- Use new ATV models (developed by the vendor) that are external to the model
- Use external tools to model ATV movement, or create new models within or integrated with the tool.

When selecting a specific simulation model or external tool the analyst should match the project planning, objectives, identified features, and needed performance metrics identified as described in Section 4.1 with the capabilities of the various available models. In the selection of a tool it is important to consider the key ATV features that must be captured by the analysis versus those that are desirable. The selected tools at a minimum should provide the required features. At this stage in ATC model development the inclusion of desirable features should made with some caution, as unnecessarily broadening the aspects of ATV captured may introduce additional error or uncertainty in the model results. For example, if a demand may be assumed to be fixed than incorporating a modeling capability that accounts for ATV related impact on demands may be unwise.

The remainder of this section discusses several microscopic simulators and their ability to replicate ATV behavior from the perspective of the four options listed above.

AIMSUN (https://www.aimsun.com/)

The tool provided by Aimsun (a Siemens company) has evolved from a microsimulator to a full suite of products related to mobility. The products include Aimsun-Next, Aimsun-Auto, Aimsun-Live, and Aimsun-Ride. The first two are the most relevant products for this research.

AIMSUN-NEXT (https://www.aimsun.com/aimsun-next/) is a microscopic simulator for evaluating traffic operations for freeways as well as arterial corridors and networks. It includes microscopic simulation, meso- and macro- functionalities, as well as travel demand modeling. Regarding microsimulation components, its car-following, lane-changing, and gap acceptance parameters can be modified when seeking to replicate the movement of ATVs. It is also possible that Aimsun-Auto allows for integration of AV logic directly into the microscopic simulator, but that is not explicitly discussed on the website.

AIMSUN-AUTO (https://www.aimsun.com/aimsun-auto/) is a new software platform developed specifically for the simulation of AVs. According to the developers, Aimsun-Auto is appropriate for developers interested in evaluating AV under a variety of scenarios.

CORSIM (https://mctrans.ce.ufl.edu/mct/index.php/tsis-corsim/features/corsim/)

CORSIM is a microscopic simulator originally developed by FHWA and now maintained and sold by McTrans at UF. It is an older product developed before ATVs were considered as a potential alternative for transportation. Similar to AIMSUN, its car-following, lane-changing, and gap acceptance parameters can be modified when seeking to replicate the movement of ATVs. It also has the ability to use an external application programing interface (API) to bypass existing models. Its visualization has been used to show the movement of ATVs on freeways using an external optimization program (Letter and Elefteriadou, 2017).

SUMO (https://www.eclipse.org/sumo/)

SUMO (Simulation of Urban Mobility) is an open-source microscopic simulation package. According to the website, it can replicate automated driving, and it can simulate vehicle communications as well as various traffic management strategies. It has been used in several FHWA projects for evaluating the CARMA platform (USDOT 2021).

Transmodeler (https://www.caliper.com/transmodeler/default.htm)

Transmodeler is a geographic information system (GIS)-based microscopic simulator that can be integrated with TransCAD to conduct travel demand forecasting jointly with traffic operational evaluations. It allows for different car-following algorithms by vehicle type, and thus it can allow for the inclusion of ATVs with the respective behavior.

PTV VISSIM (https://www.ptvgroup.com/en/solutions/products/ptv-vissim/)

PTV VISSIM is a traffic microscopic simulator that has been used to replicate the movement of ATVs in several studies. Its vehicle behavior parameters can be modified when seeking to replicate ATV movement. In addition, its external API can be used such that it can use other externally developed models. It was used to develop the HCM models described earlier (Adebisi et al., 2020; Adebisi et al., 2021). It was also used in the CoEXist project to develop microscopic simulation guidance for ATVs (Sukennik et al., 2018).

Table 4-1 provides a summary of the capabilities to replicate ATV movement for each of the packages discussed above, along with available resources, case studies, and default values used for ATVs.

Table 4-6. Software Capabilities to Replicate ATV Movement

	Website	ATV treatment (CV, AV, CAV)	Recommended default values by developer for ATV treatment?	Recent example applications found in the literature
AIMSUN	aimsun.com	AV	None found	Rahman et.al., 2021; Cummins et al., 2020; Mesionis et al., 2020
CORSIM	mctrans.ce.ufl.edu/ tsis-corsim/	None found	None found	None found
SUMO	eclipse.org/sumo/	CV, AV, CAV	None found	Zuo et al., 2020; Richter, G. et al., 2019; Li and Wagner, 2019; Wagner, 2016
Transmodeler	Caliper.com/ transmodeler	AV	None found	Stabler et al., 2018; Bradley et al., 2017
VISSIM	www.ptvgroup.com/ en/solutions/products/ ptv-vissim/	AV	Sukennik et al, 2018	Hurdado-Beltran & Rilett, 2021; Srisurin, P. & Kondyli, 2021; Bhargava et al., 2020

4.4. VERIFICATION, CALIBRATION, AND VALIDATION

Nearly all modeling efforts will include some level of calibration. However, what is meant by calibration and what calibration should include are not always clear. To help clarify, there are actually three separate, but related, processes that should be undertaken for each model: verification, calibration, and validation. Each is critical to the successful design, construction, and use of a model. Briefly, verification is the confirmation that a model has been constructed as intended (e.g., a roadway that is 3 lanes in the field is 3 lanes in the model); this is the debugging step of the model construction. Calibration is the process of adjusting underlying parameters of a verified model, e.g., car-following parameters, lane-changing behavior, pedestrian speed distribution, merging position, etc., to be representative of that in the field. Validation confirms that the model is an "accurate representation of the actual system being modeled" (Law, 2013), i.e., the model approximately matches field conditions. Loosely, in a transportation simulation, calibration is typically directed at behaviors, e.g., the aggressiveness of drivers, while validation is concerned with the performance of the model, e.g., what is the travel time on a corridor. For example, in most microscopic traffic simulations there is no "travel time parameter." Rather, the vehicle car-following parameters are calibrated (hopefully using speed, headway, etc., data from the field!) and the model is validated by considering how closely the simulated travel times match the field. Calibration and validation can be, and often are, an iterative process. Additional detail is offered on each process in the following.

4.4.1. Verification

Verification is the process of confirming that the model is built and operates as intended. This differs from calibration and validation; verification only means the model is qualitatively doing what you think it is doing, not that the model is necessarily correct. Examples include: are the number of lanes on a link as in the field; do the lane disciplines (exclusive or shared) match the field configuration; are vehicles discharging when intended; is the signal timing programmed as intended; are the volume inputs correctly entered; are the desired vehicle routes all placed, etc. Verification requires carefully stepping through a model and ensuring that each model element is constructed and operating as intended. This is particularly critical for ATV applications where the model developer may be new to CAV or CAV capabilities may be new to the model. It is imperative that the implementation be thoroughly checked.

Thus, after the initial model construction, a deliberate verification of each model element is critical. Unfortunately, and all too often, model developers will seek to use calibration techniques to account for what is actually an underlying issue in the model development. While it may be possible to calibrate a model with an error to give the expected results for an existing condition, the likelihood is that when then using the model to conduct scenario analysis that the results will be unreliable. The importance of verifying a model cannot be overstated.

4.4.2. Calibration

Calibration is the adjustment of the underlying parameters of a verified model to ensure that the model matches the real-world observations. For example, in VISSIM this is often taken to be a calibration of the underlying Wiedemann car-following parameters. However, it must be stressed that underlying traffic flow parameters represent only one part of calibration. A model developer should not solely focus on traffic flow parameters (e.g., saturation flow rate and gap acceptance). Often the desired model performance can be achieved through calibration of vehicle response to geometry (i.e., how does a vehicle response to a taper section), lane changing, stopping distance, routing, lane utilization, and other model elements. The same would apply to parameters related to vehicles and other user (pedestrians and bicyclists) characteristics. These parameters also often have the advantage of being location specific, thus an adjustment in one location does not necessarily change the behavior in other locations. For instance, in VISSIM, adjusting the Emergency Stop and Lane Change Distances, or using the alternative link-connector layouts, may provide more valid performance than adjusting the underlying Wiedemann parameters.

Calibration may require updating the underlying model construction (e.g., link-connector layout in VISSIM) as well as model parameters. For instance, when constructing a model, a guiding principle is to develop the simplest model necessary, but no simpler, to address the model objectives. However, during calibration, it may be realized that a more complicated model construction is required. For example, in an initial model construction, a relatively simply link-connector layout may be utilized for two closely spaced intersections. However, it may be found that the simple layout does not adequately reflect field observations and a more complex representation of the intersections is necessary. It may be debated if this falls under verification or calibration; however, semantics aside, during the verification-calibration-validation process, a model developer should be prepared to adjust the underlying model construction. Parameter adjustment should not be used to "force" behaviors that are better resolved through model layout adjustments.

4.4.3. Validation

Validation is the process whereby the analyst seeks to confirm that a verified and calibrated model is valid. (Generally, when considering verification vs. validation, input data are *verified*, and output data and performance metrics are *validated*.) Valid is typically defined according to some set of performance metrics, e.g., the travel time on selected routes are within some acceptable percentage of field travel times, the vehicle counts at critical locations approximately match field (or expected) conditions, etc. At a minimum, measures that will be used for decision making (e.g., are the queues and travel times acceptable, is the throughput of an interchange sufficient, etc.) should be included in the validation. Essentially, validation seeks to confirm that a model matches (approximately) the real world.

Typically, initial validation checks will occur where the modeler utilizes the model program (i.e., vendor) defaults. Based on this initial validation check, underlying model parameters will be selected for calibration. For instance, if the model is processing too few (or too many) vehicles overall, it may be decided to calibrate the traffic flow models; however, if issues are limited to certain locations, then site specific parameters may be calibrated. More detail on calibration is provided in the next sections.

Where real world conditions do not exist, validation may seek to confirm that aspects of model performance match reasonable expectations. This will often be the situation for ATV models, at least early in the technology deployment. That is, while one cannot field-validate the travel time for a technology that is not yet implemented (or at least not widely implemented), it is possible to confirm that some parameters such as the free flow speed – in the case of ATVs – will match the speed limit (or expected speed). Other measures, such as saturation flow, will need to be based on published expected saturation flows with the given technologies. However, calibration of such model aspects provides an opportunity for a sensitivity analysis of the various parameters and the development of an envelope of possible model environments.

As good practice in model development, the data used to construct and calibrate a model should not be used to validate the model. However, it is recognized that transportation simulation modeling efforts often do not have multiple available data sets or a data set that can be readily split into multiple data sets, so the data set used for validation may also used for calibration. While this may need to be the accepted process, it should be understood that this is not as robust as utilizing separate data sets for validation and calibration. For instance, if there is an underlying verification issue that is "resolved" through calibration, the use of a secondary data set for validation may help uncover the issue. Additional discussion is provided in the Calibration Guidance Data section below. The interested reader is referred to Law (2013) for a detailed discussion on validation.

4.4.4. Calibration Guidance

This report does not recommend specific methods for calibration; however, numerous examples of simulation and VISSIM calibration methods exist, such as Gomes et. al (2004), Law (2013), Park et. al (2006), VDOT (2020), and Wunderlich et al. (2019). Approaches to calibration range from iterative manual approaches to the use of genetic algorithms to search for optimal parameter values. While this report does not recommend a specific method, the following provides high-level guidance for the general application and review of a model calibration, particularly when considering emerging technologies such as ATVs. Before undertaking calibration of a model where ATVs or other emerging technologies are being incorporated, the model developer should make every effort to be familiar with the literature in these areas. Main points in this outline are further discussed below.

Key Calibration Steps include:

- Calibration objectives, including:
  - Performance measures of interest
  - Allowable deviation from the field or expected conditions
- Base or existing network to be calibrated
  - Calibration conditions to be considered
  - Network boundaries
- The calibration method
- Locations in the model identified as critical
  - Bottlenecks
- Site field data to be collected
- Data that may be utilized from other locations
- Graphical representation of the calibration effectiveness

- Statistical analyses of the calibration effectiveness
- Sensitivity analysis to be undertaken
- Flexibility in calibration
- Items specific to the calibration of the given network
- Documentation

Calibration objectives should be clearly defined.

Calibration objectives will help focus the field and simulation data collection and analysis. Figure 4-4 contains some of the more common calibration targets. The targets are generally appropriate for a model with or without ATVs.

Calibration item	Calibration Target/Goal
Capacity	Simulated capacity to be within 10% of the field measurements.
Traffic Volume	Simulated and measured link volumes for more than 85% of links to be: ▪ Within 100 vph for volumes less than 700 vph ▪ Within 15% for volumes between 700 vph and 2700 vph ▪ Within 400 vph, for volumes greater than 2700 vph.
	Simulated and measured link volumes for more than 85% of links to have a GEH* statistic value of five (5) or lower.
	Sum of link volumes within calibration area to be within 5%.
	Sum of link volumes to have a GEH* statistic value of 5 or lower.
Travel Time (includes Transit)	Simulated travel time within ±1 minute for routes with observed travel times less than seven (7) minutes for all routes identified in the data collection plan.
	Simulated travel time within ±15% for routes with observed travel times greater than seven (7) minutes for all routes identified in the data collection plan.
Speed	Modeled average link speeds to be within the ±10 mph of field-measured speeds on at least 85% of all network links.
Intersection Delay	Simulated and field-measured link delay times to be within 15% for more than 85% of cases.
Queue Length	Difference between simulated and observed queue lengths to be within 20%.
Visualization	Check consistency with field conditions of the following: on- and off-ramp queuing; weaving maneuvers; patterns and extent of queue at intersection and congested links; lane utilization/choice; location of bottlenecks; etc.
	Verify no unrealistic U-turns or vehicle exiting and reentering the network.

*GEH is an empirical formula expressed as $\sqrt{2*(M-C)^2/(M+C)}$ where M is the simulation model volume and C is the field counted volume.

Figure 4-4: Common model calibration targets (Florida, 2014; Table 7-7)

These targets should only be considered as guidance. The model developer and reviewing agency should determine which of these are most relevant for the subject project, determine the appropriateness of stated accuracy, as well as determine if other calibration targets should be considered. For instance, where the simulation is being developed for safety analysis, the calibration of accepted gaps may become more critical. Typically, as a minimum, calibration efforts should include traffic volumes, speeds, and travel times as calibration objectives. As discussed previously, the calibration objectives listed above are not directly calibrated (e.g., there is no “travel time parameter"), they are part of the validation measures by which the quality of the underlying model behavior calibrations are judged.

When considering ATVs, it may become necessary to consider additional calibration targets than those typically included. For instance, it is often stated in the literature that ATVs are expected to influence saturation flow rates and headways. The impact of ATVs on the simulation of these factors may be influenced by the CV penetration rate, by whether an ATV is following another ATV or a non-ATV, or by the aggressiveness of the ATV (see sections 1.4.1 and 1.4.2. for additional discussion). In addition, other ATV attributes may include earlier stopping (i.e., warnings provided to the ATV), cooperative lane changing, etc. While field data for calibration will likely not be available for some time, the model may be calibrated to expectations as found in the literature. For example, some of the available datasets described in Section 4.2 could be considered as providing some level of operational expectations under real world conditions.

Base or Existing Conditions Model(s) Calibration

It is often implicitly, or explicitly, stated that calibration is applied to base or existing conditions, with the calibrated parameters and then utilized for future or built conditions. However, when considering ATV (or other emerging technologies) this may not be a reasonable (or possible) assumption. That is, in most cases, the existing conditions will not include ATVs. While the existing model should be calibrated, additional calibration may be necessary for the built condition when ATVs are introduced. For instance, if saturation flow is a calibration objective (or validation measure), it will be necessary to calibrate the model for CV, CAV, and non-CAV headways, as well as possible lead-follower vehicle combinations, also depending on whether they operate in mixed traffic or exclusive right-of-way based on expectations from the literature. Thus, a potential order of calibration tasks may be to ensure a verified, calibrated, and validated existing model without ATV, then add ATV to that model and calibrate the ATV-specific elements. However, the final calibration should be the same across both the non-ATV and ATV alternatives.

The analyst or agency may wish to consider varying environmental, seasonal, or other conditions. For instance, it may be desired to calibrate a separate model for inclement conditions, for in-season and out-of-season in a high tourist area, nighttime vs. daylight (or glare conditions at dusk), weekend (majority non-familiar drivers) vs. weekday (majority familiar drivers), event traffic (i.e., the driving population near 50,000-seat stadium may have very different characteristics on game days than non-game days), etc. These varied conditions can merit unique calibration efforts and separate analysis. However, each calibration will require data for the given conditions; this will also potentially include a recalibration of the ATV parameters. For instance, ATV behavior may change under inclement weather conditions. The impact of varying conditions should not just be "assumed". The decision to calibrate separate models for different conditions should be determined prior to model development and, in the case of ATVs, based on literature or other resources being available to inform the calibration for the given condition. The FHWA Traffic Analysis Toolbox Part III: Guidelines for Applying Traffic Microsimulation Modeling Software (Wunderlich et al., 2019) provides extensive discussion and recommendations for these calibration issues.

Calibration Method

Numerous calibration methods exist, from entirely manual to full blown genetic algorithms. While a method is not recommended here, it is stressed that it is critical that the model user understand the approach selected, i.e., that it is not a "black box."

It is also recommended that all model calibration starts with model default traffic flow parameters. Where parameters are changed, the modeler should provide a justification for the change. It is recommended that the adjustments to any underlying parameters based in an effort to capture ATV behaviors be intuitively reasonable and not a result of a random combination of parameters. In addition, calibration should be based on replicate trials. It is not reasonable to assume that a model successfully calibrated for a single random seed is appropriate under multiple random seeds.

A stepwise approach through performance measures is often an efficient calibration technique. For instance, Mai et al. (2011) focuses calibration efforts first on volume, density, then speed, then travel time, queuing, weaving, and lane utilization. As stated earlier it is suggested to first calibrate for a non-ATV environment then address those model elements uniquely impacted by ATV. Attempting to calibrate multiple performance metrics simultaneously, particularly if utilizing a manual method, can lead to bouncing between solutions.

Critical Calibration Locations

Much of a calibration effort will focus on a combination of network sections and critical locations. These locations should be identified prior to model development. Critical locations commonly include major intersections, freeway interchanges, etc. Critical locations should include any bottlenecks within the model. Network measures typically include corridor travel times and throughput, critical routes through the corridor, etc. Calibration targets, such as those found in Figure 4-4 should be clearly identified prior to the calibration of the model. As stated previously, it is imperative the model developer be familiar with current ATV literature to aid in the selection of critical locations for calibration. For instance, if a ATV application applies to on-ramp weaving then these sections of the network should be selected for calibration.

Calibration Data

To the greatest extent possible, calibration and validation should utilize data from the existing site being modeled. For example, volume counts and queue length data should be obtained from the site. In some instances, it may be acceptable to use regional data. For example, the capacity of a ramp junction may be based on the known capacity of similar sites. However, when considering specific ATV application, field data may not be available. In those cases, it will be necessary to utilize values from the literature and technology developers to inform the calibration. Chapter 2 and Appendix A of this report site a number of references regarding the range of current assumptions; however, as stated previously, prior to a project model, developers should perform an updated review of latest literature for updated ATV expected behaviors.

As an aside, the use of the same data set for validation and calibration is often not raised as a significant issue in the development of off-the-shelf simulations (such as VISSIM, CORSIM, etc.) because the undertaken effort is not a simulation development in the purest sense. That is, the traffic flow algorithms, weaving logic, etc., are not being developed and coded as part of the modeling effort. For instance, in constructing a VISSIM simulation, the modeler is leveraging pre-existing model elements that have already been validated in many other models. Thus, such off-the-shelf model construction is primarily an application of existing simulation elements rather than a core simulation development effort, eliminating many of the pitfalls that separate validation data sets seek to address. However, we expect that developers of the off-the-shelf elements utilized multiple data sets. Likewise, if a modeler is developing their own ATV algorithms for implementation into an off-the-shelf simulation then multiple data sets to test the ATV aspect of the model may be critical.

Model Animation and Graphical Representations Performance Metrics

Viewing the model animation and the development of graphic representations of the model performance are critical to any calibration effort. Scatter plots, heat maps of speed over time, travel time histograms over time, graphical displays of queuing, the fundamental diagram, etc. quickly provide insight into the reasonableness of a model's operations. Special consideration should be given to developing graphics of and with ATV technology, as well as at different technology penetration rates, allowing the modeler (and end users of the simulation results) to better interpret the simulation findings.

Statistical Analysis

After the use of a graphical method, a statistical analysis of the calibration should be provided. Analysis may be based on percentage criteria as found in Figure 4-4 or more formalized goodness of fit tests. Typical goodness of fit methods include root mean square normalized error (RMSNE), correlation coefficient (CC), mean absolute percentage error (MAPE), and the Geoffrey E. Havers or GEH statistic. For additional detail on these methods please see Florida Department of

Transportation (2014), Mai et al. (2011), Law (2013), or any of the many guides on statistical tests. Even when using guidelines similar as those shown in Figure 4-4 users and reviewers must confirm that locations that fail to meet the guidance will not significantly impact model results. For example, if the speeds meet or exceed the required criteria at 85% of the links but one of the links not satisfied is a critical bottleneck ramp junction, additional calibration may be necessary.

Statistical tests provide a quantifiable measure of the calibration. Often a statistical test is treated as a numerical goal for calibration. However, regardless of the statistical test undertaken, it is critical to utilize visual inspection as the foundation of the assessment of the calibration accuracy. Should a statistical test show a calibration as "passed" but the graphical check raises concern, it is the graphical check that should drive the continuation of the calibration. (See aside at the end of this section for additional comments.)

Sensitivity Analysis

Model calibration may be improved through the use of a sensitivity analysis that covers uncongested and congested conditions. Certain model elements tend to influence stable flow operations while others have higher influence on unstable flow conditions. Low volume testing highlights issues regarding free flow speed, high speed weaves, actuated signal control, etc. High demand testing highlights issues regarding queue blockage (spillback out of turn bays, etc.), merge behavior under congested conditions, bottleneck capacity, etc. Regardless of the decision to utilize sensitivity testing, bottlenecks are locations that should receive additional attention during calibration if future conditions may experience congested or near-congested conditions; increasing the demand through these areas may be needed to ensure adequate capacity calibration.

Flexibility in Calibration

While calibration objectives, targets, critical ranges, etc. should be determined prior to the calibration effort, some flexibility must be recognized. In some circumstance, it may prove difficult or impossible to satisfy proposed calibration conditions; this may prove particularly true when considering emerging technologies such as ATVs where the field conditions are not available and the calibration may be dependent on findings for often conflicting literature. In such circumstances, the model developer and reviewing agency should consider the potential impact of the higher deviations from the field on results and recommendations. It should be determined if this is acceptable or if additional effort – or possibly a different analysis approach – is required. For instance, while a statement of absolute LOS may not be possible, will the model allow for a reasonable estimate of directionality of traffic performance changes in the build conditions? That is, will proposed changes improve or worsen traffic conditions.

Documentation

Any calibration effort should include detailed documents of the calibration.

4.5. Alternative Analysis

The sixth step listed earlier in this document, as drawn from Wunderlich et al. (2019), is alternative analysis. The following is a high-level discussion for alternative analysis when considering ATVs. Phase two of this project will provide significantly more detail and examples for such analysis.

In alternative analysis, as described in Wunderlich et al. (2019) and other sources, the analyst must model the various build alternatives under consideration as well as their associated demand forecasts. As with the no-build the alternatives analysis must account for the randomness derived from the driver behavior models. However, the potential for ATVs in any future vehicle stream provides a significant source of additional "driver" behavior uncertainty in build scenarios. Given the ongoing high state of uncertainty in ATV driving behavior characteristics and a similar level of uncertainty in the behavior of human-driven vehicles when interacting with ATVs, it is extremely difficult to incorporate ATVs into current planning and design processes with any sense of assuredness. In the near-term this uncertainty will likely only increase with the development of more ATV models, countless predictions of what vehicles will look like in the future, numerous ATV pilot deployment successes and failures, etc. Thus, an analyst will need to draw from the latest literature, ATV trends, etc. to reach the best estimate of which ATV and driver behavior models to include in the alternative analysis. While the ATV modeling approaches found in the literature and implemented in the various commercially available models will differ widely, there are several overarching vehicle behavioral components covered by each. The key components of most microscopic models are their approach to car following, platooning, and lane changing.

Car following refers to the behavior of a following vehicle behind a lead vehicle, within a lane. The output of a car following model is the following vehicle's acceleration, that is, should the following vehicle accelerate, decelerate, or maintain its current speed. There are enumerable approaches to developing car-following models, but commonly they consist of some function of a desired or minimum time gap, the spacing between vehicles, speed, and desired or maximum accelerations and decelerations. However, other parameters or traffic-condition characteristics may also be part of a car-following algorithm.

Platooning is arguably a special case of car following. However, platooning vehicles tend to travel in lock-step, that is, the reaction time between vehicles is practically (if not actually) reduced to zero. In addition, headways may be significantly lower than the minimum found in most HDV and ATV car following models. To implement platooning, it is assumed that the following vehicle is either connected (i.e., in communication) with the lead vehicle or has sufficient sensors to allow for a reaction time nearing zero seconds. Many ATV models will impose limits on the length of platoons. This may be either due to assumed technology limits or as a safety constraint where breaks in platoons are deemed necessary to allow for interaction with human-driven vehicles in a mixed-fleet environment.

Lane changing, while influenced by car following and platooning, is the process by which a vehicle decides whether and how to implement a lane change. Commonly, lane changing is considered as discretionary (e.g., a vehicle changes lanes to advance its position in the traffic stream) or mandatory (e.g., a lane change is required to enter a freeway from an on-ramp). Lane change models may also incorporate behavioral changes, such as cooperative breaking, by the vehicle in the destination lane. Lane-changing models are critical in multilane facilities and often a determining factor in the capacity of bottlenecks, weaving areas, merges, diverges, etc.
This document cannot identify the best ATV behavior models to utilize in future alternative analysis, as these will likely change over time as technologies and regulations evolve. However, given the preceding discussion a sense of the ultimate ATV behaviors may be made by tracking three primary leading indicators:

1. As ATV tests continues, or low market penetration occurs, are human-driven vehicle (HDVs) to ATV interactions tending to be cooperative or aggressive?
2. What are the headways being adopted by ATV manufactures, and what are the potential regulatory requirements?
3. Are platoons implemented in ATVs, and if so, what are the spacing requirements and maximum length restrictions, which are again potentially manufacturer and/or regulatory-agency driven?

An analyst must seek to gain the latest knowledge (or sense) regarding these indicators. As the direction of each of these indicators becomes clearer, the analyst will then be able to select models (or model parameter sets) that reflect these trends, allowing for an alternative analysis that reflects the current best understanding of likeliest ATV behaviors.

Once a model has been selected for the alternative analysis the analyst may wish to select (project analysis resources allowing) an ATV behavior model that provides better operational improvements (e.g., higher capacities, lower congestion, etc.) and an ATV model that provides lower operational service (which may or may not be better than no ATVs in the traffic stream). By undertaking the alternative analysis as discussed in Wunderlich et al. (cite) (or other relevant documents) and incorporating the ATV behavior models the analyst can model the most likely future as well as reasonable bounds.

It is acknowledged that two key factors are not included in the preceding discussion. The first is penetration rate and the second is impact due to demand changes given the introduction of ATV. Incorporation of each of these in the alternative analysis may follow the above general procedure, seeking low, expected, and high levels for each. For instance, low, expected, and high ATV penetration rates, for the design year, could be drawn from Littman et al. (cite).

However, the clear drawback is that to include three levels for ATV behavior, penetration rate, and travel demand would result in an expansion of the original alternative analysis 27 fold, likely exceeding the resources of most projects. How, this analysis expansion may be reduced by testing the boundary conditions for each characteristic with only the expected condition of the other two characteristics, as seen in the table below, reducing the total increase to a multiple of seven.

	Characteristic			
		ATV Driver Model	Penetration Rate	Demand Forecast
Alternative	1	low	expected	expected
	2	expected	expected	expected
	3	high	expected	expected
	4	expected	low	expected
	5	expected	high	expected
	6	expected	expected	low
	7	expected	expected	high

Further reduction may then be made by eliminating alternatives of limited interest or where minimal difference are expected. This may include an initial sensitivity analysis of the effect of each retaining only those levels that are most influential in the final analysis.

5. CASE STUDIES

This chapter describes a series of case studies that utilize microscopic simulation models to model various CV, AV and CAV applications. All of these case studies were done by the research team to demonstrate the use of simulation modeling to assess ATV operations and associated applications. The simulated applications in this chapter are categorized as arterial safety applications, arterial mobility applications, and freeway mobility applications.

5.1. Modeling Arterial Safety Applications

5.1.1. Red Light Violation Warning

Problem Statement

Red-Light Violation Warning (RLVW) is a connected vehicle (CV) application developed as a connected-vehicle-to-infrastructure (V2I) safety application to reduce red-light running and collisions at signalized intersections. This study utilized simulation to develop a method to evaluate the safety benefits of RLVW. Drivers' behavior in the dilemma zone is an essential parameter in the modeling of RLVW and significantly affects the probability of violating a red light. This behavior is mainly a function of the driver's stop-go probability decisions during the yellow interval. The accurate calibration of the probability distributions of this behavior in the utilized microscopic simulation model has a great impact on the validity of the RLVW simulation results. The first objective of this study is to demonstrate a method for such calibration to support the simulation modeling of RLVW. The second objective is to utilize the calibrated model to assess the potential impacts of RLVW on safety.

Methodology

This research calibrated the microscopic simulation parameters which influence simulated driving behavior regarding whether to stop at or go through the intersection during the yellow interval. The data utilized in the calibration process were based on the probability of stopping, which were collected from the field in a previous study. Nonlinear programming was applied to solve the optimization problem, aiming at deriving the best combination of simulation model parameters to replicate the probability estimated based on the data observed in the field. The traffic microsimulation tool VISSIM was used to model the RLVW application in a connected vehicle environment through the COM API (see Figure 5-1, which depicts the implemented algorithm). To quantify the safety benefits, vehicle trajectories were post-processed using the Surrogate Safety Assessment Model (SSAM).

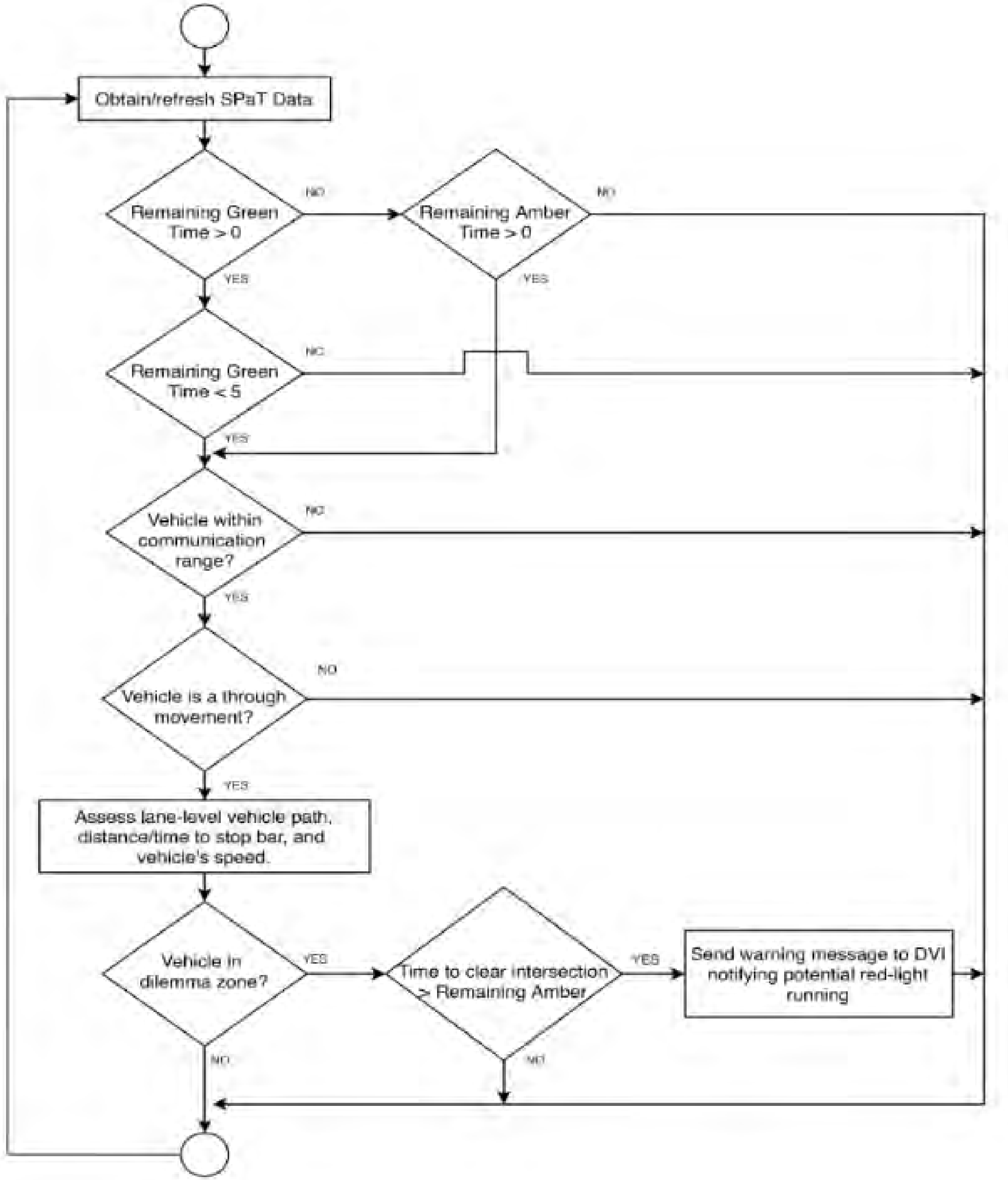


Figure 5-1: RLVW application algorithm

Findings

The study results confirmed that it is critical to calibrate the probability of stopping on yellow in the utilized simulation model to reflect real-world driver behavior when assessing RLVW impacts. Without calibration, the model was not able to assess the benefits of RLVW in reducing red-light running and right-angle conflicts. Based on the surrogate safety assessment measures, the calibrated simulation model results show that the CV-based RLVW can enhance safety at signalized intersections by approximately 50.7% at a 100% utilization rate of the application, considering both rear-end and right-angle conflicts. Figure 5-2 shows the probability of stopping resulting from the simulation model with and without calibration compared to estimates based on real-world data. Figure 5-3 shows the impact of RLVW on number of conflicts per hour with and without calibration.

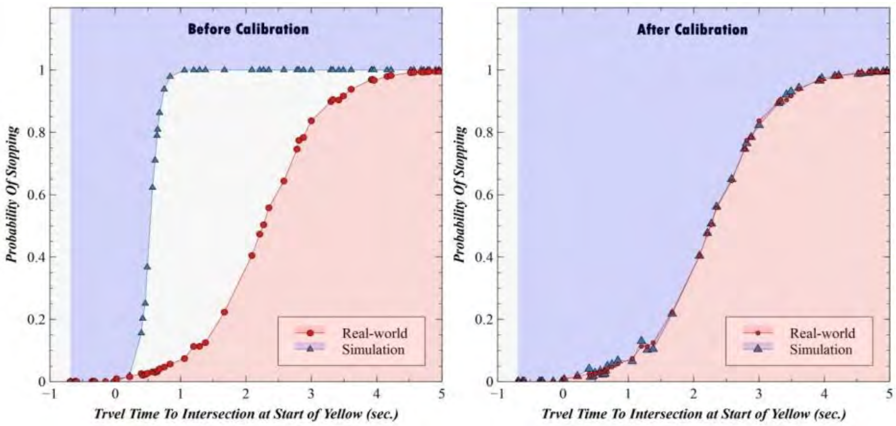


Figure 5-2: Simulation versus real-world probability of stopping

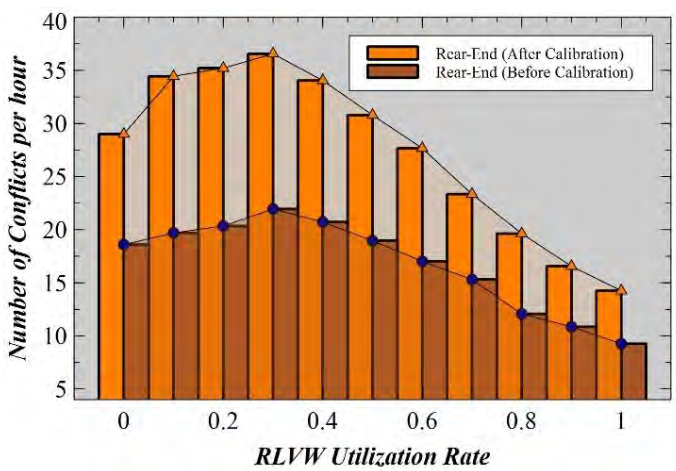


Figure 5-3: Impact of RLVW on number of conflicts per hour with and without calibration

5.1.2. Unsignalized Intersection Gap Assist

Problem Statement

Stop Sign Gap Assist (SSGA) is a connected vehicle solution that addresses the safety concerns of two-way stop-controlled (TWSC) intersections. The SSGA is designed to provide assistance to drivers on a minor road allowing their vehicles to more safely traverse or enter a major road. The application supports drivers' crossing decisions by providing advisory messages to vehicles on the minor road alerting them of the speeds and locations of the approaching vehicles on the major road. The SSGA application residing on the OBU uses this information to determine adequate and safe gaps for completing the maneuver. Thus, these applications improve safety at TWSC intersections by reducing the number of conflicts and crashes. The main goal of this study is to investigate the use of microscopic simulation models to quantify the potential benefits of SSGA CV-based applications considering both mobility and safety impacts. This study recognizes that the drivers' critical gap distributions at unsignalized intersections are essential parameters in the modeling of SSGA. The accurate modeling of such distributions in the microscopic simulation model has a great impact on simulation results.

Methodology

This research uses real-world data collected in previous studies to model the driver's behavior on minor roads and to determine the distributions of accepted gaps in the major road traffic that are available for left-turn and through vehicles on the minor road. In this study, the gap time is used for fine-tuning the gap acceptance behavior in the model to replicate the real-world gap acceptance distributions. The traffic microsimulation tool VISSIM was used to model the SSGA application in a connected vehicle environment. A methodology was developed to emulate real-world gap acceptance probability distributions, considering that VISSIM only allows the input of a constant gap acceptance parameter value. To quantify the safety benefits, the vehicle trajectory data was post-processed using the SSAM measures.

Findings

The results showed that the fixed default gap time parameter in the utilized simulation overestimated the capacity of the minor street approach of the TWSC intersection by approximately 58.5% (see Figure 5-4). The study results showed that it is important to incorporate the gap time parameter in the utilized simulation model as a probability distribution rather than a deterministic value when assessing SSGA impacts. The simulation models with the calibrated parameters were then used to assess the impacts of the SSGA on safety and mobility in a connected vehicle environment. The results showed that the SSGA can potentially improve the overall minor approach capacity by approximately 35.5% when the SSGA utilization rate reaches 100%. However, this increase in capacity depends on setting the minimum gap time parameter in the SSGA, and there is a clear trade-off between capacity and safety.

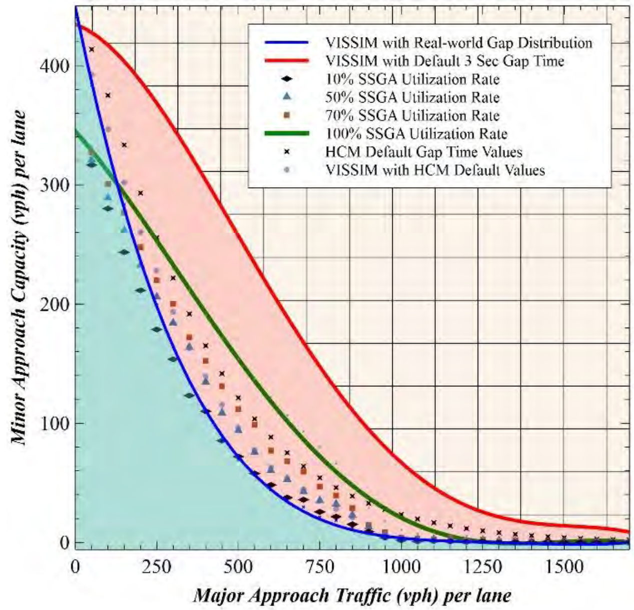


Figure 5-4: Impacts of the gap time parameter on the minor approach capacity

5.1.3. Signalized Intersection Left-Turn Gap Assist

Problem Statement

Signalized left-turn assist (SLTA) provides assistance for connected vehicles (CV) making permissive left turns during the unprotected left-turn signal phase at signalized intersections. The most common crash types addressed by the SLTA countermeasure are head-on, left-turn, and angle crashes. These crashes involve a left-turning vehicle (subject vehicle [SV]) with a conflicting vehicle from the opposing traffic (opposing vehicle [OV]). SLTA supports a left-turning driver's decision in accepting a gap in the opposing traffic by computing the speeds and locations of the opposing vehicles and determining adequate and safe gaps for completing the maneuver. Thus, it improves the safety of the permissive left-turning traffic without the need to compromise the mobility performance of the intersection by changing the left-turn phase to protected-only operation. An important aspect of simulating CV-based applications is the need for more detailed calibration based on fine-grained data. The first objective in this study is to demonstrate how such calibration is performed to support the microsimulation-based modeling of SLTA. This calibration utilizes real-world gap acceptance distributions of drivers making permissive left-turn movements at signalized intersections derived in a previous study. The second objective is to utilize the calibrated model to assess the potential impacts of SLTA on mobility and safety.

Methodology

This research calibrated the simulation parameters that influence a driver's gap acceptance behavior. A logistic function was identified to explain the real-world gap acceptance distributions.

The traffic microsimulation VISSIM was used to model the SLTA application in a connected vehicle environment. To replicate the variations among drivers in the model, it was necessary to create eight different priority rules with a minimum gap time ranging from 3 seconds to 10 seconds in 1-second intervals. Eight vehicle classes were defined, and each class was associated with one of the eight priority rules and thus had a unique minimum gap value. The data collected for the case study signalized intersection used in simulation included the traffic volumes, turning proportions, and signal timing plans for a three-hour morning peak period. The cycle length equals 150 seconds with a yellow interval of 4.4 seconds and a red clearance interval of 2 seconds for all approaches. The capacity results in Figure 5-5 are based on the HCM left-turn saturation flow model which is calculated as the difference between 1200 vph and the opposing flow. To quantify the safety benefits, the vehicle trajectory data was post-processed using the SSAM tool.

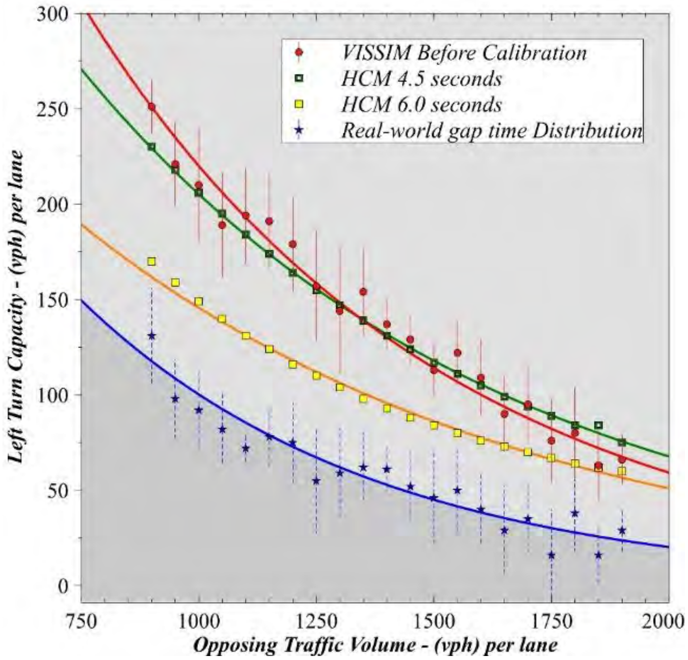


Figure 5-5: Impacts of VISSIM model calibration on the left turn capacity

Findings

The study results show that SLTA can increase left-turn capacity depending on the SLTA gap time parameter setting, reaching approximately 64.8%, 51.1%, and 35.9% when utilizing a gap time of 3 seconds, 4 seconds, and 5 seconds, respectively. In addition, the results show that with 100% utilization, the average delay for all vehicles can be reduced by approximately 58.4%. The safety benefits of the SLTA were determined utilizing surrogate measures based on vehicle trajectories generated by the microscopic traffic simulation model. The results show that by utilizing a 5-second predefined time gap in the SLTA application, the total number of observed crossing conflicts decreased from 6 conflicts per hour to zero conflicts per hour when the SLTA utilization rate increases from 0 percent to 100 percent.

5.2. Modeling Freeway Mobility Applications

5.2.1. Freeway Mobility in Mixed Traffic

Problem Statement

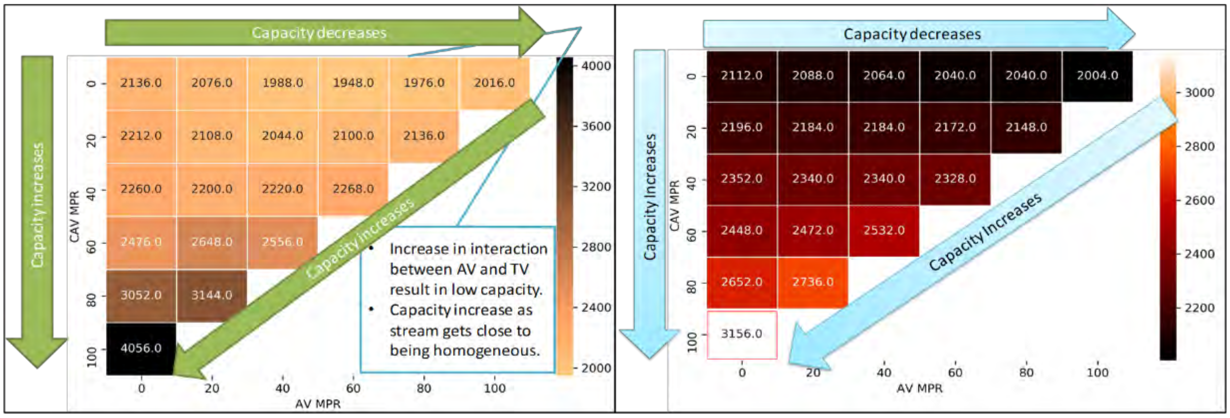
Many studies have predicted significant freeway capacity increases due to the presence of AVs and CAVs in the traffic stream. That may be true under certain high market penetrations (MPRs) but needs to be evaluated across the wide range of possible MPRs. It is also likely that during the transition to the higher MPRs for CAVs, the interaction between the various vehicle types that include AVs, CAVs, and TVs will govern the prevailing capacity. While the largest gains will likely be achieved under CAV platooning conditions, platoon formation at significant levels is unlikely in the near and medium terms. An ability to estimate capacity under various MPRs and freeway segment types can assist planners and engineers in understanding what capacity gains can be achieved and under what conditions.

Methodology

This study used the SUMO microscopic simulation model (Lopez et al., 2018), an open-source platform that is quite flexible in accepting a variety of car-following, lane-changing and desired speed algorithms that are vehicle class dependent. These include a stochastic acceleration framework for TVs, an ACC framework for AVs, and a CACC framework for CAVs. In this simulation, CAVs operating in platoons had clear gaps set at 0.6 sec; AVs at gap setting of 1.5 sec, and TVs at an average of 1.49 sec. The slightly higher gap setting for AVs reflects a more conservative bent to maintain reasonably safe headways at the expense of mobility efficiency. The simulation was run for representative basic, merge, and diverge segments 3 miles in length and having two directional lanes. Sensors were placed at key locations to capture the maximum throughput in each case. Multiple runs were made covering MPRs from 0% to 100 % with increments of 20% for each vehicle type.

Findings

The model was first validated by testing its capacity predictions under the 100% TV scenario. In all three cases, the generated capacity matched well with the HCM6 predictions at the indicated free flow speed. Sample results for the basic and merge segments are given in Figure 5-6**.** Several observations were made. First, the merge segment capacity across the board was found to be lower than that for the basic segment, especially in the presence of CAVs, due to the merging turbulence that may impact platoon formation. For example, in the absence of CAVs, capacity reductions are minimal, in the range of 1%–2%, while at 80% CAVs, those drops are in the range of 13%. This is an important clue that the presence of merging as well as diverging (not shown here) impacts the ultimate capacity that one can expect.



(a) (b)

Figure 5-6: Freeway capacity for (a) basic and (b) merge segments under mixed traffic flow

The second observation is the relative insignificance of AVs on capacity. Based on the input time gaps in the simulation, their presence tended to reduce capacity by about 1%–2% depending on the MPR. And finally, the diagonal arrow in the figure shows that capacity increases as the traffic stream becomes more homogeneous, culminating in capacities nearing 4,000 vph for a basic segment with 100% CAV MPR.

5.2.2. Freeway Mobility with Dedicated Lane

Problem Statement

Many studies have shown that the expected benefits of CAVs directly depend on their market penetration rate (MPR) in the traffic stream, and, indirectly on their interaction with unlike vehicles. At low MPRs, CAVs are shown to have little or negative impacts on mobility, safety, and the environment. An immediate solution would be dedicating lane(s) to CAVs. The introduction of dedicated CAV lanes may result in (a) increasing the density of equipped vehicles in the reserved lane, (2) increasing the chance of platooning, and (c) reducing the interactions with unequipped vehicles. However, the effect of mainline and ramp demand and the ability to access the dedicated lane along a facility are factors that would warrant further investigation.

Methodology

This study used the SUMO microscopic simulation model (Lopez et al., 2018), an open-source platform that is quite flexible in accepting a variety of car-following, lane-changing and desired speed algorithms that are vehicle class dependent. These include a stochastic acceleration framework for TVs, an ACC framework for AVs, and a CACC framework for CAVs. In this simulation, CAVs operating in platoons had clear gaps set at 0.6 sec; AVs at gap setting of 1.5 sec; and TVs at an average of 1.49 sec. The slightly higher gap setting for AVs reflects a more conservative bent to maintain reasonably safe headways at the expense of mobility efficiency. The simulation was run for representative basic, merge, and diverge segments 3 miles in length and a 6-mile-long facility with multiple on-ramps and off-ramps. Sensors were placed at key locations to capture the desired mobility data. Multiple runs were made covering MPRs from 0% to 100 % with increments of 20% for each vehicle type.

Findings

Simulation results indicate that reserving a lane for CAVs on a three-lane directional freeway segment is only beneficial when the CAV MPR varies from 20% and 60% and is optimal at 40%. Mandating CAV use of the dedicated lane outside this range increased congestion on the dedicated or general-purpose lanes. The level of mobility degradation was found to be related to the segment length which allows access to or egress from the CAV dedicated lane. Travel rate analysis showed that perturbations due to merging and diverging vehicles significantly impacted congestion and was directly related to the ramp volume levels: the higher the ramp volume, the greater the disruption and congestion. Furthermore, ramp volume level was found to be the most import factor impacting the scatter pattern in the fundamental diagram (speed flow relationship), as shown in Figure 5-7.

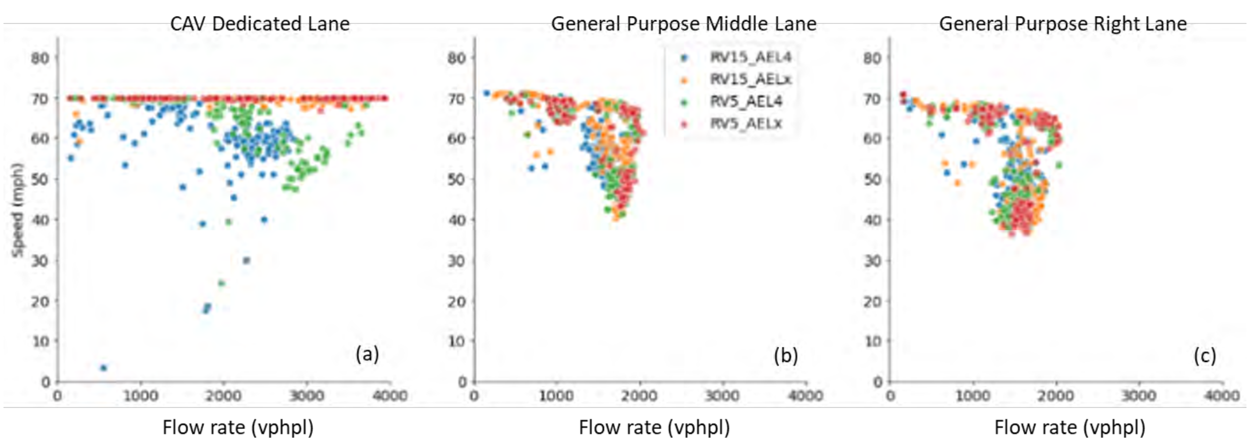


Figure 5-7: Fundamental diagrams for different dedicated lane use policy → AEL4: mandatory use of dedicated lane with access/egress length of 4500 ft; AELx: optional use of dedicated lane; Ramp Volume: RV→ Ramp Volume 5% and 15% of mainline flow; Results for 40% CAV MPR

5.2.3. Freeway Weaving to Optimize Operations

Problem Statement

Freeway weaving segments represent "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway without the aid of traffic control devices (except for guide signs)" (Highway Capacity Manual 6th Edition). At weaving sections, lane changes create turbulence which significantly affects throughput and speeds. This turbulence can result in an uneven utilization of the weaving space, with longer headways observed during lane changing, and shorter headways during merging. CAV technology can be leveraged such that they can be provided with optimal trajectories when they travel through bottlenecks such as weaving sections. In that case, turbulence can be managed, and operations at weaves can be optimized in order to maximize throughput and minimize travel time. The objective of the study was to develop an optimization model and the necessary algorithm to optimize the trajectories of CAVs in a fully automated environment at freeway weaving segments, as well as simulating and evaluating the proposed method.

Methodology

Figure 5-8 presents a schematic view of a weaving section. The algorithm divides the weaving section into N short sub-sections. In order to minimize the travel time in the weaving section, the optimization models minimize the summation of the travel time in all sub-sections considering the optimized trajectories of the vehicles already in the system and the minimum allowable headway. The combination of sub-sections which minimize the objective function of the model is selected as the optimal trajectory. The figure below explains the simulation process.

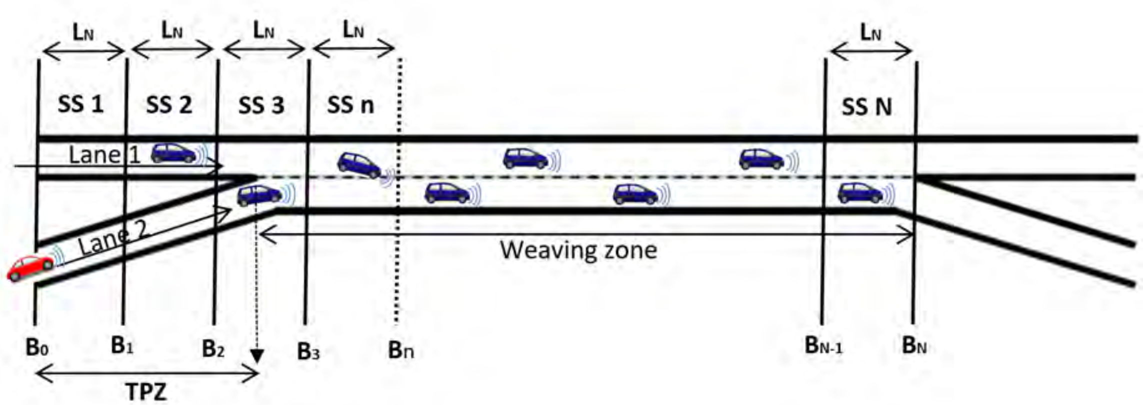


Figure 5-8: Schematic view of a weaving section

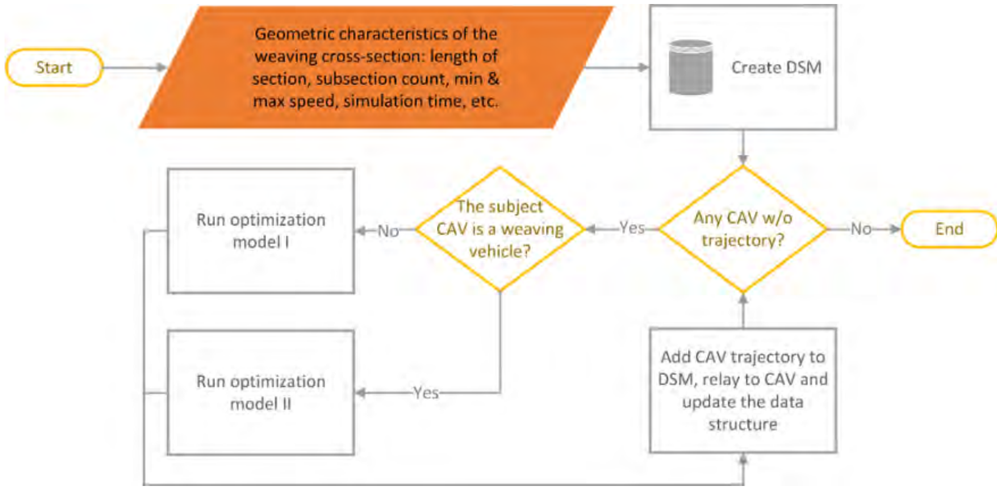


Figure 5-9: Study flowchart

Findings

The results show that the algorithm increases the average speed of the system by 16% under low and medium demand volumes. For high demand scenarios, the algorithm improves the capacity of the weaving section by 11%. The results for the case study show that by optimizing the trajectories, the average travel time along the section can be improved by 17%, 30%, and 38% when the minimum time headway is set to 1.7 s, 1.4 s, and 1 s, respectively.

5.3. Modeling Arterial Mobility Applications

5.3.1. Simulating Signal Control Optimization

Problem Statement

Actuated and adaptive signal control systems rely on sensors which detect vehicle arrivals and make a request to the controller for the right of way. A real-time intersection optimizer (RIO) was developed by the UFTI (NSF Award 1446813) to leverage connected and autonomous vehicle (CAV) technologies in order to minimize travel time and increase throughput at signalized intersections. The algorithm optimizes Signal Phase and Timing (SPaT) and vehicle trajectories which are transmitted to any CAVs approaching the intersection. One of the objectives of the study was to simulate RIO and compare it with actuated signal control.

Methodology

The study used VISSIM and simulated a four-way intersection with three incoming lanes per approach. Figure 5-10 provides an overview of the procedure used to replicate RIO. We calibrated the VISSIM model to achieve a minimum headway of 1.7 seconds by adjusting the CC1 parameter in the Wiedemann 99 car-following model. This is done to ensure a consistent minimum discharge headway so that any improvements in travel time and throughput are solely due to RIO. A simulated inquiry for vehicle arrivals is made through VISSIM's Component Object Model (COM) interface. Access to speed, lane, and vehicle localization information makes it possible for RIO to compute optimal trajectories for CAVs and to make signalization decisions. The COM interface overrides the default behavior of CAVs within VISSIM and controls their movement based on the optimal trajectory computed by RIO. It also commands the signal heads to follow the computed signalization patterns. Statistics on travel time of vehicles and allocated green times are collected as the process continues for the duration of simulation.

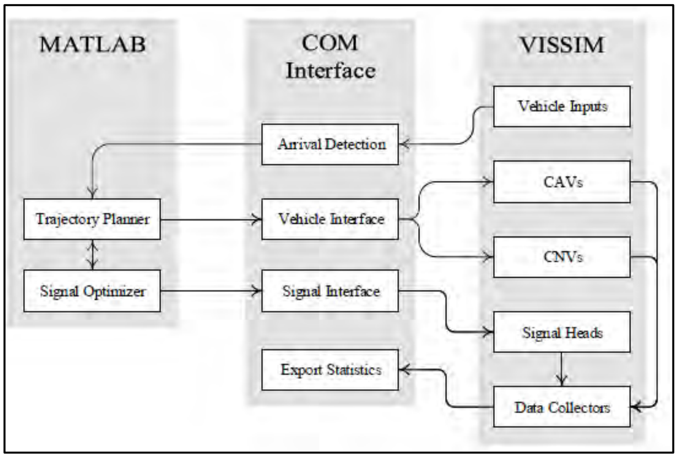


Figure 5-10: RIO study flowchart

Findings

RIO was found to achieve the lowest average travel times and highest throughputs compared with actuated control. Also, RIO resulted in lower travel time variance, indicating a lower probability for extreme travel times. This study did not consider updates to the CAV behavior to account for unplanned behaviors, sensing inaccuracies, and imperfect communications.

5.3.2. Evaluation of Operations and Environmental Quality

Problem Statement

The goal of this project was to develop a robust microscopic simulation extension to allow the evaluation of traffic operational and environmental quality considering the presence of Connected and Autonomous Vehicles (CAVs). The research team evaluated the capability of the microscopic simulator VISSIM (Version 10.0) to model CAVs. There are two external interfaces with powerful features available for CAV modeling in VISSIM: Component Object Model (COM) Application Programming Interface (API) and External Driver Model (EDM). CAV modeling was developed in VISSIM by leveraging the strengths of both interfaces: the research team used the

COM API to access network elements and the EDM to maintain the longitudinal control of vehicles. The trajectory data from VISSIM were used to estimate energy, fuel consumption, and greenhouse gas emissions. The calculations follow the Motor Vehicle Emission Simulator (MOVES) methods developed and mandated by the US Environmental Protection Agency (USEPA).

Methodology

A comprehensive simulation extension was developed to represent CAVs in VISSIM. CAVs were modeled and an isolated signalized intersection was simulated. The trajectory data from VISSIM were leveraged to estimate energy, fuel consumption, and greenhouse gas emissions using the Motor Vehicle Emission Simulator (MOVES) method. To understand the impact of CAVs on traffic operations, different penetration rates of AV, CV, or CAV under different volume-to-capacity ratios (v/c) were replicated. Eighteen scenarios were designed with different combinations of v/c and penetration rate for AV, CV, and CAV each. In addition, comparative performance analysis across different scenarios was performed on two quantities, travel-time, and total vehicular carbon dioxide (CO_2) emissions, which was estimated using EPA's Motor Vehicle Emission Simulator (MOVES) model for the 2017 fleet mix.

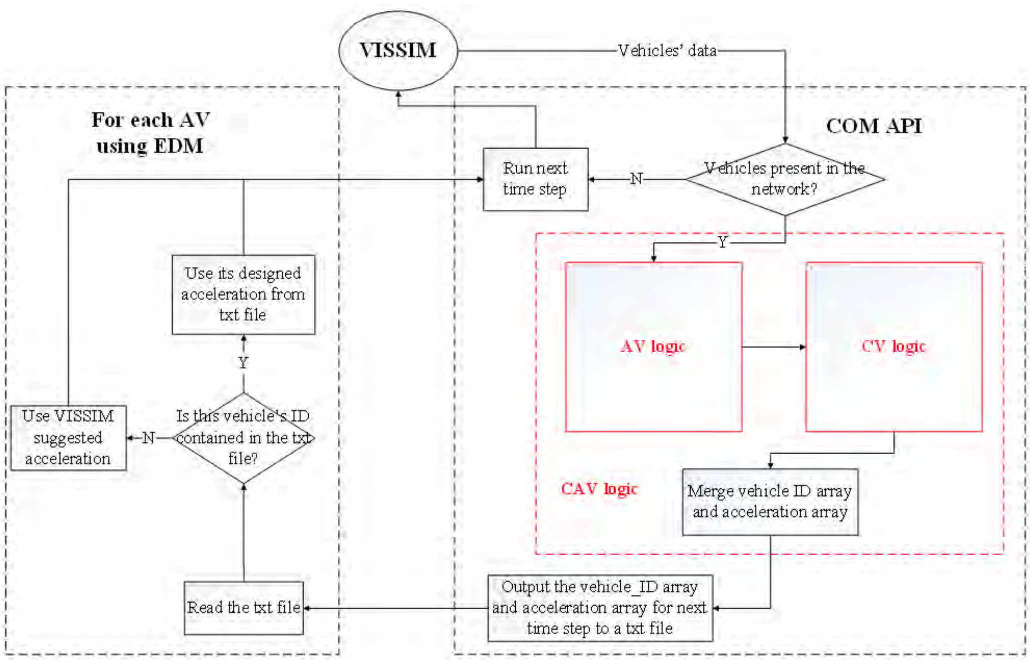


Figure 5-11: Study algorithm

Findings

While COM API has access to all VISSIM data and is helpful in modeling connectivity, it cannot provide direct and accurate longitudinal and lateral movement control. The EDM enables full control of both longitudinal and lateral movements but with limited accessibility to VISSIM data. Hence, this project developed the ability to simulate CAVs in VISSIM by using COM API to access network elements and EDM to maintain the longitudinal control of vehicles. The results show that CAV presence in the traffic stream result in net improvement in traffic operational measures (travel time and speed). CAV, which includes the combination of the two technologies (i.e., autonomy and connectivity) yields better performance than each (CV and AV) on their own. However, emissions did not follow the same trend. While increasing AV penetration rates resulted in emissions reductions, increasing CV and CAV penetration rates resulted in higher emissions. A deeper analysis into the root cause for these trends showed that while the CV logic chosen for testing in the VISSIM simulation environment seeks to maximize the likelihood of vehicle arrival-on-green, the algorithm likely results in increased variations in second-by-second accelerations, leading to prediction of overall higher emissions.

5.4. Summary

This chapter has focused on the evaluation of simulated mobility and safety treatments using combinations of CVs, AVs, and CAVs on freeway and arterial facilities. Policy makers should be aware of the different capabilities of CVs and CAVs on the one hand and AVs on the other. The latter operate autonomously, and their trajectories can neither be optimized nor platooned. Therefore, in the near future, it is unlikely that operators will experience either safety or operational improvements solely on the basis of AV presence. With respect to the case studies covered in this chapter, they show that high capacities can be achieved using CAVs, as long as the amount of merging and diverging on a freeway facility is not excessive. A corollary case study where CAV weaving vehicle trajectories are optimized shows that significant operational improvements can be gained, reinforcing the notion that lateral trajectory control in the presence of mixed traffic is critical. On the arterial side, safety-based algorithms associated with CVs to aid in optimal gap identification and acceptance have been shown to also have a positive impact on operations and capacity. Similar findings emerged from signal timing improvements with CAVs. Finally, several case studies have demonstrated that without proper calibration of driver behavioral models in microsimulation, the results from such models are likely to fall far short of reality.

6. CONCLUSIONS

This section includes some conclusions based on our work on various tasks of this project.

1. The level of ATV application deployment in the southeastern United States varies by state, with some states investing significantly, mainly in infrastructure support of CV deployment. At this point, the consideration of AV and CAV in traffic operations is limited, but this can be different with planning agencies that are interested in long-range modeling and planning.
2. One of the biggest barriers to decision making is the lack of knowledge and guidelines regarding ATV technology and the anticipated impacts. This can include the difficulty in considering the uncertainty in the technology adoption, various types of vehicle fleet considerations, and the impacts on traffic and travel behaviors.
3. Agencies are interested in methods to estimate performance metrics that allow comparing the performance of the infrastructure support of the technologies in relation to the performance improvements expected from traditional improvements. One example to consider when identifying the performance measures of ATC analysis is the federal process of approval of traditional improvements such as interchange and facility modification.
4. The ATV simulation should be considered to be part of the four main dimensions of ATV impact modeling, including supply changes, demand changes, performance changes, and network integration. In addition to advancing ATV simulation modeling, there is also a need for extending and/or converting the traditional demand models to allow them to consider ATVs in demand forecasting.
5. There are still significant uncertainties associated with ATV deployment and adoption. Scenario planning is a basic method for planning under deep uncertainty and as a step incorporated in performance-based planning at various stages of the process. It is recommended that such an approach should be used in ATV simulation projects, particularly since the timeline for adoption of ATV technology is debatable.
6. An important aspect of the hypothesis formulation as part of the ATV analysis is identifying performance measures that are relevant to the project goal and objectives and expected impacts of ATVs on different measures. The identification of the performance measures should be based on the project goal and objectives, as well as an understanding of the capabilities and impacts of the wide range of types, levels, and classes of ATV.

7. The identification of the data requirements, availability, and methods for filling the data gaps are critical considerations in planning and scoping the project and selecting the modeling approach for the project.
8. The analyst must be aware of the capabilities of the different classes, namely CVs, AVs, and ATVs, when attempting to model their operations in microsimulation
    a. CVs can use information from other vehicles and infrastructure but typically cannot use that information for platooning in order to increase capacity. Its application is ideal for improving safety, and avoiding incident locations.
    b. AVs rely primarily on their autonomous sensors but cannot communicate with other vehicles. AVs will maintain safety headways and also can customize the headway based on the owner or user preferences. They likely will have no platooning capabilities.
    c. CAVs are more flexible and can operate in platoons with other CAVs. They operate as if they were AVs in a simulation of mixed traffic.
    d. TV modeling has been widely simulated over the past decades and requires fewer interventions from current practice. What is unclear is whether driver behavior will change in the presence of driverless vehicles in their proximity and how to incorporate that in simulation.
9. The main obstacle to modeling of ATVs is lack of field data and information regarding algorithms developed by ATV manufacturers.
10. Another major obstacle is forecasting of the market penetration for various technologies.
11. The analyst should expect that OEMs will have a variety of options when marketing AVs and CAVs. These include when certain automated capabilities will deploy and options related to a desired following distance. These variations should be accounted for in the microsimulation models as well.
12. There are several AV, CAV, and CV pilot studies that have or plan to make their pilot data widely available. These data can be used to calibrate and/or validate specific algorithms in simulation.
13. While there are diverging estimates on future market penetration of AVs and/or CVs, it is likely that AV deployment will precede CAV deployment, indicating that a simulation focus on the interaction between TVs and AVs may be more relevant in the short term.

14. Because large-scale empirical data on non-TV vehicles will be lacking for a while, modeling surrogate safety measures tailored to non-TV vehicles should be considered as a short-term strategy for their safety evaluation.
15. As a result of items 1d, 4, and 5, emerging microsimulation models should be able to distinguish (algorithmically) between operations in mixed traffic and in exclusive AV and CAV right of ways.
16. State DOTs and local agencies are eager to forecast the market penetration of ATV technologies and plan their network improvements accordingly.
17. In general, the analyst has the following four options when using a commercially available micro-simulator:
    a. Adjust the existing models through changing specific simulation parameters (this is the approach followed to replicate CACC and develop the HCM models)
    b. Use new ATV models (developed by the vendor) that are internal to the simulator (this is the approach followed to replicate AM using VISSIM's existing algorithms to develop HCM models)
    c. Use new ATV models (developed by the vendor) that are external to the simulator
    d. Use external tools to model ATV movement or create new models within or integrated with the simulator.

It is recommended that Phase 2 of the project is conducted to build on the achievement of Phase 1, reported in this document, by applying the framework and guidance developed in Phase 1 to case studies in the Southeast region. Conducting the case studies will allow further identification, development, and refinement of methods and models for evaluating CAV operations and their interactions with traditional vehicles and the infrastructure.

This study focuses on assessing the mobility and safety impacts of ATV. ATV technologies are expected to have significant impacts in reducing the pollutant emissions. It is recommended that future work is conducted to provide guidance and methods to assess these impact of ATV on emission using simulation.

Most future ATVs are expected to be Electrical Vehicles (EVs). The parameters of microscopic traffic models can be different for EVs compared to combustion engine vehicles. Such difference in behavior can be considered in a future study of ATV simulation.

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