Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB’s recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB’s relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I’s recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.
The National Academies of Sciences, Engineering, and Medicine

The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

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Learn more about the National Academies of Sciences, Engineering, and Medicine at www.national-academies.org.

The Transportation Research Board is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board’s varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at www.TRB.org.
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NCHRP Report 891: Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles concentrates on identifying and evaluating opportunities, constraints, and guiding principles for implementing dedicated lanes for connected and automated vehicles. It identifies and describes conditions amenable to dedicating lanes for users of these vehicles and the necessary guidance to deploy them in a safe and efficient manner. The analysis, which relied on application of virtual, computer-based models, helps identify potential impacts associated with various conditions affecting lane dedication, market penetration, evolving technology, and changing demand. This report will be of immediate interest to transportation planners responsible for examining opportunities for integrating connected and, eventually, automated vehicles into the highway network.

Connected and automated vehicles (CAVs) are quickly expanding in the automobile and transportation industry, and their use is expected to become far more widespread during the coming decade. One of the policy catalysts that may incentivize greater market penetration of CAVs is dedicating lanes for their priority or exclusive use. To assist agencies that are preparing for this disruptive change, some guidance is needed related to (1) the intended benefits when dedicating lanes to CAVs in terms of safety, mobility, and environmental and societal considerations; (2) conditions amenable to dedicating lanes for priority and exclusive use by CAVs; and (3) a review of laws and regulations regarding dedicating lanes. This report, developed by Booz Allen Hamilton with support from WSP USA, the New Jersey Institute of Technology, and Dr. Steve Shladover, aims to provide that guidance. It also describes the project team’s approach to developing the guidance.

The research began with a detailed literature review to identify categories of benefits and disbenefits when dedicating lanes to a special category of vehicles. The literature review also identified the types of stakeholders who benefit (or do not benefit) from dedicating lanes to CAVs, factors influencing these benefits, and the potential performance measures in four categories: mobility, safety, environmental considerations, and societal equity. Building on that review, the team used an analytical process that applied virtual, computer-based models to identify variables and measures sensitive to dedicating lanes to connected and automated vehicle users and formulated a simulation-based analysis of two CAV applications, Cooperative Adaptive Cruise Control (CACC) and Dynamic Speed Harmonization (DSH). State-of-the-art analytical models and algorithms were evaluated for use in modeling these applications based on their applicability to dedicating lanes, suitability to the CAV environment, and adaptability to simulation models. Potential sites for the virtual case studies were evaluated based on their overall characteristics (e.g., geography, operational conditions, modes, and presence of managed lanes); their managed lane characteristics...
(e.g., geometry, allowed users, operating rules, access point configurations); and the feasibility of modeling CAV applications. Based on these criteria, the project team selected and developed simulation models for two case study sites: I-66 in Northern Virginia and US-101 in San Mateo, California. The modeling and simulation activity helped the project team identify parameters that are sensitive to dedicating lanes to CAV users and identify expected impacts under various conditions of lane dedication, market penetration, demand conditions, combined deployment of applications, and so forth. The project team also reviewed laws and regulations that should be considered when dedicating lanes to CAVs. Based on the findings, the project team developed specific guidance for agencies on operational characteristics and impacts, including regulatory and policy guidance for states and local agencies on conditions amenable to dedicating lanes to CAVs.
122 Chapter 8 Guidance on Operational Characteristics and Impacts

122 8.1 Shared and Exclusive DLs
123 8.2 Expected Benefits and Disbenefits from Dedicating Lanes to CAV Users
127 8.3 Guidance on Access Restrictions
127 8.4 Guidance on Lane Separation Barriers
128 8.5 Findings on Economic Equity
128 8.6 Regulatory and Policy Guidance
130 8.7 Guidance Regarding Updating Laws and Regulations

132 Chapter 9 Future Research Directions

132 9.1 Granular Energy and Environmental Impact Assessment
132 9.2 Expansion for More Test Scenarios
132 9.3 Dedicating Lanes for CAVs on Arterials
133 9.4 Dedicating Lanes to Connected and Automated Trucks
133 9.5 Modeling Higher Levels of Automation
134 9.6 Unified Definitions for CAV and Related Terminology

135 Chapter 10 Conclusions

138 Abbreviations

140 References
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

Critical issues associated with connected vehicles and automated vehicles will be faced by state and local transportation agencies and AASHTO. To identify these issues, conduct research to address them, and conduct related technology transfer and information exchange activities, NCHRP initiated Project 20-102, “Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies.” *NCHRP Research Report 891* presents the specific research and findings of NCHRP 20-102, Task Order 8, “Dedicating Lanes for Priority or Exclusive Use by CVs and AVs.”

The overall objective of this task was to develop guidance on identifying and describing conditions amenable to dedicating lanes for connected and automated vehicle (CAV) users. The project team conducted simulation-based analysis of two CAV applications, namely Cooperative Adaptive Cruise Control (CACC) and Dynamic Speed Harmonization (DSH), using two case study sites. The modeling and simulation activity helped the project team in identifying parameters that are sensitive to dedicating lanes to CAV users as well as identifying expected impacts under various conditions of lane dedication, market penetration, demand conditions, combined deployment of applications, and so forth, using virtual computer-based models. The research was done in five steps. Each step is described briefly in this summary.

**Identify Categories of Benefits and Disbenefits**

The project team started with a comprehensive literature review identifying the types of stakeholders who benefit (or do not benefit) from dedicated lanes to CAVs, factors influencing these benefits, and the potential performance measures. Specifically, the team identified three types of stakeholders:

- Dedicated lane (DL) users,
- General purpose lane (GPL) users, and
- The owners and operators of the facility.

The research team also identified the following factors as influencing the benefits and disbenefits to these stakeholders:

- CAV market penetration, representing the percentage of vehicles in the traffic mix with CAV capabilities;
- Roadway geometry, including access/egress features, lane attributes, number of lanes, and so forth;
- Enforcement intensity, which restricts unallowable categories of users to enter the DLs;
- Toll collection attributes, such as whether non-CAV vehicles can use the DLs for a fee;
- Operation hours, such as dynamic operations or peak-hour operations;
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

- CAV technology, which represents the type of applications allowed on vehicles using these lanes; and
- Functional types, which dictate the type of vehicles allowed on the DLs.

The literature review also enabled the researchers to document performance measures specific to mobility, energy and environment, safety, and societal benefits that might be achieved by users and non-users of such DLs.

Evaluate Existing Modeling and Analytical Frameworks

Several CAV applications exist in the research industry today, and assessing all of them was beyond the scope of this study. Accordingly, the project team implemented a selection process to evaluate which applications to consider in this project and which algorithm or modeling framework to use in evaluating these applications. Among the 17 available CAV applications, down-selection considered three criteria: (1) suitability to dedicating lanes, (2) suitability to the CAV environment, and (3) adaptability to simulation models. Two CAV applications, CACC and DSH, were selected for use in this project.

The project team utilized modeling and simulation-based analysis to evaluate potential benefits and parameter sensitivity of CAV applications on overall traffic efficiency and safety. Six modeling frameworks were evaluated for CACC modeling, and eight modeling frameworks were evaluated for DSH modeling to identify appropriate algorithms for use in this project. As a result, the team selected the CACC model by Lee et al. (2014) and the DSH model by Ma et al. (2016). Both models were developed for the PTV Vissim microsimulation tool; for this study, they were modified to be integrated into a unified programming interface so that they could work together or in isolation.

Identify Diverse Case Study Sites Suitable for Evaluation

The CACC and DSH models were applied to case study sites that represented real-world transportation networks. To support this, the project team evaluated and ranked nine modeling-based test sites to which the team had access. The case study sites were evaluated with regard to:
- Overall characteristics (e.g., geography, operational conditions, modes, managed lanes);
- Managed lane characteristics (e.g., geometry, allowed users, operating rules, access point configurations); and
- The feasibility of modeling CAV applications.

Based on the evaluation, the team selected two case study sites: the I-66 corridor in Northern Virginia and the US-101 corridor in San Mateo County, California.

Select, Adapt, and Apply the Evaluation Approach

The next task included development of case-study models to conduct simulation-based analysis of CAV applications to evaluate their impacts on DL scenarios under different sensitivity parameters. The project team conducted a four-step process to develop and utilize the models to conduct the simulation-based analysis: (1) develop baseline models, (2) integrate CAV application models, (3) develop scenarios for the simulation-based assessment, and (4) measure the performance of the applications.

Development of the baseline models involved calibration of Vissim-based models to represent real-world operational conditions and certain hypothetical operational conditions.
Integration of CAV application models involved development of CACC and DSH models to work within Vissim’s application programming interface, along with conducting preliminary testing to compare and calibrate the vehicle behavior to field data. Based on the following six research issues, the research team then developed a list of scenarios that provided precedence to develop DL guidance for agencies:

1. Impact of priority lane use, with CAVs permitted on high-occupancy vehicle (HOV) lanes, versus exclusive lane use, with CAVs having exclusive access to DLs;
2. Impact of market penetration rates (MPRs), assessed under both DL and non-DL scenarios;
3. Impact of a combination of CAV applications;
4. Impact of varying demand and changing operational conditions on the CAV DL benefits;
5. Impact of access restrictions to the DL under exclusive CAV lane situations; and
6. Impact of hypothetical scenarios such as an incident-related lane closure or moving bottlenecks.

For each scenario, the project team performed simulations and captured safety, mobility, and energy/environmental performance measures. Through post-processing of mobility performance measures, societal/equity performance measures also were captured to determine whether, and by how much, DL users received benefits at the expense of GPL users.

**Identify Typical Laws and Regulations**

In addition to conducting an operational analysis based on modeling and simulation, the project team conducted a literature review to identify the laws and regulations regarding dedicating lanes to specific categories of users. The review found that, historically, lanes have been dedicated to HOVs, motorcycles and bicycles, buses, alternative fuel vehicles, and trucks. The team also identified the current state of regulatory and legislative affairs with respect to CAVs, and barriers to dedicating lanes for exclusive use by CAVs.

**Summary of Guidance**

Based on the findings from the previous tasks, the project team developed specific guidance for agencies on operational characteristics and impacts of dedicating lanes to priority or exclusive use by CAVs, as well as regulatory and policy guidance for states and local agencies regarding conditions amenable to dedicating lanes to CAVs. As summarized in the following list of statements, this guidance must be used in conjunction with the type of analysis that went into developing these statements. Scenarios may occur that fall outside of the scope of the analysis conducted in this study, which could potentially enhance or change this guidance.

1. For CACC-DLs, it is advisable to have shared DLs with HOVs at lower market penetration (10%), exclusive DLs at medium market penetration (20 to 45%), and no DLs for higher market penetration (greater than 50%).
2. For lower market penetration of CACC:
   a. Under shared DL conditions, there may be slight mobility benefits for both DL users and GPL users.
   b. Under exclusive DL conditions, there may be significant mobility and energy/environmental benefits to DL uses, at the expense of GPL users.
3. For higher market penetration of CACC:
   a. Under exclusive DL conditions, there may be moderate to significant mobility and energy/environmental benefits to DL users, and slight to moderate benefits to GPL users.
4. For lower market penetration of DSH:
   a. Under shared DL conditions, there may be slight safety benefits for both DL and GPL users.
   b. Under exclusive DL conditions, there may be slight safety benefits for DL users and significant safety benefits for GPL users (at the expense of their mobility performance).

5. For higher market penetration of DSH:
   a. Under exclusive DL conditions, there may be moderate to significant improvement in safety and slight improvement in energy/environmental performance for DL users; GPL users would remain unaffected.

6. Combining DSH-enabled vehicles with CACC-enabled vehicles will improve safety, in addition to mobility and energy/environmental performance.

7. CACC DLs can especially provide mobility benefits (in terms of throughput improvement), when the corridor is subject to peak or higher-than-peak demand.

8. Mobility benefits are more when there is continuous access to the DLs because even vehicles taking shorter trips can utilize the DLs.

9. Speed differential between DLs and GPLs increases with restricted access to DLs. DLs with exclusive access for CAVs will have a much higher travel speed than GPLs.

10. Average travel speed on GPLs reduces significantly when there is restricted access to DLs. This is because the demand on GPLs will be higher when compared to continuous access, as vehicles taking shorter trips cannot use the DLs.

11. Lane friction (speed differential between DL and adjacent GPL) guidance that warrants when to have barrier separated lanes:
   a. High market penetration of CAV with shared DLs with HOV demonstrated the lowest lane friction, and does not warrant lane separation barriers or restricted lane access.
   b. Low market penetration of CAV with shared DLs with HOV also demonstrated relatively lower lane friction.
   c. High market penetration of CAV with exclusive DLs showed medium lane friction, where the average speeds of the DL and the adjacent GPL differed by 10 to 15 miles per hour (mph). According to Best Practices: Separation Devices between Toll Lanes and Free Lanes, this does not warrant physical separators, but rather buffer-separated double solid lines.
   d. Low market penetration of CAV with exclusive DLs showed the highest lane friction, on the order of 30 mph. This warrants the need for physical separation for enforcement purposes as well as for safety purposes.

Additional guidance, along with more-detailed narratives, are provided in the chapter copy.
Connected and automated vehicles (CAVs) are quickly expanding in the automobile and transportation industry and are expected to become a major share of the market in the next decade. Agencies are preparing themselves for this disruptive change, which can bring safety, mobility, and operational benefits. NCHRP Project 20-102, “Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies—Task-Order Support,” was initiated to assess the impacts of CAVs on state and local transportation agencies. The program’s objectives are to:

- Identify critical issues associated with CAVs that state and local transportation agencies and AASHTO will face,
- Conduct research to address those issues,
- Conduct related technology transfer and information exchange activities.

One of the policy catalysts to help achieve greater market penetration of CAVs is thought to be dedicating lanes for their priority or exclusive use as an initial incentive to encourage CAV ownership. The objective of this research, conducted under Task 08 of NCHRP Project 20-102, was to develop guidance for identifying conditions amenable to dedicating lanes for CAV users through modeling and simulation, as well as other qualitative ways such as investigations of laws and regulations. The balance of this chapter discusses and expands on the objectives and scope of this research and the purpose of this report.

1.1 Project Objective

The primary objective of NCHRP Project 20-102(08), “Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles,” was to develop guidance for identifying and describing conditions amenable to dedicating lanes for CAV users. To achieve this objective, the project team undertook six tasks that concluded with the development of this research report and guidance document (Figure 1.1).

- More specifically, these tasks involved: Identify the categories of benefits and disbenefits for dedicated lane (DL) users, non-DL users, and owners and operators of the facilities when dedicating lanes to CAV users;
- Evaluate existing modeling and analytical frameworks to assess the impact of dedicating lanes to CAV users, specifically for applications such as Cooperative Adaptive Cruise Control (CACC), and to propose a specific project approach;
- Identify diverse case study sites to help the researchers study the impacts and challenges of dedicating lanes to CAV users and propose specific case study sites for use in this project.
Apply the approach proposed in Task 2 to the specific sites identified in Task 3 to investigate the impacts and challenges of dedicating lanes to CAV users;

Investigate existing laws and regulations that govern or constrain agencies in dedicating lanes to CAV users; and

Develop specific guidance on identifying and describing amenable or challenging conditions to dedicating lanes to CAV users, to be included in the final research report.

Figure 1.1 also presents a basic workflow, showing the relationships among the different tasks associated with the project.

1.2 Background

Connected vehicles (CVs) use various communication technologies to exchange information with other cars on the road: vehicle-to-vehicle (V2V) communication, roadside infrastructure such as vehicle-to-infrastructure (V2I) or infrastructure-to-vehicle (I2V) communication, and the “cloud.” These technologies can help improve vehicle safety, vehicle efficiency, and commute times (U.S.DOT n.d.c). Consequently, dedicated short-range communication (DSRC) is expected to be one of the leading communication technologies to be used in a CV environment (FHWA 2017a).

In the classical sense, CVs may offer little or no automated control; rather, they focus on enhancing driver awareness through advanced warnings received by the in-vehicle communication equipment. The CVs may transmit a range of messages containing various types of information about the condition of the vehicle and higher-level applications of interest to the driver and/or passengers. The most elementary (and likely to be legally required) message broadcast by an in-vehicle device (or onboard equipment) is known as the Basic Safety Message (BSM) (SAE International 2016a). The BSM contains information about a vehicle’s speed, position, size, heading, acceleration, and other representative elements (U.S.DOT n.d.a). When other vehicles or roadside devices receive this information, applications can use the data to provide warnings,
alerts, and advisories that can mitigate danger in certain situations. For example, a driver in a vehicle nearing an intersection could receive notifications of another car that is about to run a red light. Similarly, a driver in a vehicle approaching a blind curve could receive alerts about an oncoming car—currently out of sight beyond the curve—that is swerving into the driver’s lane to avoid an object on the road.

Roadside equipment, consisting of infrastructure-based devices that also receive BSMs, can broadcast messages such as MapData and Signal Phase and Timing (SPaT), which in-vehicle devices receive and use to continuously monitor the infrastructure-based warnings and alerts.

Automated vehicles (AVs) are those in which some portion of the dynamic driving task occurs without direct driver inputs to control the steering, acceleration, and braking. Highly automated driving systems are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode (SAE International 2018). According to SAE International, vehicle automation can fall under five different levels of automation:

- **Level 1 (Driver Assistance).** This level represents the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.
- **Level 2 (Partial Automation).** This level represents the driving mode-specific execution of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.
- **Level 3 (Conditional Automation).** This level represents the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene.
- **Level 4 (High Automation).** This level represents the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task within a specifically constrained operational design domain, even if a human driver does not respond appropriately to a request to intervene.
- **Level 5 (Full Automation).** This level represents the full-time performance by an automated driving system of all aspects of the dynamic driving task (DDT) under all roadway and environmental conditions that can be managed by a human driver.

In the above definitions, the DDT includes the following decision-making tasks that are performed while driving:

- **Operational driving tasks.** These tasks include the operational aspects such as steering, braking, accelerating, and monitoring the vehicle and roadway.
- **Tactical driving tasks.** These tasks involve higher-level decision making such as responding to events or determining when to change lanes to achieve a higher headway or expected desired speeds.
- **Strategic driving tasks.** These tasks are strategic in nature, such as determining destinations and waypoints, selecting parking spots, and so forth.

The operational design domain (ODD) is the set of operating conditions within which a given driving automation system is specifically designed to function. The ODD includes, but is not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics. For example, a dedicated lane with clear lane markings and free-flow traffic is an ODD for a system with Adaptive Cruise Control and Lane Centering.
Requests to intervene are notifications by the automated driving system (ADS) to fallback-ready users that they should promptly perform the DDT fallback. The DDT fallback may entail:

- The user (a human driver) resuming manual operation of the vehicle (i.e., taking active control over one or more driving tasks), or
- The user taking steps to achieve a minimal risk condition (i.e., by taking control of all DDTs long enough to safely park the vehicle), or
- The ADS itself responding to achieve a minimal risk condition.

The DDT fallback is the response by the user, either to perform the DDT or to take whatever steps are needed to achieve a minimal risk condition after occurrence of a DDT performance-relevant system failure or upon ODD exit, or the response by an ADS to achieve minimal risk condition, given the same circumstances.

CAVs use the data provided over the wireless communication links to and from the vehicles to support driving automation systems at any of the five SAE International levels. CAV technologies are quickly expanding in the transportation and automotive markets and are envisioned to bring tremendous operational, safety, environmental, and institutional impacts at sizable market penetration rates (MPRs) (Shladover and Bishop 2015). The CAV MPR can be the percentage of vehicles on the roadways that are equipped with CAV technologies. To foster increased CAV market penetration within the near future, agencies are exploring a variety of strategies. One strategy, based on lessons learned from the implementation of managed lanes, is dedicating lanes to these special vehicles. By providing CAV users preferred access to some specific rights-of-way, CAV DL strategies could improve the performance of the transportation system and expedite the deployment of CAV applications.

One highly researched CAV technology is the CACC system, which uses a combination of sensors and V2V and I2V communication to enable a vehicle to adjust its speed automatically to the speed of the preceding vehicle in the same lane (Shladover et al. 2015). Given the level of research and development activity associated with CACC systems, the research team decided to use CACC as the evaluation model for conducting CAV research in this project. The team also utilized dynamic speed harmonization (DSH), which dynamically adjusts the speeds of equipped vehicles on a freeway, in response to downstream congestion, to improve throughput and reduce shockwaves and the associated possibility of secondary crashes (Ma et al. 2016).

For NCHRP 10-102(08), CAVs were defined as the class of vehicles that use CV technology to support some safety-critical and efficiency improvement functionality, and use automated control to manage the dynamic driving task for certain driving modes. In the modeling conducted for this project task, the CAVs were assumed to be partially automated (SAE International’s Level 2). Specifically, the CAVs were assumed to have an automated driving system performing the operational driving tasks (steering, braking, accelerating, and monitoring the vehicle and roadway) under a cooperative vehicle-following mode when in a DL. It was assumed that, under all other situations in the model, a human driver was operating the vehicle. Additionally, it was assumed that for all vehicles, including the CAVs, the human drivers performed all tactical and strategic driving tasks.

1.3 Report Overview

This report documents the analysis conducted as part of this research project, presents the analysis results, and provides generalized guidance. The report is organized into 10 chapters, as follows:

- **Chapter 1: Introduction.** This chapter introduces the research report, expands on the project scope, and defines CAVs in terms of automated versus human control.
• **Chapter 2: Categories of Benefits and Disbenefits to Stakeholders.** This chapter summarizes the literature review and identifies the types of stakeholders benefited (or disbenefited) when dedicating lanes to CAVs, factors influencing these benefits, and the potential performance measures.

• **Chapter 3: Connected and Automated Vehicle Applications.** Several CAV applications exist in the research industry today. Assessing all of them was beyond the scope of this study. This chapter documents the research team’s approach to down-selecting two CAV applications and suitable modeling techniques for use in this project.

• **Chapter 4: Case Study Site Selection.** This chapter documents the approach to choosing the right case study sites for conducting the analysis. The project team used modeling and simulation-based analysis to evaluate potential benefits and parameter sensitivity of CAV applications on overall traffic efficiency and safety.

• **Chapter 5: Analysis and Evaluation Approach.** This chapter documents the researchers’ analysis and evaluation approach to conducting simulation-based analysis on the selected case study sites. The chapter also expands on some of the analysis assumptions that readers should be aware of when utilizing the results and recommendations provided in this report.

• **Chapter 6: Evaluation Results.** This chapter expands on the results of the modeling and simulation-based analysis. The results are categorized based on sensitivity parameters analyzed in this research project. This chapter is highly technical and should be read in conjunction with the technical tables and figures provided.

• **Chapter 7: Review of Laws and Regulations Regarding Dedicating Lanes.** This chapter summarizes the literature review and identifies the laws and regulations regarding dedicating lanes to specific categories of users. Historically, lanes have been dedicated to HOVs, motorcycles and bicycles, buses, alternative fuel vehicles, and trucks.

• **Chapter 8: Guidance on Operational Characteristics and Impacts.** Based on the evaluation results presented in Chapter 6 and the laws and regulations presented in Chapter 7, this chapter expands on specific guidance for agencies interested in dedicating lanes to CAVs.

• **Chapter 9: Future Research Directions.** Although this project expanded the current spectrum of understanding with respect to dedicating lanes to CAVs, unknowns remain that require further research to understand how different applications may impact managed lane facilities. Chapter 9 presents specific research directions that may need to be undertaken in the near future.

• **Chapter 10: Conclusions.** This chapter summarizes the project analysis.
This chapter discusses the categories of benefits and disbenefits associated with dedicating lanes to CAVs. The discussion includes: (1) types of stakeholders who will be impacted directly by dedicating lanes to CAV users, (2) factors influencing the benefits and disbenefits, and (3) categories and lists of performance measures that represent these benefits and disbenefits. Figure 2.1 provides a summary of this discussion.

2.1 Types of Stakeholders

Dedicating lanes to CAVs directly impacts three categories of stakeholders:

- **DL users.** Depending on which vehicles are allowed on the DLs, these stakeholders could include CVs, AVs, or even HOVs and tolled single-occupancy vehicles (SOVs) in the case of high occupancy toll (HOT) lanes.
- **GPL Users.** These stakeholders include all CAVs and HOVs that do not use the DLs, as well as the unequipped SOVs that are not allowed on the DLs.
- **Facility Owners and Operators.** These stakeholders will see a shift in lane/facility usage as well as other performance measures.

2.2 Factors Influencing Benefits and Disbenefits

Based on a preliminary analysis, the impacts on each of these categories of stakeholders depend on factors pertaining to the DLs as well as the CAV technology and market penetration. The following subsections describe these influencing factors.

2.2.1 CAV Market Penetration

The CAV MPR represents the percentage of CAV users in a traffic stream at a given location. When evaluating various lane-use strategies, it is critical to estimate the potential economies of scale that attend CAV MPRs. Basically, the more people choose to use CAVs, the better the overall gain in corridor efficiency. Ongoing research has shown that incorporating DLs can make a significant difference in cases of low CAV MPR (e.g., less than 30%) (Talebpour et al. 2017). Moreover, the benefits to three user types—CAV users, GPL users, and facility owners/operators—increase as the CAV MPR increases. As more vehicles move to the DL, the level of service (LOS) of the GPL increases. Potentially, the GPL can achieve a drastically larger carrying capacity, resulting in improved overall system performance from the perspective of facility operators/owners. The CAV MPR can be a significant factor in determining the total benefits/disbenefits for different users.
2.2.2 Roadway Geometry

Roadway geometric configurations are likely to affect the impacts of CAV DLs. These configurations may include physical barriers, access points, length of the facility, multi-lane treatments, and shoulder use. The following sections briefly explain each of these configurations.

2.2.2.1 Physical Barriers

In some instances, physical separation of a managed lane may be necessary to ensure higher performance for the DL. Physical barriers may be needed when: (1) the prevailing speeds of the DL and GPL are significantly different; (2) undesirable weaving movements between the DL and GPL need to be limited; and (3) instances of toll evasion need to be prevented.

The phenomenon by which the speed of traffic on the DL is affected by the speed of traffic on the GPL is termed the frictional effect; the degree of congestion in the GPL impacts the speed of the managed lane (Fitzpatrick et al. 2016b). This study also found that the placement of soft but visible barriers (e.g., pylons) mitigated the influence of the GPL speed on managed lane operation: for an increase in speed of 1 mph on the GPL, the increased speed on the managed lane was 0.42 mph without pylons and 0.3 mph with pylons (Fitzpatrick et al. 2016b). For DL users, the primary benefit of a physical barrier is minimized impact of the GPL speed on the DL. However, a physical barrier also can have disbenefits. For example, the physical barrier reinforces the “snail” effect, whereby the slowest moving vehicle in an HOV lane can govern the speed of the entire lane (Kwon and Varaiya 2008). Furthermore, a physical barrier would produce disbenefits such as requiring an additional construction budget for building the barrier and potential delays for accident clearance due to limited access to the lane.
2.2.2.2 Access Points

In conjunction with the common trip characteristics, the number and locations of DL access points need to be considered thoroughly. Classification of a DL as having unlimited access or restricted access affects the lane’s design and operational characteristics. An inappropriate or poorly planned design for access points would likely waste investment funds, downgrade the performance of the DL, and erode public support for the DL. Furthermore, the number and locations of the access points could affect enforcement and even the safety of a DL. Continuous access is a common approach (and the least expensive approach) for part-time operation of a DL. Restricted access using features such as access zones or ramps generally is more expensive to implement and typically is reserved for large concurrent-flow or reversible facilities. With restricted access DLs, the major benefits for both DL users and GPL users are (1) a reduction in the number or length of road sections that involve possible weaving and (2) the same positive effects as those mentioned under physical barriers. The disadvantage of a restricted access DL is reduced safety at locations approaching the access points. Weaving motions can become concentrated at such locations as drivers experience more pressure to complete lane changes than would be the case with continuous access. Operating agencies need to evaluate closely the return on investment for constructing restricted access points in comparison to the performance trade-off for using a continuous access point.

2.2.2.3 Length of the Facility

It is suggested that the length of the managed lane be carefully considered and constructed based on the regional traffic patterns. The length of the DL could spark potential equity issues. For example, given the high investment cost of DLs, the owner can be expected to be sensitive to the return on investment.

Greater benefits can be expected for CAVs with a longer facility.

2.2.2.4 Multi-Lane Treatments

When warranted by the intended demand and given available space, developing a DL policy that incorporates multiple lanes is an effective way to scale up the DL deployment. Kwon and Varaiya (2008) showed that the capacity of a single-lane DL could be reduced by 20% due to the so-called “snail” effect, when a faster vehicle cannot pass the slower one in front of it. Eliminating the snail effect and increasing capacity requires the DL to have more than one lane. The 14.5-mile, 2-lane HOV segment on SR-91 in Orange County, California, does not seem to suffer from the snail effect. The Port Authority of New York and New Jersey (PANYNJ) is considering adding a second bus-exclusive lane on I-495 with the option of passenger-vehicle usage on payment of an additional toll (Hess et al. 2011).

2.2.2.5 Shoulder Use

Shoulder use is an important influencer for DL management. For example, a Bus on Shoulders (BOS) policy was implemented in 2006 by the New Jersey Department of Transportation (New Jersey DOT) as part of the Enhanced Bus Improvement Program. The original shoulder of a 6-lane arterial highway was improved by adding full-depth pavement for buses on the shoulder. A speed limit of 35 mph was imposed on the shoulder, which is reserved for buses from 5 am to 9 am during weekdays. Approximately 440 buses and 6,800 passengers were served daily during the peak period when BOS is in effect (Martin et al. 2012).
2.2.3 Enforcement Intensity

Enforcement of the proper use of DLs is vitally important, regardless of whether the vehicles are operated using manual or automated methods. For CAV users, enforcement ensures both a high LOS on the DL and greater safety, as it reduces the likelihood that GPL vehicles will cut into the DL. Regardless of the enforcement method chosen, however, enforcement comes with a cost. Consistent, effective enforcement confers the greatest benefits when significant differences exist in the LOS between the GPL and the DL. In the context of CAV DLs, a system that can discern GPL vehicles from CAVs needs to be developed and implemented. Additionally, the facility design should be conducted with enforcement in mind. For CAV DLs, the primary enforcement task involves confirming DL user eligibility, by detecting the CAV equipment of individual vehicles (e.g., the DSRC onboard unit). This enforcement task can be performed easily through roadside equipment deployed along the lane. If the DL allows HOV/HOT users, however, it can be challenging for roadside equipment to detect in-vehicle passengers. To enhance DL enforcement and reduce violations, suggested actions include:

- Conducting engineering meetings with state highway patrol officials to determine roadside enforcement locations;
- Introducing prominent roadside signs that specify the consequences of violations; and
- Adopting methods for conducting random visual and special enforcement that can be deployed in addition to routine enforcement methods (FHWA 2016a, FHWA 2016b).

2.2.4 Toll Collection Technology and Toll Pricing Methods

Electronic toll collection technology makes variable pricing simple and easily accomplished. The deployment of DSRC and other technologies (e.g., license plate capture) can further automate enforcement tasks. Several products are market-ready, but more research is needed with regard to developing technologies that can automate enforcement for all possible operating scenarios, including cost-effective, large-scale deployment of automated passenger occupancy detection technologies. Enabling legislation also may be warranted (McCune 2015).

Toll collection information (e.g., pricing, travel times) also could impact adoption and usage of DLs. Ideally, CAV users could receive the toll collection information directly into their cars, potentially reducing the need for expensive overhead signage.

2.2.5 Operation Hours

The hours of operation for managed lanes typically are determined by traffic congestion conditions (Fisher 1995, Dahlgren 2002, Kwon and Varaiya 2008, and Avelar et al. 2016). During highly congested periods (such as a.m. and p.m. peaks), access to the managed lanes is restricted to the users designated by the owner/operator’s policies; during other time periods, the lanes typically are opened to all GPL users. The hours of operation for managed lanes can affect the performance of one or several travel lanes dramatically. Careful consideration of the hours of operation of managed lanes can minimize potential adverse effects of the managed lanes on the rest of the traffic.

2.2.6 CAV Technology Types and Implementation

CAV technology and applications are evolving rapidly. The U.S.DOT has conducted significant research on a wide range of CV applications. These applications include both V2V and V2I technologies. The specific CAV technology implemented will have a huge impact on the benefits and disbenefits achieved.
2.2.7 Functional Types

Given low MPRs during the initial stages of dedicating lanes for CAVs, CAVs may need to share the DL with other users, or even GPL users (e.g., in the case of HOV/HOT lanes). Various functional DLs can be listed based on their user types, as follows:

- **CAV DL.** A lane that can be used by both CV and AV groups;
- **CAV + HOV Lane.** A lane that allows CVs, AVs, and HOVs to travel, making this type of lane one of the viable transition options to promote both CV and AV usage with existing HOV lanes; and
- **CAV + HOV and HOT Mixed-Use Lane.** A lane that gives priority for CAVs, HOVs, and HOT vehicles with the goal of moving as many passengers as possible on the managed lane.

The demand for HOV travel heavily affects the success of HOV lanes, as demonstrated by multiple case studies shown in Murray et al. (2000). The same logic can be applied to other DL strategies. Underutilization of a DL not only creates a negative impression of DLs among GPL users, it also can worsen the mobility performance of the GPL if more vehicles are forced to use the GPL because of ineligibility to access the DL. Since the passage of the Transportation Equity Act for the 21st Century (TEA-21) in 1998, broadening access to HOV/HOT lanes for low-emission and energy-efficient vehicles when available capacity exists has expanded the user group for these DLs. As of October 2013, 13 states had adopted provisions that allow special groups of vehicles to use HOV/HOT lanes. Some states issue special license plates, stickers, permits, or decals to identify the exempted vehicles, and some states charge a small fee (e.g., $8 per use in California) (Turnbull 2014). For example, a physically separated managed lane facility was initiated on the reversible 2-lane stretch of I-15 in northern San Diego County, California. The managed lane was designed initially for use only by HOV traffic, but the policy was adjusted to allow SOV users to pay to travel on the HOV lane. The fee for using the HOV lane varies depending on the level of congestion of the corridor. Information to motorists is provided via changeable message signs—also called dynamic message signs or variable message signs (VMS)—that can be updated as frequently as every 3 minutes (Brownstone et al. 2003).

Taking a similar approach to CAV DL implementation, CAV users could preserve a higher right-of-way on the DL. Such a policy would attract more CAV demand into the DL. As a result, GPL users could benefit from reduced CAV demand on the GPLs, which improves the LOS for the GPLs. In turn, the owner/operator could retain public support for the DL policy being implemented.

2.3 Performance Measures

Increasingly, CAV applications have gained attention due to their potential to enhance traffic operations fundamentally. To implement the managed lane strategies for CAV technologies successfully, the research team grouped the relevant factors into four subcategories for dedicating lane(s) to CAVs (see Figure 2.2). Details on each subcategory are discussed in the balance of this section.

2.3.1 Mobility

Mobility performance measures can be used to assess improvements in the ease of moving travelers and vehicles in a network. These measures can include origin-destination patterns, daily peak hours, recurrent congestions, and so forth. When implementing managed lane strategies, it is important to ensure that the strategies are suitable for the traffic flow characteristics.
Four major factors are associated with mobility: level of congestion, travel time reliability, average speed, and vehicle occupancy.

2.3.1.1 Level of Congestion

On most occasions, the level of congestion of a roadway or a corridor provides justification for the authority to implement appropriate managed lane strategies. Dahlgren (2002) studied the relationship between the effectiveness of a managed lane and congestion level of a roadway, concluding that adding a mixed-flow lane is more effective in delay reduction than an HOV or HOT lane when initial maximum delay is 30 minutes or less. If initial delay and HOV MPR are very high, however, an HOV lane would become more effective than either a mixed-flow or HOT lane (Dahlgren 2002). Dedicating lanes to CAV users may alleviate traffic congestion in a similar way. DL users gain benefits from the increased mobility under heavy congestion, GPL users remain at the same LOS, and the operator likely gains the benefit of a more productive facility.

2.3.1.2 Travel Time Reliability

In measuring both recurrent and non-recurrent congestion for a specific roadway, travel time reliability factors indicate the extra time a traveler has to allocate for likely on-time arrival. Value of time (VOT), along with value of reliability (VOR), are primary indicators for whether a road user will pay to use a managed lane (i.e., a HOT lane). As discussed in the I-394 MnPASS case, the VOT is the monetary value that a managed lane user places on the reduction of travel time, whereas the VOR is the monetary value that the user places on improvement of travel time predictability (Carrion and Levinson 2012, Janson and Levinson 2014).

2.3.1.3 Average Speed

One operational goal of DLs is to prevent demand from reaching the roadway’s carrying capacity, because the stability of the flow deteriorates as the demand of a roadway approaches its capacity. Unstable flow is likely to result in delays at best and in breakdown conditions at worst. A study in California by Kwon and Varaiya (2008) showed that HOV lanes typically achieve 1,600 vehicles per hour per lane (vphpl) at 45 mph speed, and that throughput is not linearly
related when demand is close to carrying capacity. To harness the optimal cruising speed for the DL, optimal average speed needs to be determined after considering the trade-offs with mobility. CAVs could achieve smaller headways using applications such as CACC systems, which could enable free-flow speeds to be maintained even at higher traffic volumes.

### 2.3.1.4 Vehicle Occupancy

Vehicle occupancy is less influential on performance outcome when the MPR for CAVs is low. When the MPR becomes high, however, depending on the CAV lane-use strategies, change in occupancy could alter the outcomes for performance. Thus, the vehicle occupancy rate can be a direct indicator to examine the impact of CAV technologies for both GPL and DL users, depending on the lane management policies adopted by the operator (e.g., HOV 2+, HOV 3+).

### 2.3.2 Safety

Traffic safety is a crucial factor in the implementation of CAV technologies. In this study, the two performance measures considered for safety were crash rate and speed fluctuation/difference.

#### 2.3.2.1 Crash Rate

The crash rate is a reliable representation of roadway safety. It is the ratio of the number of crashes at a given period to the vehicle-miles traveled (VMT). Combined with appropriate managed lane strategies, CACC has the potential to reduce the overall crash rate at an implemented roadway. Given that managed lane strategies can provide CACC-equipped vehicle groups with an exclusive right-of-way, a homogeneous traffic stream could be achieved in the managed lane, thereby resulting in traffic conditions that reduce the human drivers’ interference with vehicle maneuvers. CAV applications also could provide enhanced information and faster reaction times to the CAVs’ ”driving systems” in order to reduce crash rates. For example, CAV applications could provide advance information about congestion queues in order to reduce the frequency of secondary crashes that occur when fast-moving vehicles suddenly approach much slower or stopped vehicles.

#### 2.3.2.2 Speed Fluctuation/Differences

Given that crash statistics rely on a large amount of data, collecting data on direct safety performance measures such as crash rates would have been challenging for this study. To overcome this issue, surrogate safety measures were applied to examine the safety impacts of transportation system improvements. Unfortunately, the surrogate measures that have been developed have only been validated for human-driven vehicles, not for vehicles that are partially (or completely) driven by computer. As a result, and reflecting the differences in the factors that determine traffic safety for CAV versus human-driven vehicles, these surrogate measures can only be applied to CAV systems with extreme caution.

Among the various surrogate safety measures, speed fluctuation is one of the primary factors for the occurrence of both initial and secondary traffic crashes. Speed fluctuation can be measured in terms of the difference in 95th percentile spot-speeds of vehicles, between lanes, segments, or even time frames. After implementing CV, AV, and CV and AV DL strategies, any changes in speed fluctuation should be studied to quantify the actual effects of these strategies on safety performance. The implementation of CV, AV, and CV and AV DL strategies will likely reduce speed fluctuations (and therefore improve traffic safety), but to date measurement of speed fluctuation has been conducted indirectly, using data collection technologies such as
inductive loop detectors, radar sensors, and probe vehicles (Gettman et al. 2003). For implemented CAV DL lanes, the existing approaches to measure speed differences can be retained while CV technologies enable the capture of individual vehicles’ speed profiles. Speed information could be obtained from basic safety messages from CVs equipped with DSRC. Moreover, while it is not mandatory to share the data, AVs that are capable of detecting adjacent vehicle movements could produce high-fidelity local speed fluctuation data.

2.3.3 Energy and Environment

Frequent braking and acceleration has been shown to be energy inefficient and can increase emissions (Rakha and Ding 2003). Specifically, energy is lost through decreased momentum when vehicles brake and increased fuel is used to create the energy needed when accelerating to return to the original speed. CAVs on a DL can mitigate the impacts of braking and acceleration because the CAVs can coordinate and smooth out their speed changes, accelerating and decelerating in an automated manner. Kall et al. (2009) used the MOBILE-Matrix model to predict the change in emissions resulting from the conversion of an HOV lane to a HOT lane on I-85 in Georgia. Four pollutants—carbon monoxide, hydrocarbons, oxides of nitrogen, and particulate matter—were considered in the study, which found that the vehicle emissions are influenced by change in VMT, speed, and vehicle fleet characteristics (Kall et al. 2009). Similar model-based approaches could be applied to estimate emissions and fuel consumption. Furthermore, the CAV environment with sufficient MPRs will enable direct collection of emission and fuel consumption from CAVs to improve the quality of emission and fuel consumption models.

2.3.4 Societal Justice

It is necessary to consider the societal impacts of CAV technologies. This section describes three performance measures covering the perspectives of social justice and public relationships.

2.3.4.1 Perception of Exclusivity

The concept of dedicating some lanes for use by particular vehicle groups is philosophically debatable and could potentially create or aggravate social justice bias related to incomes and social class. Depending on the strategy and policies applied to create a CAV DL, some groups of people may not be able to afford access. Studies of the willingness to pay for HOT service concluded that high-income users were more likely to consider alternative travel means, compared to low-income users (Finkleman et al. 2011).

2.3.4.2 Equity

Approaches to equity issues can be considered in developing DL strategies for combinations of CV, AV, HOV, and HOT users. Possible considerations include:

• Providing GPL vehicle users with subsidies or cost incentives to expedite the transition from GPL vehicle to CAV;
• Ensuring the presence and designation of redundant/alternate roadways so that users have choices beyond the GPLs; and
• Conducting DL design with consideration for the limited availability of and accessibility to CAV lanes for low-income people.

Agencies can involve individuals with low income in the planning process by providing various incentives (e.g., partial tax relief, monetary subsidies, educational advantage) depending on
the situation of the community. Addressing potential equity and environmental justice issues often is vital to obtaining the support needed to implement and design DL projects. It is important to consider equity at all stages of the project to ensure a successful implementation and establish the foundation for future similar projects in the region. Equity issues should be analyzed and presented proactively and as early as practical. It can be difficult to gain public support, especially if perceived equity issues are not adequately considered. Some general guidelines have been used by public agencies to address similar concepts (e.g., road pricing projects), and these can be considered when developing CAV DLs.

Despite pervasive references to equity, consensus on the definition of equity has not been reached, because the possible dimensions for what constitutes an equitable policy depend on the context and community priorities. Regarding equity for DLs, key concerns include:

- Whether it is reasonable and acceptable for certain groups to disproportionately receive positive impacts (benefits) or negative impacts (disbenefits) from the DL,
- How large the differences are between the benefits received by favored groups and the disbenefits received by disfavored groups, and
- What compelling public policy objective is served by introducing the inequity (Weinstein and Sciara 2004).

The most common concern regarding DLs is affordability for low-income groups to use the facilities or technologies. With HOT lanes, it was observed that low-income groups of users used the service depending on the importance of a trip (FHWA 2008a); however, users of CAV technologies are likely to have higher incomes in areas of low MPR. The necessary initial investments for acquiring CAV technologies make it challenging to use the HOT lane case as a model for implementation of a CAV DL.

Geographic equity is important with respect to the spatial patterns or apparent segregation in accessibility for different constituencies. In the case of Maryland’s US-50, it was argued that suburban commuters with higher incomes received disproportionately more benefits from the HOT lane, compared to residents who lived near downtown and had no access to the lanes (Weinstein and Sciara 2004). It is not uncommon that the geographic equity implications change as a project expands or changes.

Modal equity should not be overlooked, especially when the operator would like to promote certain modes of transportation (e.g., HOV, transit, CAV) and provide incentives to users for choosing one mode of travel over another. Similarly, when considering the improved mobility of goods, which directly affects the nation’s economic growth, truckers should be considered in the distribution of CAV DL benefits from modal equity perspective. The Minnesota legislature decided to direct 50% of HOT lane revenues in excess of project cost on I-394 to transit in the corridor. Some advocacy groups proposed that the pricing on the HOT lane on SR-167 in Seattle, Washington, should include a minimum toll, which is higher than the transit fare in the same corridor.

Environmental justice is an important aspect of social equity and should be given a fair consideration. During the planning and design phase for dedicating lanes for CAVs, it is important to ensure that the project does not have a disproportionately high and adverse human health and environmental effect, which often has a greater or more direct impact on minority and lower-income populations. It is also important to prevent denial of, reduction in, or significant delay in the receipt of DL benefits by minority and low-income populations. Similar to HOT lanes, the CAV DL should be carefully evaluated in all categories of equity, as the mobility of the CAV DL is expected to be higher than that of the GPL due to the inherent advantages of CAV technologies (e.g., V2V communication, V2I communication, CACC, self-driving). No policy, not even a well-designed and carefully considered one, will impact all groups equally. The operator
should strive to attain the most equitable and feasible distribution while factoring in community acceptability and the overall transportation system impacts.

2.3.4.3 Public Outreach

Public acceptance is vital for the sustainability of any DL strategy. Cases have shown that a near-empty lane can adversely affect public support. Public outreach about “empty-lane syndrome” is necessary to ensure understanding that the DL actually moves more people through the corridor despite carrying fewer vehicles. Agencies can perform stakeholder engagement activities prior to the planning stage to assess the level and outlets of public outreach to help develop project goals and objectives. Furthermore, outreach efforts from government agencies (e.g., U.S.DOT, state DOTs) need to be actively performed through various types of activities (e.g., webinars, educational outreach, public hearings, field demonstrations) to achieve successful deployment of CAV and ITS technologies.
CHAPTER 3

Connected and Automated Vehicle Applications

This chapter summarizes the process used to select the CAV applications and evaluate the available modeling frameworks for use in this project.

3.1 Selection of CAV Applications

Given that the objective of this research was to evaluate the conditions amenable for dedicating lanes to CAVs, the team evaluated the various CV applications that have been envisioned by the U.S.DOT.

Table 3.1 lists the CV applications and their suitability in being modeled as a CAV application in a dedicated freeway lane facility. The three criteria utilized in this selection process were:

- Suitability to DLs, in the sense that the applications should support CAVs throughout their travel on a freeway corridor;
- Suitability to the CAV environment (to eliminate CV applications that rely on human driving behavior); and
- Adaptability to simulation models, so that their sensitivity and impacts could be assessed through modeling and simulation.

The team evaluated 17 freeway applications. For informational purposes, Table 3.1 also includes the non-freeway applications on the U.S.DOT’s list of applications.

Based on Table 3.1, the following nine applications are suitable for modeling as a CAV application within a freeway DL environment.

- **Application 1: Reduced Speed/Work Zone Warning.** This application utilizes I2V communication to broadcast alerts to drivers or vehicle control systems, warning them to reduce speed, change lanes, or come to a stop within work zones. In a CAV environment, this application utilizes the connectivity part to receive localized speed restrictions or closure information to adapt the desired speed and lane choice. Owing to its limited applicability (based on vicinity of work-zones), however, the team did not recommend modeling this application in a DL environment.
- **Application 2: Connected Eco Driving.** This application uses V2V/V2I data to provide customized real-time driving advice to drivers as well as vehicle control systems, including recommended driving speeds and optimal acceleration/deceleration profiles, so that they can adjust their driving behavior to save fuel and reduce emissions. In a CAV environment, this application would be similar to platooning vehicles using an energy/emissions-optimized CACC system.
- **Application 3: Eco-Lanes Management.** This application establishes parameters and defines the operations of eco lanes. Eco lanes are managed lanes that use traffic management strategies or enforce in-vehicle applications that aim at reducing energy consumption or emissions by the vehicles. Eco lanes require other applications, such as connected eco driving or eco speed...
harmonization, to be enforced to gain environmental benefits. In a CAV environment, an eco-lane would be a DL that provides exclusive access to vehicles controlled using an energy/emissions-optimized CACC system or a speed harmonization system.

- **Application 4: Eco-Speed Harmonization (ESH).** This application determines speed limits optimized for the environment based on traffic conditions, weather information, and greenhouse gas and criteria pollutant information, allowing for speed harmonization in appropriate areas. This application is similar to variable speed limit applications that are optimized for energy and emissions. In a CAV environment, the application would use V2I information to obtain dynamic speed limits and automated longitudinal control to govern the speed.

- **Application 5: Eco-CACC.** This V2V application uses CV technologies to collect speed, acceleration, and location information from other vehicles and integrate these data into a vehicle’s ACC system, thus allowing for automated longitudinal control capabilities and vehicle platooning to reduce fuel consumption and emissions. This application is similar to the CACC application, but the speed-selection function utilizes energy/emissions modeling to minimize fuel use and emissions.

- **Application 6: DSH.** This application aims to recommend target speeds to equipped vehicles in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes. This application is similar to dynamic speed limits, where speed limits are governed to reduce sudden decelerations or shockwaves across the network. In a CAV environment, the application would use V2I information to obtain dynamic speed limits and automated longitudinal control to govern the speed.

- **Application 7: Queue Warning.** This application aims to provide drivers with timely warnings of existing and impending queues. For purposes of CAV DL modeling, this application needs to be coupled with speed harmonization or route guidance applications.
• **Application 8: CACC.** This application aims to dynamically adjust and coordinate cruise control speeds among platooning vehicles to improve traffic flow stability and increase throughput. CACC uses connectivity to link the speed-selection functions of vehicles in a platoon and automate control for precisely following a given speed profile. This application was already selected for modeling under this project.

• **Application 9: Incident Scene Work Zone Alerts for Drivers and Workers.** This application warns on-scene workers of vehicles with trajectories or speeds that pose a high risk to their safety. It also warns drivers passing an incident zone if they need to slow down, stop, or change lanes. The reduced speed/work zone warning application is a subset of this application. In a CAV environment, V2I information would be utilized for vehicles to receive advisory speed and lane closure information. Automated control would adapt to this precise speed change and engage automated lane-change for this application. Owing to its limited application (based on vicinity of work-zones/incident zones), however, the team did not recommend modeling it in a DL environment for this project.

### 3.1.1 Recommendations

After careful review of these applications, the following applications were selected for implementation in NCHRP Project 20-102(08). Each of these applications is representative of multiple applications reviewed in the previous section.

• **Recommended Application 1: CACC.** This application aims at platooning equipped vehicles on a lane by adjusting and coordinating vehicle cruising speeds and headways. In addition, the vehicles use connected and automated control to form CACC platoons via rear, front, and cut-in joining as more equipped vehicles are found within the vicinity of each other. This application was reviewed in detail in Shladover et al. (2015). For purposes of this study, Eco-CACC and Connected Eco-Driving are similar applications, except that they aim at reducing energy/emissions as opposed to improving throughput and safety.

• **Recommended Application 2: DSH.** This application aims to harmonize vehicle speed on the freeway to minimize shockwaves and potentially improve system mobility by detecting congestion or queues downstream. In a connected environment, vehicles use V2I communication to transmit information about their traffic states to a central command, which finds the optimum speeds for the vehicles to travel in the upstream sections and uses V2I communication to provide this information back to the vehicles. Similarly, ESH aims to optimize vehicle speeds to reduce energy/emissions of the vehicles in the network. DSH and ESH usually are coupled with Queue Warning, which is used to detect downstream traffic states that are congested or queued. Depending on downstream traffic states, the Queue Warning application will engage a speed reduction strategy to prevent sudden deterioration of traffic states over the freeway networks, thereby reducing chances of shockwaves. For this project, the research team proposed using a version of the DSH application that aims to implement an advanced speed control strategy over the DLs. The application seeks to adjust vehicle speeds to maximize throughput through a bottleneck or gradually reduce the speed of traffic approaching a congestion queue to reduce secondary crashes at the end of the queue.

### 3.2 CACC Application

The CACC is a CAV application that uses a combination of sensors and V2V communication to enable vehicles to adjust their speeds automatically in relation to the preceding vehicles in the same lane. CACC-equipped vehicles utilize connectivity and a range of sensors to increase situational awareness and engage automated methods of acceleration and deceleration, which are more accurate than human control. CACC-equipped vehicles dynamically and automatically coordinate cruise control speeds within groups of vehicles to increase traffic throughput.
significantly (Figure 3.1). By tightly coordinating vehicle movements, vehicle headways can be significantly reduced, resulting in a higher vehicle density. The coordination also produces a smoothing of traffic flow, or an improvement in traffic flow stability. A CACC string is defined as a group of CACC-equipped vehicles that use connectivity and automated longitudinal control to act as a platoon of vehicles with short headways (Shladover et al. 2015).

3.2.1 Existing CACC Application Models

Precisely modeling CAV applications such as CACC is vital in understanding the conditions amenable to dedicating lanes for CAVs using modeling and simulation. Additionally, the analysis of CAV technologies generally requires detailed, high-resolution data, and advanced functionalities to properly deal with the uniqueness of CAVs. This analysis differs from traditional traffic analysis studies such as signal optimization traffic impact analysis. Specifically, connected and automated technologies rely on sensor-based and CV data and need to be modeled into any assessment framework.

This section reviews the state-of-the-art CAV modeling tools used to conduct the analysis of CAV DL strategies. Six models are included for in-depth review and represent the most advanced DL applications for CAV. They are:

- A macroscopic model by Nikolos et al. (2015), referred to as Nikolos’ Model;
- A hybrid CAV analysis framework proposed by the Volpe National Lab (Smith et al., 2016), referred to as the Volpe model;
- An Aimsun-based CACC evaluation model by Shladover et al. (2012), referred to as the CACC-Aimsun model;
- The MICroscopic model for Simulation of Intelligent Cruise control (MIXIC) by Van Arem et al. (2006), referred to as the MIXIC model;
- The Flexible Agent-Based Simulator of Traffic (FAST) by Arnaout and Bowling (2011), referred to as the FAST model; and
- A Vissim-based CACC DL analysis model by Lee et al. (2016b), referred to as the CACC-Vissim Model.

With some modifications to the tool, each of the selected modeling tools could be implemented to conduct the analysis of CAV DL strategies. In this report, additional discussion in Chapter 4 presents additional discussion combining the results of the research team’s review with an evaluation of each modeling tool in relation to its applicability for analyzing CAV DL strategies.

3.2.1.1 Nikolos’ Model

Nikolos et al. (2015) proposed a macroscopic approach to examine the impact of ACC and CACC by incorporating traffic dynamics into a gas-kinetic traffic (GKT) flow model initially developed by Ngoduy (2013). Such a macroscopic approach can only represent the density difference between manual driving, ACC, and CACC; it cannot represent the vehicle-following dynamics differences among these different modes of operation. The GKT model handles the behavior of a group of vehicles, specified by their location (X), speed (V), and desired speed (V0) at any instant (t) and phase space density (p). Put another way, the

Figure 3.1. Illustration of CACC application for CAVs (Semsar-Kazerooni et al. 2016).
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

Phase space density ($p$) represents the expected number of vehicles driving with speed ($V$) while having desired speed ($V_0$) for a certain roadway segment at a specific location ($X$) and time ($t$). The GKT model describes the changes in $p$ caused by both the inflow and outflow in the phase space and the interactions (such as gaps between consecutive vehicles) between the vehicle groups. Thus, the $p$ can be changed depending on the significance of the interaction. Given the CACC environment that enables the exchange of real-time driving information, the gap between vehicles in the CACC group will decrease, resulting in increased phase space density.

Nikolos et al. (2015) applied the GKT model to evaluations of ACC and CACC under mixed-traffic conditions. Two simulation scenarios were tested: (1) a 6-mile-long basic freeway segment with homogenous traffic and (2) an 18-mile-long freeway segment with an on-ramp. Figure 3.2 and Figure 3.3 show the spatio-temporal changes of densities in manually driven vehicles and

**Figure 3.2.** Density change in homogenous traffic condition: ACC (left) and CACC (right).

**Figure 3.3.** Density changes with an on-ramp: ACC (left) and CACC (right).
CACC-equipped vehicles for both scenarios. No validation efforts were made, but this model produced reasonable results as demonstrated by the density changes in these figures. The results for CACC showed fewer instances of traffic shockwave—and almost no instances of aggressive propagation of traffic shockwave—due to vehicle acceleration and deceleration trajectory when compared to trajectory results for ACC. The results for ACC showed several instances of traffic turbulence caused by fluctuating density due to queuing propagation. Considering the length of the test segment, the model appeared suitable for evaluating the impact of CAV technologies in a large-scale area. However, because it assumes 100% MPR for either ACC or CACC, Nikolos’ Model was challenging to work with in relation to effectiveness under various MPR scenarios. To overcome this challenge, Delis et al. (2015) had extended the model by incorporating distinctive values for the relaxation time parameter of the phase space density function depending on the market penetration. Figure 3.4 displays the changes of densities with 10% and 50% of CACC MPRs for the homogeneous traffic conditions and Figure 3.5 displays the changes for the on-ramp case (Delis et al. 2015).

**Figure 3.4. Density change in homogenous traffic condition: 10% CACC (left) and 50% CACC (right).**

**Figure 3.5. Density change with an on-ramp: 10% CACC (left) and 50% CACC (right).**
3.2.1.2 Volpe CAV Analysis Framework

Smith et al. (2016) have proposed an analytical modeling framework for assessing the benefits of AV operations. The proposed Volpe CAV Analysis Framework is a comprehensive approach for the quantitative assessment of the wide-ranging impacts of various automation scenarios (or levels). Given that these scenarios serve as inputs to the framework, the outputs of the framework are intended to help inform policy decisions. The framework is designed to facilitate the comparison of multiple scenarios—the degree of V2I and V2V connectivity and the different level of automation. At the time of the research for this study, the Volpe model was a work in progress and therefore was not available for modeling as part of this project; nonetheless, the project team wished to include discussion about this proposed analysis framework owing to its overarching capabilities in modeling components of a transportation system.

The Volpe CAV Analysis Framework also incorporates several interrelated sub-models to assess the impacts in terms of safety, mobility, energy/environment, transportation system utilization, accessibility, land use, and economic analysis, as shown in Figure 3.6.

Figure 3.6 illustrates the data flow among the sub-models in the framework. The outputs from the safety, land use, accessibility, regional mobility, and energy/environmental sub-models feed into the economic analysis sub-model. The safety and vehicle mobility sub-models feed each other. The output of the vehicle mobility model also feeds into the energy/environmental and regional mobility sub-models. The regional mobility sub-model feeds to the sub-models for the land use, accessibility, and transportation system usage models. There are feedback loops from the land use and accessibility models to the transportation system usage model and from there to the vehicle mobility and safety models. With the sub-models, the framework is designed to evaluate the following AV applications:

- Collision Avoidance,
- Traffic Jam Assistance,
• CACC,
• Automated Platooning, and
• Full Automation in a Controlled Environment.

As shown in Figure 3.7, the framework is triggered from the safety and mobility sub-models. Once an application is selected, the safety sub-model estimates the likelihood of crash occurrence by considering the behavior of the driver/vehicle. Inputs to the safety sub-model include the initial safety environment (e.g., position, driving condition), the attributes of the unequipped and equipped vehicles, including the vehicle itself (e.g., light vehicle versus truck), vehicle control (e.g., the level of automation that exists), and the driver (e.g., reaction time distribution).

The safety sub-model estimates safety performance measures such as crash probability and severity, which feed into the next sub-models in Figure 3.6. In parallel, the vehicle mobility sub-model handles longitudinal and lateral maneuvers of individual vehicles (e.g., car following, lane changing, braking). The same inputs as the safety sub-model are applied for the vehicle mobility sub-model, as shown in Figure 3.7. Given the inputs, the vehicle mobility sub-model calculates the driving performance of individual vehicles such as speed, travel time, speed difference, headway, and acceleration/deceleration rate. These performance measures are provided to the next sub-models to estimate link-wise and region-wise performance for mobility, safety, and environmental assessment. Economic analysis combines all the outputs produced by each sub-model.

Source: Smith et al. (2016).

Figure 3.7. Overall data flow diagram in the Volpe framework.
At publication of this report, the sub-model for vehicle mobility remained in the development stage, utilizing a microscopic traffic simulation platform. Employing a step-wise approach, the entire framework is designed to evaluate selected AV applications in a simple single-lane condition and expand to more complex road networks. The research team suggests that, once it is complete, the proposed Volpe framework will be extremely useful to conduct large-scale evaluations for CAV applications; however, it will not be available for use within this project’s timeframe.

### 3.2.1.3 CACC-Aimsun Model

Shladover et al. (2012) developed a microscopic simulation model to evaluate the performance of ACC and CACC on highway capacity under various market penetration conditions. Utilizing Aimsun (a commercial-off-the-shelf microscopic traffic simulator) with a Software Development Kit (SDK), the authors constructed an evaluation platform to handle the various scenarios reflected by the MPRs of ACC and CACC. In addition to ACC and CACC, the authors introduced a vehicle group to represent vehicles equipped with a vehicle awareness device (VAD) capable of providing adjacent equipped vehicles with real-time Here-I-Am (HIA) information. This information includes real-time position, speed, and heading information. Although the HIA vehicles are unable to conduct automated operation, the information disseminated from them will be helpful for the operation of CACC under low MPRs that could represent an early stage of CAV deployment.

Using 10% increments for each HIA, ACC, and CACC driver group, the researchers evaluated 192 simulation scenarios to assess the impacts of different combinations of HIA, ACC, and CACC on roadway capacity (Shladover et al. 2012). Starting from the baseline case (i.e., 0% MPRs for HIA, ACC, CACC), the impacts of the HIA versus CACC case and the ACC versus CACC case, producing 81 scenarios for each case, were examined using a 4-mile-long single-lane hypothetical freeway segment modeled in Aimsun. Significantly, to achieve all the flow measurement in a steady condition, the test segment was modeled with no on- and off-ramps, resulting in no lane changes. The longitudinal control dynamic models for both ACC and CACC were obtained from empirical data. The ACC car-following rules are proprietary to Nissan, and the CACC longitudinal control was customized from Bu et al. (2010). Both algorithms were simplified to be modeled in Aimsun using its Micro-SDK. The car-following behaviors for both manually driven and HIA vehicles were controlled by the NGSIM oversaturated freeway flow model developed by Yeo (2008) and Yeo et al. (2008), which are based on Newell’s linear model. The desired target time gap settings of the ACC or CACC-equipped vehicles were selected based on field test observations (Shladover et al. 2009, Nowakowski et al. 2014, and Shladover et al. 2014). The distributions of target time gap for ACC and CACC were as follows:

- **ACC**: 31.1% at 2.2 seconds, 18.5% at 1.6 seconds, and 50.4% at 1.1 seconds; and
- **CACC**: 12% at 1.1 seconds, 7% at 0.9 seconds, 24% at 0.7 seconds, and 57% at 0.6 seconds.

The base-case condition consisted of all manually driven vehicles and was calibrated to produce a capacity of 2,018 vphpl by considering the potential disturbances in vehicle motions and the diversity of driver gap selections. For the ACC and manually driven vehicles, the MPRs of ACC had a negligible influence on the achievable capacity, resulting in the narrow range from 2,030 to 2,100 vphpl. For the CACC and manually driven vehicles, the capacity increased from nearly 2,000 vphpl to nearly 4,000 vphpl, as shown in Figure 3.8. In this experiment, the CACC mode was available only when the CACC-equipped vehicle was behind another CACC-equipped vehicle or a vehicle equipped with a VAD, with the exception of the first vehicle of the CACC group, which used ACC mode to follow an unequipped lead vehicle. Thus, the increase of capacity grew quadratically as the MPR increased, resulting in 3,970 vphpl of capacity at the 100% CACC rate. It was also discovered that introducing VAD devices provides real-time vehicular information to the following CACC-equipped vehicle, which enables increased capacity. Figure 3.9 shows the capacity
increase with respect to the combination of CACC and HIA on the left and the combination of CACC and ACC on the right (Shladover et al. 2012).

More recently, the CACC-Aimsun model was extended to include multi-lane freeway scenarios with entry and exit ramp traffic, allowing for assessment of more complex traffic scenarios under a current FHWA Exploratory Advanced Research Program project (Shladover et al. 2018). That model was calibrated for the baseline all-manual-driving scenario by use of detailed archived traffic data from the SR-99 freeway corridor in the Sacramento region.

3.2.1.4 MIXIC Model

MIXIC is a non-commercial microscopic traffic simulator developed by the Netherlands Organization for Applied Scientific Research (also known as Toegepast Natuurwetenschappelijk Onderzoek, or TNO) for the assessment of the impacts of CAV applications (Van Arem et al. 2006). With a simulation resolution of 0.1 second, the MIXIC model estimates various performance measures covering mobility (e.g., travel time, delay), safety (e.g., time to collision), and
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

environmental impacts (e.g., exhaust-gas emission, noise, fuel consumption). Based on a modular structure, MIXIC is flexible to customize vehicle models for handling longitudinal and lateral maneuvers. Making use of this flexibility, the authors conducted an assessment of Advanced Driver Assistance Systems (ADAS) such as ACC, automated platooning, special lane for intelligent vehicles, cooperative following and merging, V2V communications (also known as CarTalk), and CACC (Van Arem et al. 1997).

Van Arem et al. (2007) also used MIXIC to examine the traffic flow impact of CACC on a 3-mile-long four-lane highway with a lane drop in the downstream causing a bottleneck (Figure 3.10). The lane drop corresponded to a mandatory lane change in the MIXIC traffic simulation model. When a mandatory lane change is carried out, the drivers turn off their CACC systems. Under the normal conditions maintained by MIXIC, once the mandatory lane change has been carried out, the CACC systems are turned back on. A lane drop makes it possible to measure the maximum traffic volume at different MPRs of CACC when the traffic volume on the link before the lane drop nears congested state. In addition, a number of experiments were conducted with a special lane for CACC-equipped vehicles to study whether this would lead to additional traffic flow benefits (Van Arem et al. 2007).

Using the hypothetical corridor shown in Figure 3.10, mobility performance was measured to examine queue length and speed around the bottleneck and throughputs under various CACC MPRs (i.e., from 0% to 100% in increments of 20%) for a single heavy-traffic-volume case (i.e., 7,600 vph). The simulation study demonstrated that CACC produced up to 80% reduction in queue length and up to 10% improvement in average speeds under 100% MPR, although no significant throughput improvements were observed (Van Arem et al. 2007). The MIXIC Model enabled development of a simulation test bed for CACC, but because the case study was conducted using only a single traffic-volume case, it did not explore the effectiveness of CACC under varying factors such as MPR, target headways, and so forth. Figure 3.11 shows the results.

3.2.1.5 FAST Traffic Simulation Model

FAST is an agent-based microscopic traffic simulation model extended from the two-lane microscopic traffic simulation model originally developed by Treiber (2016). Figure 3.12 provides a snapshot of the user interface. FAST uses a microscopic simulation approach to mimic

![Diagram of simulation segment](Source: Van Arem et al. (2007).

Figure 3.10. Layout of simulation segment.)
Figure 3.11. Queue length and speed improvement by CACC.

Figure 3.12. Snapshot of FAST.
the behavior of individual driver’s longitudinal and lateral driving maneuvers and macroscopic approach to handle collective dynamics of traffic flow (like density, flow, shockwaves) to analyze the traffic performance. It is also flexible in allowing simple calibration of various parameters to conduct differing scenarios depending on the values assigned to the parameters. Employing the Intelligent Driver Model as a primary car-following model and MOBIL (Minimizing Overall Braking Induced by Lane Changes) as a lane-changing model, FAST is well suited for simulating complex traffic patterns developing over time. It is also flexible in allowing simple calibration of various parameters to construct differing scenarios depending on the values assigned to the parameters. Using an agent-based modeling structure, FAST handles thousands of agents to represent individual vehicles at the micro level while collecting measures of effectiveness (MOEs) at the macro level. Pursuing open-source policy, FAST allows modelers to customize and share the source codes with other modelers.

Arnaout and Bowling (2011) investigated the performance of CACC by customizing FAST. For a hypothetical 3-mile, 4-lane hypothetical freeway network with an on-ramp, the authors assessed the benefits of CACC under five traffic-volume scenarios (4k, 5k, 6k, 7k and 8k vph) and six discrete MPR levels (0%, 20%, 40%, 60%, 80% and 100%) using throughput and average speed measures. Assuming 0.5 seconds of CACC headway and 0.8 to 1.0 seconds of non-CACC headways, they showed that CACC dramatically improves both roadway capacity (Figure 3.13) and speed (Figure 3.14), resulting in up to 140% increase in throughput and up to 180% improvement in average speed at 100% MPR. Although they pursued realistic traffic conditions to generalize CACC performance, the authors’ experiments were somewhat limited, as only a single fixed on-ramp traffic volume was used, no CACC-equipped vehicles from the on-ramp were assumed, and only one CACC headway case was explored.

3.2.1.6 CACC-Vissim

PTV Vissim is a commercial, off-the-shelf, multimodal microscopic traffic simulation software in which each entity (e.g., car, train, pedestrian) is simulated individually. Vissim’s ability to isolate the behavior of each entity is one of the most crucial elements for CACC concept implementation as well as evaluation. Lee et al. (2014, 2016a) used a customized version of

![Figure 3.13. Capacity changes by CACC MPRs.](source: Arnaout and Bowling (2011).)
Vissim to conduct evaluations of the impact of CACC DL on traffic flow. In their 2014 study, Lee et al. focused on DL uses for CACC-equipped vehicles, with a set of lane-changing models for the interactions between the CACC lane and adjacent GPL. The simulation experiment was conducted using Vissim and its Application Programming Interface (API) and Component Object Model (COM) modules. For their 2016 research, Lee et al. developed a CACC add-on package made up of three major modules—a Vissim Network module, a Simulation Manager module, and a customized API module, as shown in Figure 3.15.

A 13-mile freeway segment of I-66 in Northern Virginia was selected as the simulation test-bed for both evaluations (see Figure 3.16). The selected site is a major corridor in Northern Virginia with severe recurrent congestion. The a.m. peak hour is eastbound into Washington, D.C., and the p.m. peak is westbound out of the District. During the peak hours in both directions, the left-most lane is designated as HOV-only and hard shoulder running. The primary goal of the simulation was to examine the system-wide impacts of early deployment CACC DL strategies on roadway performance based on a variety of external factors, as follows (Lee et al. 2014, 2016a):

- **Overall Demand:** 100% (base condition) to approximately 120%, with 5% increments;
- **CACC MPR:** 0% (base condition) to approximately 60%, with 5% increments;
- **DL Use Strategy:** Base (current HOV lane), Mix-Managed (HOV + CACC); and CACC-Dedicated (CACC-only);
- **CACC Inter-Vehicle Target Headway:** 0.6 second, 0.8 second, and 1.0 second;
- **Critical Lane-Changing Headway for the Leading Vehicle**;
- **Critical Lane-Changing Headway for the Following Vehicle**; and
- **Critical Lane-Changing Speed Difference for Both Leading and Following Vehicles.**

The *mixed managed lane use strategy* (shown in Figure 3.17) clusters the CACC-equipped vehicles in one lane to create locally high market penetration during the early, low market penetration phase. Dedicated CACC lanes can be adopted when the number of CACC-equipped vehicles is sufficient to fully utilize a lane. The research by Lee et al. (2016a) also examined lane-changing activities. Lane-changing activities for a new CACC-equipped vehicle to join a CACC platoon were considered in the simulation model by employing trigger conditions calculated by combining headways and speed differences for the target vehicle in the CACC lane. Specifically, the CACC simulations showed that when the headway for the leading and the following

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**Figure 3.14. Speed improvement by CACC MPRs.**

Source: Arnaout and Bowling (2011).
Figure 3.15. CACC simulation tool architecture.

Figure 3.16. Simulation network.
vehicles was less than the critical safety threshold, and the speed difference between the leading vehicle and the following vehicles in the target lane was lower than the threshold, a lane change was activated. Notably, the CACC-equipped vehicles’ lateral behavior was not calibrated; this is because no knowledge yet exists of how the human drivers of non-CACC-equipped vehicles will behave when joining or leaving CACC platoons.

The key modeling objective of the research by Lee et al. was to evaluate the mobility benefits of multiple CACC early deployment strategies under low to medium market penetrations. One important question with respect to CACC early deployment is whether a DL should be used. Several relevant prior studies had shown the effectiveness of CACC under low MPRs, but these prior studies did not consider the real-life difficulties of doubling a lane’s flow rate, such as lane changes under speed differentials and short gaps, how to dissipate vehicles from the lane, and so forth.

Lee et al. (2016a) used three types of car-following behavior for their 2016 analysis:
1. Vissim’s default car-following model (i.e., psycho-physical car-following) for non-CACC drivers;
2. The Intelligent Driver Model (IDM) for adaptive cruise control (ACC) vehicles to represent the lead vehicle of a CACC platoon; and
3. A customized IDM to manage CACC longitudinal maneuvers.

Both the ACC and CACC models were based on the collision-free IDM and were implemented using Vissim’s driver-behavior API. Compared to other models, Lee’s Vissim-CACC model can assess the potential system-wide benefits, such as total travel time, total throughput, total delay, and average speed, under a wide range of traffic scenarios. As an example, Figure 3.18 shows the system-wide performance measures for up to 30% CACC MPR. In addition to the network-wide performance evaluation, it also can evaluate the localized impacts of CACC, such as mainline travel time and headway distribution of a certain location for safety analysis, as displayed in Figure 3.19.

### 3.2.2 Evaluation of Existing Analytical Models

The previous section discussed six approaches to modeling DLs for CACC application that were considered by the project team for use in this project. One major shortcoming observed in many of these models was the lack of availability of the source-code or API for implementation in a state-of-the-art modeling software. Among the six models, Nikolos’ Model and the MIXIC
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

Source: Lee et al. (2016a).

Figure 3.18. CACC simulation results: network-wide performance.

Source: Lee et al. (2016a).

Figure 3.19. CACC simulation results: mainline performance.
Model were unavailable for use by the project team. Because the Volpe framework was under development, it was dropped from the evaluation. Employing an open-source architecture, the FAST model was available for use and appeared to be flexible in relation to customizing for CAV simulations, as had been demonstrated by Arnout and Bowling (2011); however, the maturity of the FAST model appeared insufficient to fulfill certain crucial requirements for the evaluation of CAV DL strategies, such as modeling DLs, scripting capabilities, as well as flexibility to address certain performance measures. APIs to two commercial microsimulation models were available to the project team: CACC-Aimsun and CACC-Vissim, and the research team selected these modeling tools for further evaluation for use in this project. The next section describes the research team’s evaluation of these two models to select the best base model using a specific set of criteria.

3.2.2.1 Evaluation Framework

Precisely examining the suitability of existing modeling tools for analyzing the impact of CAV DL strategies depends on proper design of the evaluation measures. This section presents the evaluation measures utilized to determine the best modeling tools for conducting CAV DL analysis. The research team categorized the evaluation measures by considering the benefit/disbenefit analysis discussed in Chapter 2.

The evaluation measures for the existing modeling tools were categorized as follows:

1. Ability to create a variety of vehicle classes with ability to specify class-specific parameters such as:
   a. Passenger car class: SOV, HOV;
   b. Transit vehicle class: bus, tram, train, taxi;
   c. Heavy vehicle class: truck, trailers;
   d. CAV class: CV, AV;
   e. Geometrics of the vehicles (e.g., dimension); and
   f. Driver behavior parameters (vehicle following parameters, vehicle lane-changing parameters, etc.).

2. Ability to model various facility types for lane restriction scenarios relative to vehicle category for separated and non-separated CAV-only lanes, including:
   a. CAV DLs;
   b. HOV/HOT lanes;
   c. On/off ramps;
   d. Auxiliary lanes for merging/diverging activities;
   e. Toll plazas/booths; and
   f. Lane drops/bottlenecks.

3. Ability to model CAV driving maneuvers such as:
   a. Longitudinal maneuvers for CAVs;
   b. Lane-changing (lateral) maneuvers for CAVs;
   c. Platooning manipulations (join, leave, create);
   d. CAV operational malfunctions; and
   e. Shorter time gap selections (fewer cut-ins, possible drag reductions).

4. Flexibility to customize modeling tools through API/scripting, such as:
   a. Parameters necessary to quantify the benefits and disbenefits of dedicating lanes to CAVs that are not native to the modeling framework in the “off-the-shelf” version of the software;
   b. Dynamic re-routing of AVs and/or CVs to the most efficient route for an Origin-Destination pair (application to future study);
   c. Roadway capacity as a variable function of the CACC proportion in each iteration;
d. Modeling incidents/accidents;
e. Modeling dynamic lane-drops/bottleneck conditions; and
f. Modeling wireless communications characteristics such as latency and losses.

5. Ability to handle a variety of network sizes, including:
   a. Segments;
   b. Corridors;
   c. Regional areas; and
   d. States.

6. Ability to generate various MOEs, including:
   a. Mobility: LOS, throughput, travel time, average speed, delay, density, queue length, travel time reliability, volume-to-capacity ratio, total travel distance, number of stops;
   b. Environment: Gas emissions, fuel consumption;
   c. Safety: Surrogate measures (e.g., time to collision), crash rate; and
   d. Other: Ridership, benefit-cost analysis.

7. Usability of modeling tools, including:
   a. Graphic display of modeling operations (e.g., animations);
   b. User-friendly interface (e.g., Graphical User Interface) for operation;
   c. Graphical and user-friendly network builder;
   d. Input data requirements (e.g., roadway geometry, origin/destination tables, turning designations);
   e. Computational time;
   f. Calibration efforts;
   g. Default values for model parameters; and
   h. Ability to integrate with other relevant software (e.g., GIS tools, database software, the MOtor Vehicle Emission Simulator [MOVES]).

Using the evaluation measures in these seven categories, the two models were ranked for their suitability to model CAV applications in DLs. The project team used qualitative analysis to determine the availability of each evaluation measure. The following indicators were applied for the evaluation:

- **Fully Available (●)**. This indicator means the subject modeling tool is able to provide a functionality required to conduct and/or handle the corresponding evaluation measure within the current capability of the modeling tool.
- **Highly Available (●●)**. This indicator means the subject modeling tool is able to perform and handle the evaluation measure with minor additional customization efforts. Minor customization efforts could include model parameter value adjustment, simple scripting, network enhancement, and additional data provision, which can be achieved without source code modification.
- **Limited Availability (●●●)**. This indicator means the subject modeling tool is able to perform and handle the evaluation measure with major additional customization efforts. Major customization efforts could include source code modification, adding new models (e.g., car-following/lane-changing), and complex scripting if applicable in the tool.
- **Unavailable (●●●●)**. This indicator means the subject modeling tool requires a model change to incorporate the feature (e.g., macroscopic to microscopic).

### 3.2.2.2 Evaluation Results, by Category

The project team ranked the two tools by assigning qualitative indicators (ranging from unavailable through fully available) identifying the availability of each feature in the categorized evaluation framework. This section summarizes the evaluation results, by category.

1. **Ability to Create a Variety of Vehicle Classes.** Vehicle classes were divided into SOV, HOV, transit, heavy vehicles, and CAVs, which have diverse characteristics such as length, height, width, and driving performance (e.g., acceleration/deceleration). As summarized in Table 3.2,
the Aimsun- and Vissim-based CACC modeling tools developed by Shladover et al. (2012) and Lee et al. (2016a), respectively, were capable of handling the various vehicles classes without requiring additional customization.

2. **Ability to Model Various Facility Types.** The ability to model various facility types is one of the most crucial elements for precisely assessing the impact of CAV DL strategies. Highway facilities such as on- and off-ramps, auxiliary lanes, and toll plazas and booths also affect the operation of CAV DLs. Furthermore, lane drops and/or bottlenecks caused by various reasons (e.g., work zone, incident/accident) also directly affect the performance of CAV DL operation. Thus, a modeling tool for CAV DL analysis must handle a variety of roadway facility types. As summarized in Table 3.3, the Vissim-based CACC modeling tool can handle such a need within the current modeling functionality. The Aimsun-based CACC model developed by Shladover et al. (2012) can deal with the modeling requirement with minor modifications to the current modeling tool.

3. **Ability to Model CAV Driving Maneuvers.** As reviewed in Chapter 2, CAV driving maneuvers for longitudinal and lateral movements differ from those of human-driven vehicles. As summarized in Table 3.4, both the CACC-Aimsun and CACC-Vissim modeling tools are equipped with a longitudinal maneuver model for CAV and appear capable of handling CAV driving maneuvers. Notice that the CACC-Aimsun model has only been applied to a limited number of studies involving lane changing.

4. **Flexibility to Customize Modeling Tools Through API Scripting.** Unlike traditional traffic analyses (e.g., traffic impact analysis), analyzing the impact of CAV DL strategies likely requires advanced functionalities that are not native to off-the-shelf modeling tools. To conduct seamless analysis, the modeling tools should be able to provide some extent of modeling flexibility. Table 3.5 shows the evaluation results regarding the flexibility of the selected modeling tools.

<table>
<thead>
<tr>
<th>Evaluation Measure: Ability to Create a Variety of Vehicle Classes with Ability to Specify Class-Specific Parameters</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOV</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>HOV</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Transit Vehicle Class (e.g., bus, tram, train, taxi)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Heavy Vehicle Class (e.g., truck, trailers)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>CAV Class</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Geometrics of the Vehicles (e.g., dimension)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Separated Driving Behavior Parameters for Each Class</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evaluation Measure: Ability to Model Various Facility Types</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAV DLs</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>HOV/HOT Lanes</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>On/Off Ramps</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Auxiliary Lanes for Merging/Diverging Activities</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Toll Plazas/Booths</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Lane Drops/Bottlenecks</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Table 3.2. Evaluation results for ability to create variety of vehicle classes.

Table 3.3. Evaluation results for ability to model various facility types.
tools. Utilizing commercial-off-the-shelf products, Aimsun- and Vissim-based CACC modeling tools are fully capable of customizing recorded MOEs. However, the Aimsun-based modeling tool needs to be modified to deal with incident/accident modeling and dynamic lane-drop/bottleneck modeling.

5. **Ability to Handle the Variety of Network Sizes.** CAV DLs will be deployed on a multi-lane freeway corridor with multiple interchanges producing the wide variety of lane-changing activities. To some extent, such a corridor would have existing dedicated/exclusive lane facilities, such as an HOV/HOT lane with a barrier and HOV/HOT-dedicated access ramp. It is necessary to examine the collective impacts of CAV DL strategies on adjacent corridors. Furthermore, measuring region- and state-wide effectiveness of CAV DL strategies is also crucial for planning purposes. As shown in Table 3.6, the Aimsun- and Vissim-based modeling tools are unable to conduct region- and state-wide analysis owing to their microscopic nature. The Vissim-based CACC modeling tool, however, has been applied for evaluating the impact of a CACC lane on a single corridor with multiple interchanges.

6. **Ability to Generate Various MOEs.** Depending on the benefit/disbenefit categories examined, evaluations of CAV DL strategies can incorporate a wide spectrum of performance measures. Thus, producing proper performance measures is the most critical requirement for the modeling tools for CAV DL analysis. Table 3.7 summarizes the capabilities of each modeling tool to generate performance measures critical for assessing the benefits and disbenefits of CAV DLs. The MOEs summarized in Table 3.7 are quantitatively measurable; qualitative performance

### Table 3.4. Evaluation results for ability to model CAV driving maneuver.

<table>
<thead>
<tr>
<th>Evaluation Measure: Ability to Model CAV Driving Maneuver</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Maneuver for CAV</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Lane-Changing Maneuver for CAV</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Platoon Formation and Dissolution</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Minimum and Maximum Size of the Platoon</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Shorter Time Gap Selections (Fewer Cut-Ins, Possible Drag Reductions)</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>CAV Operational Malfunction</td>
<td>★</td>
<td>★</td>
</tr>
</tbody>
</table>

〇: Unavailable; 〇: Limited Availability; ★: Highly Available; ★: Fully Available

### Table 3.5. Evaluation results for flexibility to customize modeling tools through API scripting.

<table>
<thead>
<tr>
<th>Evaluation Measure: Flexibility to Customize Modeling Tools Through API Scripting</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters to Estimate MOEs That Are Not in the “Off-the-Shelf” Version of the Software</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Ability to Define the Capacity as a Variable Function of the CACC Proportion in Each Iteration</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Dynamic Re-Routing for CAV</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Modeling Incident/Accident</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Modeling Dynamic Lane-Drops/Bottleneck Conditions</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Wireless Communications Impact on Modeling CAVs</td>
<td>★</td>
<td>★</td>
</tr>
</tbody>
</table>

〇: Unavailable; 〇: Limited Availability; ★: Highly Available; ★: Fully Available
measures for societal justice such as equity and perception of exclusivity were excluded from the table. As seen in Table 3.7, almost all mobility measures are available through the selected modeling tools.

Combining the Aimsun or Vissim tools with external environmental models such as MOVES (U.S. EPA 2016) and the VT-Micro Model (Rakha et al. 2004) could potentially enable estimation of the environmental impacts of CAV DL strategies. Obtaining safety measures appeared challenging, however, as neither Aimsun nor Vissim could generate the necessary number of crashes and crash severity. Methods such as the Safety Impact Methodology (SIM), developed by Carter et al. (2009), also could be used to enhance these tools to account for safety. The SIM is a systematic approach for evaluating the safety impacts of a new vehicle system by incorporating historical crash, driver performance, and system performance data to enable a rigorous comparison of baseline and treatment vehicle crash conflicts. SIM has been used to assess the safety impacts of V2V technologies (Harding et al., 2014). As Harding et al. had used SIM in

Table 3.6. Evaluation results for ability to handle the variety of network sizes.

<table>
<thead>
<tr>
<th>Evaluation Measure: Ability to Handle the Variety of Network Sizes</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment (Without Interchanges)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>A Single Corridor Including Multiple Interchanges</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Multiple Corridors</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Region</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>State</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

●: Unavailable; ○: Limited Availability; ●: Highly Available; ●: Fully Available

Table 3.7. Evaluation results for ability to generate various MOEs.

<table>
<thead>
<tr>
<th>Evaluation Measure: Ability to Generate Various Measures of Effectiveness</th>
<th>CACC (Aimsun)</th>
<th>CACC (Vissim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of Service</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Throughput</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Total Travel Time (VHT)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Total Travel Distance (VMT)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Average Speed</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Delay</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Queue Length</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Travel Time Reliability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Emission (Carbon Monoxide, Carbon Dioxide, Nitrogen Oxides, Hydrocarbons)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Fuel Consumption</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surrogate Measure (e.g., Time to Collision)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Speed Difference (Delta V)</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Number of Crashes</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Crash Severity</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ridership</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Route Diversion</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Mode Diversion</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

●: Unavailable; ○: Limited Availability; ●: Highly Available; ●: Fully Available
assessing safety impacts, the NCHRP project team could use the Surrogate Safety Assessment Model (FHWA 2008a) in this study by integrating it with the Aimsun or VISSIM modeling tools to enable estimates of surrogate measures such as time to collision, post encroachment time, and speed difference (delta V). Other measures, mainly required for planning purposes, were unavailable from the selected modeling tools.

7. **Usability of Modeling Tool.** From the perspective of an analyst, the usability of a modeling tool is a critical element significantly affecting the efficiency of modeling activities. Table 3.7 summarizes the usability requirements commonly acceptable for the practice of transportation modeling. Based on commercial-off-the-shelf product platforms, the Aimsun- and Vissim-based modeling tools provide the highest usability, as shown in the table. In Table 3.8, the input data requirement, computational time, and calibration efforts are not ranked using an Unavailable (⊙) to Fully Available (●) scale, but rather using a Low, Moderate, and High scale.

### Overall Evaluation Results

Table 3.9 summarizes the overall evaluation results for the two modeling tools based on their usability scores to the evaluation measures established. Owing to high scores in this evaluation and availability as an open-source code in the U.S.DOT’s Open Source Application Development Portal, the project team suggested selecting CACC-Vissim as the selected modeling tool, with minor modifications. A modeling approach was proposed to use the CACC-Vissim model with enhancements related to DSH. Modifications required to execute the scope of this project are discussed in Chapter 5.

### DSH Application

DSH is another CAV application that is mature in terms of prototype development and field testing and can be implemented in a freeway DL environment. Several algorithms exist, but the general objective of the application is to harmonize the speeds of vehicles upstream on a freeway.
to minimize shockwaves and potentially improve system mobility by detecting congestion or queues downstream (Ma et al. 2016). Figure 3.20 demonstrates the process: once the traffic management center (TMC) identifies congestion in a freeway segment, the speed harmonization application will compute speed recommendations for upstream freeway segments to enhance the throughput and avoid sudden deceleration and braking (thereby reducing shockwaves and the probability of secondary collisions).

In a connected environment, the vehicles use V2I communication to inform a TMC of their traffic states. When vehicles slow at a bottleneck, the TMC identifies their V2I communication as a signal of impending congestion. The TMC selects the optimum speeds for vehicles traveling upstream and uses I2V communication to relay this speed information to the upstream vehicles. The upstream CAVs receive and implement the recommended speeds, which has the effect of reducing congestion and attendant risks.

### 3.3.1 Existing DSH Application Models

The general objective of DSH is to smooth traffic speeds on a freeway in both temporal and spatial dimensions. The application functions as a derivative of variable (or dynamic) speed limits. Several algorithms exist for dynamic speed limit strategies, and many of them have been modified to provide a more granular traffic-smoothing strategy for DSH implementation using CV technology. Table 3.10 provides a summary of the different speed harmonization applications previously researched.

### 3.3.2 Modeling the DSH Application

As a starting point in modeling the DSH application, the team used a simplified speed-based algorithm developed by Ma et al. in 2016. This algorithm uses a simplified space-time relationship to approximate the typical complex models used by previous approaches. The vehicles upstream of congestion were provided a speed recommendation that is a linear function of spatial \((x)\) and temporal \((t)\) speed measurements at appropriate intervals. The speed recommendation for a vehicle in space \((x)\) and time \((t)\) is given by:

\[
s(x, t) = \left( \frac{s_n(t) - s_m(t)}{\Delta x_{nm}} \right)x + s_n(t),
\]

where: \(s_n(t)\) represents the speed measurement at a point in space \((n)\) at a specific time \((t)\), and \(\Delta x_{nm}\) is the distance between point \((n)\) and a second, downstream point \((m)\).

After preliminary tests, this algorithm was modified to include a system that propagates the speed recommendations upstream to further reduce shockwaves and improve traffic flow.
Table 3.10. Review of previous speed harmonization algorithms (adapted from Ma et al. 2016).

<table>
<thead>
<tr>
<th>Study</th>
<th>CAV/CAV</th>
<th>V2I or V2V</th>
<th>Control Algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lu et al. (2005)</td>
<td>CV</td>
<td>V2I</td>
<td>Application aimed at reducing the speed limits of freeway segments upstream of a bottleneck in proportion to the observed bottleneck speed if vehicle flow throughputs are above the bottleneck capacity.</td>
</tr>
<tr>
<td>Talebpour et al. (2013)</td>
<td>CV</td>
<td>V2I</td>
<td>A wavelet-transform based algorithm was used to detect formation of perturbations, and a cognitive risk-based microscopic simulation model was adopted to account for human behavior. A reactive speed limit was selected to implement speed harmonization.</td>
</tr>
<tr>
<td>INFLO Project (Dowling et al. 2015)</td>
<td>CV</td>
<td>V2V, V2I</td>
<td>The algorithm grouped freeway sub-links with similar recommended speeds to produce harmonized speeds, which was calculated as the speed of the slowest vehicle or within 5 mph interval of the downstream sub-link.</td>
</tr>
<tr>
<td>Li et al. (2014)</td>
<td>CAV</td>
<td>V2V</td>
<td>Used a CAV car-following rule that effectively suppressed the development of oscillations and consequently mitigated fuel consumption and emissions.</td>
</tr>
<tr>
<td>Ma et al. (2016)</td>
<td>CAV</td>
<td>V2I</td>
<td>Used a simplified space-time relationship to reduce traffic state oscillations to enhance traffic flow.</td>
</tr>
<tr>
<td>Wang et al. (2015)</td>
<td>CAV</td>
<td>V2I</td>
<td>Used aggregated traffic state information to detect the formation of congestion at a bottleneck, and each CAV processes the VSL signals from the central control unit individually.</td>
</tr>
<tr>
<td>Yang and Jin (2014)</td>
<td>CV</td>
<td>V2V</td>
<td>Advisory speed limit is calculated by each individual vehicle and then averaged among equipped vehicles.</td>
</tr>
<tr>
<td>Ahn et al. (2013)</td>
<td>CAV</td>
<td>V2V</td>
<td>Used a rolling horizon-based optimization approach to control vehicle speed within a preset speed window in a fuel-saving manner.</td>
</tr>
</tbody>
</table>

The team used speed measurement stations at 0.1-mile spacing and mapped vehicle locations to 0.1-mile resolution. The speed recommendations were updated every 15 seconds and provided to the equipped vehicles as their desired speeds. A minimum speed recommendation was kept at 25 mph, and the application was initialized only if a congested condition was detected on the DL.

With these modifications, the final recommended speed for each vehicle space \( (x) \) and time \( (t) \) was:

\[
s(x, t) = \min \left[ 25, \frac{s_i(t) + 5}{\frac{s_i(t) - s_m(t)}{\Delta x_m}}x + s_n(t) \right] \text{ mph.}
\]
A COM-based application was used to implement this DSH algorithm. The application watched for inputs from freeway sensors (data collection devices) that recorded speeds every 15 seconds. When congestion was detected, the application calculated speed recommendations for every sub-link of 0.1-mile length. For each sub-link, desired speed points (similar to speed limit signs) were integrated into the network, which was updated every 15 seconds via the COM-based DSH application. To provide granularity, space-resolution of 0.1-mile was chosen based on the studies conducted by the U.S.DOT under the Dynamic Mobility Applications Program’s Impact Assessment (Dowling et al. 2015). The update frequency of 15 seconds was chosen as a trade-off between the computation intensity of the algorithm and the travel time of vehicles on each sub-link.

The DSH algorithm modeled in this project was implemented as a soft-control of the vehicle speeds in the sense that the vehicle controls assume the harmonized speeds as the new “desired speed.” As vehicles receive harmonized speeds as desired speeds, their vehicle dynamics model makes adjustments to maintain the vehicle speeds close to the received speed. In reality, the DSH application might be paired with a combination of vehicle controls such that some vehicles could assume the new speed as their strict speed control while, in other vehicles, human drivers might perceive them as informational only and may not follow the harmonized speed recommendations.
To study and find the conditions amenable to dedicating lanes for CAV users, the team conducted a modeling and simulation-based study of CAV driver behavior on DLs on a selected set of diverse case-study sites. This chapter details the process that was used to select the case study sites based on the project objectives. The team identified a set of evaluation criteria to assess the case study sites. Figure 4.1 presents the overall approach to identifying and selecting the case study sites used for modeling CACC DLs.

As shown in Figure 4.1, a set of initial candidate case study sites was created based on the team members’ extensive experience with modeling managed lanes and CACC applications. Evaluation criteria pertaining to case study site characteristics, managed lane characteristics, and CAV modeling feasibility were developed to down-select these case study sites to two or three that could help define guidelines for agency use in determining whether their specific applications would merit lane dedication.

Case study site characteristics include features that define their operational and geographic characteristics, demand, modes, ITS strategies, and the existence of managed lanes. Managed lane characteristics include the features of the existing (or proposed) managed lane facility. These characteristics include operational rules, priority conditions, allowable modes, and access features. The team used CAV modeling feasibility to rank the test sites.

### 4.1 Initial List of Candidate Sites

The team analyzed nine case study sites that were available for use in the modeling effort. Each candidate site represented a simulation-based corridor model for which a managed lane facility existed or had been proposed. The map in Figure 4.2 shows the initial candidate case study sites. Because of map scaling, some candidate test beds overlap (i.e., the candidate sites in St. Paul and Minneapolis, Minnesota, and in Maryland and Northern Virginia).

Table 4.1 shows the preliminary list of case study sites that were evaluated and assessed for their effectiveness in achieving the project goals.

The next section presents a brief description of the geographic and modeling characteristics of these candidate case study sites.

#### 4.1.1 I-66 Corridor, Northern Virginia

The candidate site on the I-66 corridor in Fairfax, Virginia, starts from the outside of the Capital Beltway (I-495) and extends for 13 miles as a 4-lane freeway segment that includes an HOV lane on the left-most lane and stretches to the west all the way through the interchange with US-29 to SR-234 (see Figure 4.3).
This suburban test site includes six interchanges and two dedicated on-and-off ramps for an HOV lane that is separated from the GPLs. The average distance between interchanges is approximately 1.2 miles, yielding 0.6 miles and 2 miles of minimum and maximum interchange spacing, respectively. The test site experiences recurring congestion caused by high directional daily demand every weekday for the eastbound lanes (i.e., toward Washington, D.C.) during the a.m. peak and the westbound lanes (i.e., toward Fairfax, Virginia) during the p.m. peak. Between 2:00 p.m. and 8:00 p.m., traffic volumes of the test bed range from 900 vphpl to 2,100 vphpl and include approximately

Source: NCHRP 20-102(08) project team; base map from www.HERE.com.

Figure 4.1. Selection process for the case study sites.

Figure 4.2. Initial candidate case study site mapping.
Table 4.1. Initial candidate case study sites.

<table>
<thead>
<tr>
<th>No.</th>
<th>Case Study Corridor</th>
<th>Location</th>
<th>Length of Corridor</th>
<th>Freeway Average Annual Daily Traffic (AADT) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I-66</td>
<td>Northern Virginia</td>
<td>13</td>
<td>150,000–160,000</td>
</tr>
<tr>
<td>2</td>
<td>US 101</td>
<td>San Mateo, California</td>
<td>8.5</td>
<td>200,000–250,000</td>
</tr>
<tr>
<td>3</td>
<td>I-15</td>
<td>San Diego, California</td>
<td>22</td>
<td>250,000–300,000</td>
</tr>
<tr>
<td>4</td>
<td>I-35 MnPASS Lanes</td>
<td>St. Paul, Minnesota</td>
<td>15</td>
<td>39,000–125,000</td>
</tr>
<tr>
<td>5</td>
<td>I-94</td>
<td>St. Paul–Minneapolis, Minnesota</td>
<td>14</td>
<td>132,000–179,000</td>
</tr>
<tr>
<td>6</td>
<td>I-290 Managed Lanes</td>
<td>Chicago, Illinois</td>
<td>14.5</td>
<td>159,000–211,000</td>
</tr>
<tr>
<td>7</td>
<td>I-75 HOV Lanes</td>
<td>Detroit, Michigan</td>
<td>18.5</td>
<td>105,000–180,000</td>
</tr>
<tr>
<td>8</td>
<td>I-270 Corridor</td>
<td>Maryland</td>
<td>26</td>
<td>175,000–270,000</td>
</tr>
<tr>
<td>9</td>
<td>I-95 Express Lanes</td>
<td>Miami, Florida</td>
<td>20</td>
<td>94,000–260,000</td>
</tr>
</tbody>
</table>

1,500 vphpl of peak HOV traffic volumes. This simulation model is currently available in the U.S.DOT’s Open Source Application Development Portal for academic/research use.

Based on field observations, the existing simulation model includes a traffic stream with varying vehicle compositions (FHWA Class 4 and above). The existing freeway deploys several ITS strategies along the corridor—hard shoulder running, lane use control signals, VMS, and advanced ramp metering. US-29 is a parallel arterial and an alternate route to I-66 and is accessible via the six interchanges included in the existing model. Currently, the parallel roadway is not included in the simulation model.

The I-66 managed lanes operate as far-left, single-lane, time-of-day HOV-2 lanes in both eastbound and westbound directions. User-type restrictions along the existing HOV-2 lanes allow only vehicle classes with two or more vehicle occupancy requirements. The existing managed HOV-2 lanes operate on a time-of-day basis with restrictions applying during a.m. and p.m. peak periods on weekdays. No physical barrier separates the managed HOV-2 lanes from the mixed-use lanes. Currently, only double solid white lane markings are used to...
separate the lanes and to indicate no lane changing and no access. Access points between the dedicated HOV-2 lanes and the mixed-use lanes are permitted only along areas with dashed lane striping.

The I-66 also has hard shoulder running lanes on the far-most right lanes in both directions. These lanes operate from 5:30 a.m. to 11:00 a.m. in the eastbound direction and from 2:00 p.m. to 8:00 p.m. in the westbound direction. Lane utilization is indicated via VMS, which show a green arrow for permitted use and a red cross for closed for use unless exiting.

The simulation case study was developed and calibrated using the PTV Vissim micro-simulation software, which allows external API-based control of simulation components, including driver behavior, making it a good candidate for CAV modeling. Driver behavior was calibrated to replicate field-observed corridor travel time, speed, and traffic volume. Freeway speed and volume information for the case study site are available, in 5-minute intervals and classified by lanes, via the FHWA’s Saxton Transportation Operation Laboratory (U.S.DOT 2018). The existing ITS strategies along the corridor were included in the traffic simulation model.

4.1.2 US-101 Corridor, San Mateo, California

The US-101 case study site is located within the County of San Mateo, California, and stretches from Redwood City to the City of Burlingame. The length of the modeled US-101 freeway facility is approximately 8.5 miles, with a parallel arterial, El Camino Real (SR-82), of similar length. Drivers can divert to the parallel arterial via seven possible interchanges. The extent and coverage of the US-101 corridor model is illustrated in Figure 4.4.
4.1.3 I-15 Corridor, San Diego, California

The I-15 case study site is made up of a 22-mile stretch of the I-15 corridor facility and associated parallel arterials. It extends north-to-south from the interchange with SR-78, just below the City of Escondido, California, to the interchange with Balboa Avenue, approaching San Diego, California. This facility is shown in Figure 4.5. The corridor passes through a suburban area. A network of arterials runs concurrent with the I-15 freeway, and drivers on the Interstate are able to divert via 18 possible interchanges, including Pomerado Road and Ted Williams Parkway.

The I-15 corridor has a ramp metering information system and traffic light synchronization, both used for an active traffic demand management system. Speed and volume detectors are located throughout the freeway. Existing ITS strategies, specific to active traffic demand management systems, were included in the existing model. Within the limits of the simulation model, congestion during peak periods has been recorded to be approximately 50% higher than...
off-peak hours in the peak direction. The measured daily VMT varies from the average value of all days observed by no more than a 10% margin. The simulation model includes varying heavy vehicle percentages within the traffic stream by time of day. No transit vehicles were included in the model.

The I-15 freeway also includes express lanes that are separated by a concrete median barrier. These lanes are located between the GPLs northbound and southbound. The median barriers are moveable to manage congestion during peak hours. The standard lane configuration is two northbound lanes and two southbound lanes. This configuration can be changed to three southbound lanes and one northbound lane to mediate peak-hour traffic demand. Currently, these are the only two-lane configuration choices available.

The managed lane facility operates as HOT lanes using distance-based dynamic pricing. Motorcycles and all vehicles with two or more occupants can access the express lanes with no charge. SOVs also are allowed to access the express lanes, but pay a fee. Heavy vehicles (Class 4 and above) are restricted from the express lane facility.

Designated ramp entrances and exits to this facility exist to and from SR-163, the I-15 south GPLs, and the I-15 north GPLs. There are two entrances and two exit flyover access ramps near the center of the express lanes facility granting direct access to and from SR-56. There are six access points each in the northbound and southbound directions between the express lanes and the GPLs.

The simulation case study site was developed and calibrated using Aimsun microsimulation software. This software allows external API-based control of simulation components, including driver behavior, making it a good candidate for CAV modeling. Driver behavior was calibrated to replicate field-observed corridor travel time, speed, and traffic volume. Roadway speed and volume data were available through the Caltrans Performance Measurement System (PeMS) by specific days with precision of 1-minute intervals (Caltrans 2018). The detector data also classifies the traffic volume by lanes.

4.1.4 I-35E MnPass Lanes, St. Paul, Minnesota

The I-35 MnPASS lanes that pass through the dense urban area of St. Paul, Minnesota, also represent conditions for assessing feasibility of dedicating lanes to CAVs. On the northern half of the 15-mile study corridor, the managed lane freeway transitions to suburban and rural structures. The freeway corridor also contains a system-to-system interchange with I-694 where the two freeways run concurrently for approximately 1 mile. This facility is shown in Figure 4.6.

Existing calibrated models in both CORSIM and Vissim formats are owned by the Minnesota Department of Transportation (Minnesota DOT). Traffic count and speed data detection by lane is archived daily. For this study, traffic count and speed data along the ramps and mainline were obtained through Minnesota DOT’s Regional Traffic Management Center detector data (Minnesota DOT 2017). Turning-movement counts at the ramp terminals, which were available from previous signal retiming projects at most of the study area interchanges, also were used in the model.

This corridor experiences typical a.m. and p.m. peak-hour commuter demand and mild to moderate congestion, with the southbound traffic experiencing heavier demand during the a.m. peak and the northbound traffic experiencing greater demand during the p.m. peak. Outside of these commuter rush hours, demand drops off considerably, and traffic moves under free-flow conditions. Alternate arterial routes exist (i.e., US-61), and even the regional freeway network provides alternate routes; however, these regional routes were not included in the scope of this microsimulation project. Traffic on the corridor is largely commuter traffic and mostly consists
of passenger vehicles with a small proportion made up of commercial trucks. On this corridor, transit is not significant enough to affect operations greatly; therefore, transit was not explicitly modeled. Existing ITS strategies include VMS, ramp metering, and traffic speed/volume detectors feeding to the traffic management centers.

The existing managed lane facility is present on the southern half of the study corridor (south of I-694) and consists of a single lane in each direction. Studies are being performed to assess the feasibility of expanding the current facility to the north. HOV, transit vehicles, and motorcycles can use the current facility at no charge, whereas SOVs pay to use the facility. Large commercial vehicles (with more than two axles and weighing more than 26,000 pounds) are restricted from the managed lane during peak hours but can use the managed lane during non-peak travel times. The facility is currently operated as a managed lane during commuter rush and as a GPL during off-peak hours. A solid double white line indicates that access to the managed lane is restricted. Frequent access areas, which also are major weaving areas, are indicated with striping. Buses are permitted to run along the shoulders of I-35E in the northbound and southbound direction for an approximate 2-mile stretch north of I-694 and an approximate 3-mile stretch south of I-694. Buses can use the outside shoulder along these stretches of I-35E when congestion slows travel speeds to 35 mph or slower. Buses using the shoulder may only exceed adjacent general traffic speeds by 15 mph.

Figure 4.6. I-35E case study site coverage.
Driver behavior was calibrated in CORSIM per Minnesota DOT guidelines. Vissim models were calibrated as well to replicate existing travel speeds and congestion levels during the a.m. and p.m. peak-hour rush periods.

### 4.1.5 I-94 Managed Lanes (Proposed), Minneapolis, MN

The proposed I-94 managed lane facility will be in a dense urban area between Minneapolis and St. Paul, Minnesota, and will include system interchanges with I-35W and I-35E (see Figure 4.7). The length of the facility included in the simulation model is approximately 14 miles, extending from I-394 on the west to US-61 on the east, with 32 interchanges modeled. Traffic on the existing corridor is largely commuter traffic and mostly is made up of passenger vehicles with a smaller proportion of commercial trucks. Transit is not a significant enough component of this corridor to impact operations greatly; therefore, transit was not explicitly modeled.

The corridor experiences typical a.m. and p.m. peak-hour commuter demand and moderate to heavy congestion during these peak periods. Alternate arterial routes are available with limited river crossings, but the alternate routes were not included in the microsimulation modeling of this project. The facility currently has VMS, ramp metering, and traffic speed/volume detectors. The proposed project is to construct an expansion of the managed lane (MnPASS) system to include this corridor. The managed lane would be a single lane in each direction. Buses would be permitted to run along the shoulders of I-94 between Highway 280 and Downtown St. Paul. As with other bus shoulder-running applications in the area, buses would be permitted to use the outside shoulder when congestion slows travel speeds to 35 mph or slower, with bus speeds limited to no more than 15 mph faster than the adjacent general-purpose traffic.

The proposed facility would be operated as a HOT lane, allowing free access to high-occupancy passenger cars, transit vehicles, and motorcycles. SOVs would be able to access this facility with a fee. Heavy vehicles are restricted from access to the facility. The proposed operating rules involve time-of-day plans, operating each managed lane as a mixed-use lane during off-peak hours while operating it as a HOT lane during peak periods. Driver behavior was calibrated in CORSIM per Minnesota DOT guidelines.

Source: NCHRP 20-102(08) project team; base map data © 2018 Google.

**Figure 4.7.** I-94 case study site coverage.
The existing calibrated models were in CORSIM format and owned by the Minnesota DOT, which presented significant challenges to modeling CAV behavior due to limitations in utilizing external API to code varying driver behaviors. Traffic count and speed data along the ramps and mainline were obtained through Minnesota DOT’s Regional Traffic Management Center detector data (Minnesota DOT 2017). Traffic count detection is by lane and is archived daily. Turning-movement counts at the ramp terminals were available from previous signal retiming projects at most of the study area interchanges. At interchanges where turning-movement counts were not available, new turning-movement counts were collected.

### 4.1.6 I-290 Managed Lanes, Chicago, Illinois

The I-290 facility runs through a dense urban area in Chicago and metropolitan communities to the west of downtown Chicago (see Figure 4.8). A managed lane facility, which includes a single lane in each direction, is proposed on this corridor. The length of the facility included in the simulation model is approximately 14.5 miles, extending from I-294 on the west to I-90 on the east, with 21 interchanges modeled. The corridor experiences typical a.m. and p.m. peak-hour commuter demand and heavy congestion during these 2- to 3-hour peak periods. Outside of these peaks, traffic demand reduces enough to allow for free-flow operations along I-290. There are no restrictions on transit or heavy vehicles on the existing facility and, due to left-side entrance/exit ramps along the corridor, commercial heavy vehicles can utilize all lanes. Alternate arterial routes are available (Roosevelt Road being the primary alternate route), but the alternate routes were not included in the microsimulation modeling of this project.

Traffic on the I-290 case study corridor is largely commuter traffic, consisting mostly of passenger vehicles with a smaller proportion of commercial trucks. Transit is not a significant component of this modeled corridor. Commuter rail is present, running immediately adjacent to

Source: NCHRP 20-102(08) project team; base map data © 2018 Google.

*Figure 4.8. I-290 case study site coverage.*
I-290 and within the I-290 median for the eastern half of the study corridor; however, due to limited interaction with the freeway, transit—including commuter rail—was not included in the microsimulation modeling. VMS are present indicating travel time along the corridor. Ramp metering, closed-circuit television (CCTV), and traffic speed/volume detectors also are present on the corridor.

The operating rules proposed for this managed lane facility are HOV and HOT time-of-day restrictions by which the facility operates as a managed lane during peak hours and as a GPL during off-peak hours. Access to and from the managed lane is proposed to be indicated using dashed white line pavement striping only, and restricted (no) access is to be indicated with a solid double white line.

Existing calibrated models in the Vissim model format were owned by the Illinois Department of Transportation (Illinois DOT). Traffic count and speed data along the ramps and mainline were used for calibration of the models and obtained from the Illinois DOT’s detector database. Traffic count detection is by lane and is archived daily. Turning-movement counts at the ramp terminals were collected at most of the study area interchanges as part of the project.

### 4.1.7 I-75 HOV Lanes, Detroit, Michigan

The I-75 freeway corridor is based in a dense urban area immediately north of the Detroit city limits. This area includes a major system interchange with I-696. The length of the facility included in the simulation model is approximately 6 miles, extending from M-102 on the south end to 12 Mile Road on the north end, with five interchanges included (see Figure 4.9). The microsimulation model was prepared for detailed analysis of a subarea of a larger (18.5-mile) corridor being studied for the addition of a managed lane (from M-102 on the south end to M-59 on the north end). The corridor experiences typical a.m. (southbound) and p.m. (northbound) peak-hour commuter demand and moderate congestion during these peak periods. Outside of these peaks, traffic demand reduces enough to allow for free-flow operations along I-75 during most of the day.

A managed lane facility with a single lane in each direction was proposed for immediate construction. The construction would require widening along the corridor for the addition of this lane in each direction. The proposed managed lane facility would extend 12.5 miles, from SR-59 to approximately 12 Mile Road. This would be the first managed lane facility along the freeway system in Michigan. Operational rules for this managed lane facility would be based on a time-of-day HOV restriction, by which the facility would operate as a managed lane during peak hours and as a GPL during off-peak hours. Alternate arterial routes are available, with Woodward Avenue being the primary alternate route; however, the alternate routes were not included in the microsimulation modeling of this project.

Traffic on this corridor is largely commuter traffic, consisting mostly of passenger vehicles with a smaller proportion of commercial trucks. Transit is not a significant component of this modeled corridor. Existing ITS strategies and technologies along the corridor include VMS, CCTV, and traffic-count stations.

Areas providing access to and from the managed lane are proposed to be indicated by dashed white line striping only. Restricted areas (with no access to or from the managed lane) are proposed to be indicated by a solid double white line.

The entire corridor (18.5 miles) was given a macroscopic *Highway Capacity Manual* analysis of the basic freeway segments, merge/diverge areas, and weave areas. A more detailed microsimulation analysis was conducted for a 7-mile section containing the system interchange with I-696 and proposed ramp-braiding alternatives. The microsimulation was conducted in Vissim (Version 6), and traffic count data was obtained from the Michigan Department of...
Transportation (Michigan DOT) traffic count web portal for ramps and mainline counts along the corridor (Michigan DOT 2018). The model was set up as a ramp and mainline model only. Full interchange operations were not modeled. Speed and congestion data used for calibration were obtained from the Regional Integrated Transportation Information System (RITIS) maintained by the University of Maryland (CATT Lab 2018).

4.1.8 I-270 Corridor, Maryland

I-270 is a 34.7-mile auxiliary Interstate Highway that travels between I-495 (the Capital Beltway) just north of Bethesda, in Montgomery County, Maryland, and I-70 in the city of Frederick in Frederick County, Maryland. The corridor consists of a 32.60-mile main line plus a 2.10-mile spur that provides access to and from southbound I-495 (see Figure 4.10). Most of the southern part of the route in Montgomery County passes through suburban areas around Rockville and Gaithersburg. This portion of I-270 is up to 12 lanes wide and consists of a local-express lane configuration as well as HOV lanes that are in operation during peak travel times. North of the Gaithersburg area, the road continues through the northern part of Montgomery County as a 6- to 8-lane highway with an HOV lane in the northbound direction only. Farther north, I-270 continues through rural areas into Frederick County and toward the city of Frederick as a 4-lane freeway. The modeled length is approximately 26 miles.
This corridor experiences very little diversity in demand conditions and traffic patterns, and currently operates at a high level of congestion throughout most typical days. The only parallel alternate route is SR-355, an arterial corridor with signalized intersections and significant business activity.

Modes of transportation included in the model were passenger cars, buses, and heavy vehicles. The parallel alternative routes were not included in the model. The model included immediate facilities, such as highway interchanges and immediate signalized intersections at the interchanges.

The current ITS infrastructure consists of speed detectors, video monitoring infrastructure, and VMS. The Maryland DOT is in the process of procuring an innovative congestion-management upgrade project ($100 million) that could introduce a range of new technologies/strategies.

The facility’s managed lane is currently a single HOV lane in each direction. HOV operating restrictions apply during the traffic peak period in the peak direction only. The HOV lane is concurrent with other lanes and is distinguished by special pavement markings. Vehicles can access the managed lane from the GPL throughout the entire facility with no restrictions. The simulation platform used to develop the model was Vissim. No existing ITS strategies were included in the existing model.

4.1.9 I-95 Express Lanes, Miami, Florida

Interstate 95 (I-95) is a key component of the Interstate Highway System, running along the east coast of the country from Miami, Florida, to the U.S.-Canada border in eastern Maine. The study segment of this facility is an urban freeway with directional commuter traffic flows that runs through the densely urban cores within Miami-Dade and Broward Counties in South Florida.
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles (see Figure 4.11). The managed lane section currently runs approximately 20 miles between Davie Road, near Downtown Ft. Lauderdale, to just north of Downtown Miami at SR-836.

I-95 operates at high levels of congestion throughout most of the day, with concentrated congestion at various bottlenecks during off-peak hours while distributed throughout the facility during peak periods. The closest parallel facility is the signalized arterial of US-1/Federal Highway/Biscayne Boulevard. Another parallel alternative route located along the northern portion of the facility is the Florida Turnpike. The various transportation modes include passenger cars, heavy vehicles, and buses. Heavy vehicles are restricted from using the express lanes. Existing ITS strategies used along the I-95 corridor include VMS, video monitoring, and various detectors.

The I-95 express lanes represent a conversion from HOV to HOT operation and were implemented to provide more reliable trip times for corridor users. The facility allows for toll-free access for HOV3+ users and transit but requires carpools to pre-register. SOVs can access the lane by paying a toll that is assessed on a dynamic basis in response to congestion. As volumes increase, so does the price for access. Currently, the maximum rate for an SOV is $1.50 per mile or $10.50 over the full length of the express lanes. This cap may be raised if the LOS on the facility.

Source: NCHRP 20-102(08) project team; base map from Florida DOT (www.95express.com).

Figure 4.11. I-95 case study coverage.
consistently declines below 45 mph over a 90-day period, a policy that is largely the result of the project’s initial funding through the Federal Urban Partnership Agreement. The Florida DOT estimates that about 2% to 3% of the traffic in the express lanes is travelling toll free.

The managed lanes are separated from the GPLs by flexible delineator posts. The model currently includes four northbound entrances, five southbound entrances, four northbound exits, and four southbound exits between the managed lanes and GPLs (see Figure 4.12).

The simulation platform used to develop this network was Vissim. The Vissim modeling included the GPLs, the managed lanes, and the individual interchange operations.

### 4.2 Evaluation Criteria

This section describes the evaluation criteria used for modeling the initial candidate case study sites. These evaluation criteria were ranked as being of low, medium, or high priority based on their relevancy in assessing DL conditions. For example, model availability is considered a high-priority criterion, whereas having a moderately sized facility is of low priority. Based on the relative importance of each evaluation factor, the team used weighted scoring when ranking case study sites.

#### 4.2.1 Case Study Site Characteristics

The team used eight evaluation criteria to identify characteristics and rank the case study sites. This evaluation included characterization of the geographic and operational conditions that exist in the test sites.

##### 4.2.1.1 Geographic Characteristics

Managed lanes generally are an urban/suburban roadway feature; hence, it is desirable that the final selected case study sites represent reasonable use of dedicated/managed lanes in or near metropolitan area conditions. Drivers in larger metropolitan areas will be more accustomed to regularly encountering recurring or nonrecurring congestion. In larger metropolitan areas, congestion will tend to be more ubiquitous and bidirectional. For this criterion, the characteristics assessed reflected diverse sites that ranged from less urban to more urban in terms of number of lanes, AADT, and location. This evaluation criterion was given medium priority in the case study selection process because managed lanes are mostly an urban feature (Figure 4.13).

##### 4.2.1.2 Availability of Data/Case Study Site Model

Successful modeling of CACC in DLs depends on the model’s closeness to the real world. Hence, availability of a calibrated case study site model is of extreme importance. The team selected case study site models that were available for use in a calibrated state. To evaluate the impacts of DLs for CACC-equipped vehicles, the case study sites needed to be validated and calibrated using historical, near real-time, and real-time data. The data had to represent a case study site’s geographic and temporal scope as well as characteristics such as existing ITS infrastructure and managed lane configurations. The availability of case study models and the associated calibration data was a high-priority evaluation criterion, given the importance of a fully calibrated simulation model in assessing realistic and credible benefits and sensitivity parameters of CACC application on a DL facility. The research team gave preference to models that were available in an open-source portal such as the U.S.DOT’s Open Source Application Development Portal (OSADP) or the U.S.DOT Data Repository, as well as models that were available upon request from local agencies (see Figure 4.14).
Figure 4.12. I-95 express lane configurations and access points.
4.2.1.3 Diversity in Demand/Operational Conditions

Operating demand of a corridor facility determines the operational conditions for the drivers. For this case study selection, we assess the demand in terms of traffic volumes over the entire case study site. Traffic demand for low (uncongested), medium (near capacity), and high (congested) levels will yield different traffic patterns and a wide range of cases to assess and compare their performances. Although low-demand conditions do not present challenging conditions for the deployment of CAV applications, having a variable demand would allow assessment of impacts under different saturation rates. Hence, the selection included a case study site with varying traffic demand, or multiple case study sites that represent different demands. Having differing demand conditions is important to analyze the sensitivity of DLs under various saturation rates, but the demand can be scaled easily from existing models. Therefore, this criterion was considered medium priority (see Figure 4.15).

4.2.1.4 Length of Facility

The length of a DL facility relative to the overall case study site is an important factor in gauging its influence on the overall network, parallel corridor, and parallel arterials. The length of the facility corresponds directly to the proportion of benefits or disbenefits imposed on the assessment boundary, which is defined as the limits of the roadway facility that have been included in the assessment. Effects like the proportion of a given trip utilizing the DL versus not using the DL can be compared between facilities with longer DLs versus shorter DLs. At the same time, modeling the CACC application entails computationally intensive driver-behavior capture to an external interface and trajectory implementation, and larger models can become difficult to
model. The team selected medium-sized facilities to enable full evaluation of trip-based performance measures as well as manage the computation size. This evaluation criterion was given a medium priority in the case study selection.

4.2.1.5 Availability of Alternate Routes

One consideration in assessing CACC DLs’ impact on non-users is the availability of alternate routes, such as parallel arterials. The case study sites were assessed to determine whether a parallel route was explicitly included in the model and whether vehicle rerouting was possible through these alternate routes. For the case study selection, the team prioritized models that included alternate routes. Because most of the candidate models had been developed for corridor analysis, however, only a few might have included alternate parallel routes. This evaluation criterion was given a medium priority in the case study selection due to this limitation (see Figure 4.16).

4.2.1.6 Diversity in Modes

Varying modes of transportation within the traffic stream composition is an important consideration due to its impact on traffic flow characteristics. Freeways and interstates in urban environments have a significant composition of heavy and transit vehicles unless heavy and/or transit vehicle access is restricted. Heavy and transit vehicles have different acceleration and deceleration profiles compared to passenger cars. For evaluation purposes, the selected case study sites needed to have varying vehicle type composition or be restricted by time-of-day access to heavy and transit vehicles so that their impacts could be assessed. This evaluation criterion was given a medium priority in the case study selection (see Figure 4.17).

4.2.1.7 Existence of Managed Lanes

Managed lanes commonly are used within urban metropolitan areas. Types of managed lanes may include HOV lanes, HOT lanes, and express toll lanes (ETLs). One important factor for consideration is the traffic and safety impacts of using several types of managed lanes on the same corridor. Other impacts include mixed use of managed lanes, which may include dedicated CACC with HOV, HOT, and ETLs. These scenarios could be compared to a scenario with complete conversion of existing managed lanes to dedicated CACC lanes. For this study, the research team gave preference to case study sites with existing managed lanes or where managed lanes had been proposed for deployment in the near future. This evaluation criterion was given a medium priority in the case study selection (see Figure 4.18).
4.2.1.8 Existence of ITS Strategies

ITS strategies are implemented to maximize roadway carrying capacity and increase safety. Concurrent implementation of ITS strategies with CACC DLs may have either synergistic or conflicting effects on roadway capacity and driver safety. For example, CACC is expected to work synergistically with dynamic speed limits because it improves the string stability of CACC platoons. The research team assessed the case study sites to determine whether ITS strategies existed and were modeled in the available simulation model. These existing ITS strategies could then be screened for conditions that can cause synergies or conflicts with CACC applications. This evaluation criterion was given a low priority in the case study site selection because currently implemented ITS strategies may or may not exist in conjunction with CACC implementation.

4.2.2 Managed Lane Characteristics

The existing or proposed characteristics of the managed lanes for each of the case study sites also were assessed. Specifically, the following five characteristics were used for case study site scoring: managed lane geometry, user types, operating rules, physical barrier types, and diversity in access point configurations.

4.2.2.1 Managed Lane Geometry

The number of lanes available for use as managed lanes is a critical factor to assess the capacity benefits of additional lanes. Capacity impacts are an important determining factor in deciding on the implementation of additional lanes due to roadway widening or hard running shoulder uses. Additional lanes mitigate the “snail” effect by which the slowest-moving vehicle in the managed lane can govern the speed of the entire lane. Additional lane design should complement the access management strategy to accommodate traffic safety and capacity due to lane changes. Case study sites with a diverse number of DLs and varying roadway geometries were preferred so that these impacts could be assessed. This evaluation criterion was given a low priority in the case study selection.

4.2.2.2 User Types

Within the selected case study sites, existing managed lanes (e.g., HOT lanes, HOV lanes, and ETLs) with a mix of user-types (e.g., SOVs, HOVs, transit vehicles, and heavy vehicles) were preferred. To assess the benefits and disbenefits of imposing future restrictions on current user types (e.g., through conversion of existing managed lanes to dedicated CAV lanes) the team identified case study sites with a diverse user base. Among the project objectives, a major consideration was to evaluate the feasibility of mixed lane use by CAV vehicles and non-CAV vehicles. Hence, this evaluation criterion was given a medium priority in the case study selection (see Figure 4.19).

4.2.2.3 Operating Rules

Managed lanes can have a variety of operating rules to manage the facility for both operational and safety reasons. For example, time-of-day and vehicle-class access restrictions commonly are used along certain managed lane facilities. These operating rules influence traffic patterns...
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

throughout the day at the imposed area. Other operating rules may include the enforcement of left-lane passing only laws, which may involve safety concerns for vehicles that must pass multiple platooned vehicles to find an acceptable gap for a lane change. The team categorized the testbed operating rules as:

a. **Time-of-day operation**, wherein lanes operate as managed lanes only during peak hours. During non-peak hours, no lanes are dedicated to special vehicle categories such as HOVs or toll-paying SOVs.

b. **Time-of-day pricing**, wherein lanes always operate as managed lanes, but the pricing depends on the time of day and follows a schedule. This category includes managed lanes for which off-peak usage may be free.

c. **Dynamic congestion pricing**, wherein the usage fee for the managed lanes is determined based on existing travel conditions.

This evaluation criterion was given a medium priority in the case study selection because the variance in these factors is somewhat limited (see Figure 4.20).

### 4.2.2.4 Physical Barrier Types

Managed lanes that are separated from the GPLs by physical barriers like flexible delineator posts or concrete median barriers may have different posted speed limits from the GPLs. The potential difference in speed limits distinguishes managed lanes with physical barriers from managed lanes that are separated only by pavement striping. Differences in posted speed limits will have considerable effects on roadway capacity, traffic characteristics, and driver behaviors. The impacts on driver behaviors and traffic characteristics caused by varying physical barrier separations can be assessed and compared to the impacts on driver behaviors and traffic characteristics at managed lanes with no physical barrier separations. Accordingly, the research team gave preference to a testbed portfolio that included varying barrier types. This evaluation criterion was given a medium priority in the case study selection (see Figure 4.21).

### 4.2.2.5 Diversity in Access Point Configurations

Access points to and from the DLs have a significant impact on the roadway capacity. The frequency of available access points along a DL directly correlates to drivers’ wayfinding and

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**Figure 4.19.** Case study characterization based on managed lane user characteristics.

**Figure 4.20.** Case study characterization based on managed lane operating rules.
access to the facility. Driver lane-changing behaviors on both GPLs and DLs will be affected by advanced knowledge of access availability. Treatments that mediate the impacts of traffic turbulence caused by weaving vehicles making lane changes to enter or exit the DLs also are important factors to consider. The two types of access point configurations categorized by the team were continuous access and restricted access, with the latter type defined by access point frequency, strictness of access point location, and access section length. Access point frequency and weave management treatments, such as shorter access lengths (which challenge weaving movements), could be compared to assess the treatments’ impacts on both the GPLs and DLs. This evaluation criterion was given a medium priority in the case study selection (see Figure 4.22).

### 4.2.3 CAV Modeling Feasibility

The feasibility of modeling CAVs also represented an important set of scoring criteria. Specifically, the case study site needed to be modeled in an environment that permitted modeling of customized vehicle and driver behavior. Specific feasibility criteria considered by the research team were the possibility of external programming interface and available driver behavior calibration data.

#### 4.2.3.1 Possibility of External Programming Interface

For the purposes of this project, the simulation environment needed to allow for modeling CACC driver and automatic car-following behaviors. The environment needed to allow for the inclusion of external API or a software-in-the-loop-system, if the CACC driver behavior was not already readily available with the model. External API also was required to query and receive vehicle parameters that were not already catalogued for analysis. This evaluation criterion was given a high priority in the case study selection because modeling CACC applications without external API was not possible (see Figure 4.23).

#### 4.2.3.2 Available Driver Behavior Calibration Data

The case study sites selected would need driver behavior calibration data specific to the local environments to allow for a detailed replication of conventional local driving behavior. A case study model that closely mimicked existing driver behavior would provide for a high-fidelity representation of the case study area and better comparisons among analyzed scenarios. Assessing

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**Figure 4.21.** Case study characterization based on managed lane separation.

**Figure 4.22.** Case study characterization based on managed lane access features.
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

The traffic flow performance under a mixed-use case including CAV and non-CAV was critical to determining their traffic impacts, so this criterion was given a high priority.

4.3 Selected Case Study Sites

The project team used the scoring criteria discussed in the preceding sections of this chapter to score and rank the nine candidate case study sites.

4.3.1 Case Study Site Scoring

The study team developed a comprehensive scoring process to rank the initial candidate case study sites and select a portfolio of case study sites that could be used to effectively model the CAV applications and determine the implications on dedicating lanes to such vehicles. The selected case study sites needed to be able to define guidelines that agencies can use to determine whether their specific applications would merit lane dedication. These guidelines should include different levels of traffic congestion, network connectivity, availability of alternate routes and modes, spacing of access/egress points, truck traffic, and traffic patterns (e.g., core focused versus dispersed). Selecting a single case study site would not be sufficient to model the diversity in conditions that needed to be assessed, whereas modeling numerous test sites would be resource-intensive. Consequently, the team used the evaluation criteria scoring process to select two case study sites.

4.3.1.1 Mapping of Evaluation Criteria

The team used the evaluation criteria it had developed to identify a set of 15 parameters (see Table 4.2). The nine initial candidate testbeds were then evaluated based on these 15 parameters. For each parameter, the team identified corresponding site-specific value(s), which are shown in Table 4.2 and Table 4.3. Multiple values were selected for certain parameters that involved a mix of different values. For example, the case study from St. Paul, Minnesota involved a mix of rural, suburban, and urban geographical areas.

4.3.1.2 Scoring of Case Study Sites

Once the site-specific value for each parameter had been assessed, the team scored the parameter based on whether it was least preferred (0) to most preferred (3), as shown in Table 4.4.

For example, for availability of model and data, the Northern Virginia test site received a score of 3 because the model is available as open source, whereas case study sites such as the Chicago site received a score of 2. A weighted factor to indicate the priority of that specific evaluation factor was assigned. A weight value of 1 through 3 was used for factors with priority low to high, respectively. The final score of each testbed was calculated as a sum-product of each of the evaluation scores and their corresponding weights ($w$). Thus, for a testbed ($i$), the final score ($S_i$) was calculated as follows:

$$S_i = \sum_j s_{ij} w_j,$$

where $j$ represents the variable evaluation scores.
Table 4.2.  Modeling feasibility given site-specific values for case study site and managed lane characteristics (Part 1 of 2).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Northern Virginia</th>
<th>San Mateo, California</th>
<th>San Diego, California</th>
<th>St. Paul, Minnesota</th>
<th>Minneapolis, Minnesota</th>
<th>Chicago, Illinois</th>
<th>Detroit, Michigan</th>
<th>Maryland</th>
<th>Miami, Florida</th>
</tr>
</thead>
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<td>●</td>
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<td>●</td>
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<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Suburban</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
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<td>●</td>
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<td>●</td>
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<td>●</td>
<td>●</td>
<td>●</td>
</tr>
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<td>Availability of Model and Data</td>
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<td>●</td>
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<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Available on Request</td>
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<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td></td>
<td>Unavailable</td>
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<td>●</td>
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<td>●</td>
<td>●</td>
<td>●</td>
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<td>●</td>
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<td>●</td>
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<td>●</td>
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<td></td>
<td>High</td>
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<td>●</td>
<td>●</td>
<td>●</td>
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<td>Size of Model</td>
<td>Length (Miles)</td>
<td>13</td>
<td>8.5</td>
<td>22</td>
<td>15</td>
<td>14</td>
<td>14.5</td>
<td>18.5</td>
<td>26</td>
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<tr>
<td>Case Study Site Characteristics</td>
<td>Alternate Routing</td>
<td>Unavailable</td>
<td>Available, but not modeled</td>
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<td>●</td>
<td>●</td>
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<td>●</td>
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<td></td>
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</tr>
<tr>
<td>Modal Diversity</td>
<td>Cars</td>
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<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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</tr>
<tr>
<td></td>
<td>Trucks</td>
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<td>●</td>
<td>●</td>
<td>●</td>
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</tr>
<tr>
<td></td>
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<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<td>●</td>
<td>●</td>
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<td>●</td>
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<tr>
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<td>Managed Lane Characteristics</td>
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<td>San Diego, California</td>
<td>St. Paul, Minnesota</td>
<td>Minneapolis, Minnesota</td>
<td>Chicago, Illinois</td>
<td>Detroit, Michigan</td>
<td>Maryland</td>
<td>Miami, Florida</td>
</tr>
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<td>Operating Rules</td>
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<td>●</td>
<td>●</td>
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<td>Access Point</td>
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<td>●</td>
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<td>●</td>
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<td>Feasibility</td>
<td>Modeling Platform</td>
<td>API Unavailable</td>
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</table>
### Table 4.4. Case study site scoring criteria.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scoring and Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Case Study Characteristics</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Geographic Characteristics         | 3 = Urban region.  
                                      | 2 = Suburban region.  
                                      | 1 = Rural region.                                                                                     |
| Availability of Model and Data     | 3 = All models that were available as open-source.  
                                      | 2 or 1 = The score was lowered based on the increasing difficulty of obtaining the model.         |
| Demand Levels                      | 3 = Sites that replicate low, medium, and high demand conditions.  
                                      | 2 or 1 = The score was lowered depending on the model’s inability to mimic certain demand conditions. |
| Size of Model                      | 3 = Sites between 7 miles and 14 miles in length.  
                                      | 2 or 1 = The score was lowered for smaller or larger sites owing to the relative increase in complexity/computational intensity of modeling CAV applications at these sites. |
| Alternate Routing                  | 3 = Sites with an available alternate route that also could be modeled.  
                                      | 2 or 1 = The score was lowered when an alternate route was not available for modeling.               |
| Modal Diversity                    | 3 = Sites with a diverse modal set (including cars, trucks, and transit).  
                                      | 2 or 1 = The score was lowered when the number of modes was reduced.                                 |
| Existing ITS Strategies            | 3 = Sites with existing ITS strategies (e.g., ramp metering, hard-shoulder running, variable speed limits).  
                                      | 1 = Sites without existing ITS strategies.*                                                          |
| **2. Managed Lane Characteristics**|                                                                                                                                                    |
| Existence of Managed Lanes         | 3 = Sites with existing managed lanes.  
                                      | 2 = Sites with proposed managed lanes.  
                                      | 1 = Sites with no managed lanes.                                                                      |
| User Types                         | 3 = Sites that allow all types of users in the managed lanes.  
                                      | 2 = Sites with some restrictions on vehicle types allowed in the managed lanes.  
                                      | 1 = Sites with the greatest restrictions on vehicle types allowed in the managed lanes.               |
| Operating Rules                    | 3 = Sites with an operating rule.  
                                      | 1 = Sites without an operating rule.*                                                                 |
| Physical Barriers                  | 3 = Sites with separation or barriers.  
                                      | 1 = Sites without separation or barriers.*                                                           |
| Access Options                     | 3 = Sites with limited-entry managed lanes.  
                                      | 1 = Sites with continuous access.*                                                                    |
| **3. CAV Modeling Feasibility**    |                                                                                                                                                    |
| CAV Modeling Ability               | 3 = Sites with available API.  
                                      | 1 = Sites without available API.*                                                                     |
| Driver Behavior                    | 3 = Sites that can be calibrated to realistic driving behavior.  
                                      | 1 = Sites not calibrated to realistic driving behavior.*                                              |

*Scoring for this parameter did not include a score of 2.*
With regard to parameters for which variety was preferred, the case study sites that represented a diverse set of values were given higher scores. For example, St. Paul, Minnesota, received a high score for demand levels because the case study site is subject to varying demand levels. These scores were generated for each parameter and a total score was assessed as shown in Table 4.5.

Based on the case study site scores provided in Table 4.5, the top-ranking testbeds were:

1. Northern Virginia, and
2. San Mateo, California.

Chapter 5 provides a detailed description of these two testbeds along with details on their calibration data and operational conditions in terms of traffic demand, weather conditions, and occurrence of incidents.
Using modeling and simulation, the research team evaluated the specific conditions and factors that influence the performance of CAV applications when such users are in a DL. The team used a four-step evaluation approach to evaluate the performance of CAV applications under different conditions and to quantify factors that influence these impacts (see Figure 5.1).

This chapter expands on each of the four steps of the evaluation process. As was discussed in Chapter 1, the team conducted extensive research to identify the scope of this evaluation, including the test sites, the CAV applications to be included, and the specific performance measures and research questions.

5.1 Develop Baseline Models

The team ranked the various simulation testbeds that were available based on evaluation criteria pertaining to (1) case study site characteristics, (2) managed lane characteristics, and (3) CAV modeling feasibility. In the end, two case study sites were selected: the I-66 corridor in Northern Virginia and the US-101 corridor in San Mateo County, California. The next step was to develop baseline simulation models that could replicate the real-life traffic behavior of the two selected sites. The models for both simulations were developed using PTV VISSIM microsimulation software.

The first step to effective analysis using modeling and simulation is to develop baseline models that are representative of the field conditions. As per the FHWA’s Traffic Analysis Toolbox, the microsimulation model development process consists of several steps, as shown in Figure 5.2. The four steps highlighted in grey in the figure are required to develop a well-defined baseline-calibrated model that provides a good representation of the field conditions.

As shown in the figure, once the pre-calibrated model (which includes data about the lane geometry, turn permissions, infrastructure, and traffic control features as well as traffic demand and vehicle types) has been developed, the model is iteratively adjusted such that the measured performance resembles the field conditions. This includes comparing vehicle volumes and speeds at differing locations of the network in order to match the simulation with the field conditions and to ascertain whether congestion occurs at the right places along the network.

The models adopted by the project team for this evaluation—I-66, in Northern Virginia, and US-101, in San Mateo County, California—were at differing levels of maturity. For example, the I-66 model required complete calibration based on field data to conduct the analysis, whereas the US-101 model had already been calibrated during previous projects. This chapter provides details on the calibration process and calibration results for the I-66 corridor, and provides the baseline system performance for both testbeds. These performance measures formed the baseline to which application performance was compared, as described in Chapter 6.
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

5.1.1 I-66 in Northern Virginia

Interstate Highway 66 (I-66) in Northern Virginia was the primary case study site for this project. The I-66 corridor is an east-west corridor taking traffic between the suburbs of Northern Virginia and Washington, D.C. The selected test site represents the segment of I-66 between the I-495 interchange and the SR-234 interchange, spanning approximately 13 miles, as shown in Figure 5.3. The corridor has an AADT of 150,000 to 160,000 vehicles and includes one peak-hour peak-direction HOV-2+ lane in addition to two to three GPLs and a peak-hour peak-direction shoulder lane. The freeway corridor has a posted speed limit of 55 mph. This suburban test site includes six interchanges and two dedicated on-and-off ramps for the HOV lane, separate from the GPLs. The average distance between interchanges is approximately 1.2 miles, yielding 0.6 miles and 2 miles of minimum and maximum interchange spacing, respectively. The test site experiences recurring congestion caused by high directional daily demand every weekday for the eastbound lanes (i.e., traffic moving toward Washington, D.C.) during the a.m. peak and the westbound lanes (i.e., traffic moving toward Fairfax, Virginia) during the p.m. peak. Between 2:00 p.m. and 8:00 p.m., the traffic volumes of the testbed range from 900 vphpl to 2,100 vphpl, including approximately 1,500 vphpl of peak HOV traffic volumes (Lu et al. 2014).

The I-66 managed lanes are single-lane, time-of-day, HOV-2 lanes in both eastbound and westbound directions and are located in the left-most lanes. User-type restrictions along the existing HOV-2 allow for all vehicle classes with occupancy requirements of two or more occupants per vehicle. The existing managed HOV-2 lanes operate on a time-of-day basis with restrictions applying during a.m. and p.m. peak periods on weekdays. No physical barrier separates the managed HOV-2 lanes from the mixed use lanes. Currently, only double solid white lane markings are used for lane separation and to indicate no lane changing/no access. Access points between the dedicated HOV-2 lanes and the mixed use lanes are permissible only along sections with dashed lane striping.

The I-66 also has hard-shoulder running lanes on the right-most lanes in both directions. The hard-shoulder running lanes operate from 5:30 a.m. to 11:00 a.m. in the eastbound direction and from 2:00 p.m. to 8:00 p.m. in the westbound direction. Lane utilization is indicated via VMS that show a green arrow for permitted use and a red cross for closed unless exiting.

The I-66 Northern Virginia VISSIM base model was obtained through the U.S.DOT OSADP (U.S.DOT n.d.b). However, the base model calibration was not suitable for this project.

Figure 5.1. Overall evaluation process.

Figure 5.2. Microsimulation model development and application process.
Therefore, the project team collected field traffic data for vehicle counts, incident records, spot speeds, and probe data from the Virginia Department of Transportation (Virginia DOT). Figure 5.4 shows the data used for calibrating the network and represents a typical day peak-hour traffic at 1-hour resolution for the HOV and non-HOV lanes for October 2016.

The simulation model was calibrated to field observations using the traffic analysis toolbox performance measure for model validation developed by Dowling et al. (2004) and the GEH statistic, an empirical formula devised by Geoffrey E. Havers. The GEH statistic compares the simulated and real-world hourly traffic volumes. Figure 5.5 shows a comparison of the field data with the model travel-time data.

In Figure 5.5, the red line represents the field travel time data and the blue region represents the acceptable ±10% margin of error. The field travel time was computed from the probe vehicle speed data provided by the Virginia DOT from the RITIS database. These data were computed on an hourly basis; therefore, the red line is plotted from five data points representing 3:00 p.m., 4:00 p.m., 5:00 p.m., 6:00 p.m., and 7:00 p.m. The VISSIM model was simulated and recorded over multiple speeds to achieve statistical significance, and the travel time was averaged and represented by the blue line. The green region represents the boundary of all the travel time for individual random speeds.

The calibration results shown in Figure 5.5 indicate that all model travel times are within the acceptable margin of error and the average travel time replicates field travel time by increasing from the start until it peaks (at approximately 5:00 p.m.) and subsequently declining until the end of the simulation time frame.

Table 5.1 shows the calibration results using traffic counts as a performance measure with the GEH statistic to validate the model’s ability to replicate existing traffic patterns.

The results shown in Table 5.1 indicate that, out of 32 comparisons, only two yield a GEH value larger than 5.0. Taken together, the cases result in 93.75% target values falling within the acceptable 85% of freeway mainline links and within the maximum GEH value of 5. Havers’
Figure 5.4. Traffic volumes and speed for calibrating the I-66 model.
Figure 5.5. I-66 westbound travel time field and simulation data with calibration threshold.

Table 5.1. I-66 field and simulation vehicle counts with the GEH statistic.

<table>
<thead>
<tr>
<th>Location</th>
<th>Field Vehicle Counts</th>
<th>Simulation Vehicle Counts</th>
<th>GEH Statistic</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>3:00 p.m.</td>
<td>4:00 p.m.</td>
<td>5:00 p.m.</td>
</tr>
<tr>
<td>East of VA-243</td>
<td>4,194</td>
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<td>3,810</td>
</tr>
<tr>
<td>VA-234 and VA-123</td>
<td>3,432</td>
<td>3,141</td>
<td>2,926</td>
</tr>
<tr>
<td>VA-123 and US-50</td>
<td>4,161</td>
<td>4,154</td>
<td>3,890</td>
</tr>
<tr>
<td>VA-286 and VA-28</td>
<td>4,670</td>
<td>4,056</td>
<td>3,738</td>
</tr>
<tr>
<td>East of VA-243</td>
<td>4,484</td>
<td>4,415</td>
<td>4,509</td>
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</tbody>
</table>
GEH statistic functions as an empirical parameter similar to the chi-squared statistic that compares two sets of traffic volumes.

5.1.1.1 Baseline System Performance

This section expands on the baseline system performance. Although the model was calibrated on both eastbound and westbound directions, the research team’s performance measurement focused on the westbound direction because that was the direction of peak traffic flow. Figure 5.6 shows the calibrated baseline freeway speeds of I-66 westbound with data collected using data collection points spaced at 0.1-mile increments. The speed profile shows several bottleneck locations near the interchange locations, with traffic congestion also forming from the network downstream location. The spatio-temporal speed profile is a useful technique to demonstrate how the DSH application can help in reducing congestion and shockwaves over the network.

Figure 5.7 shows the baseline average hourly throughputs of the freeway. The throughput shown in this figure is an average of 12 cordon lines representing different sections of the freeway. The traffic changes over both spatial and temporal dimensions, but for easier demonstration, only the temporal changes are shown. Spatial changes were averaged into
computation of the throughput values. The time-series in Figure 5.7 shows that the volumes increase between 5:00 p.m. and 6:00 p.m. and then steadily decrease, as was expected from the field data. Given that the CACC application aims to improve the capacity of freeway lanes, average freeway throughput was considered an effective way of demonstrating the impact of CACC-equipped vehicles in the network.

Figure 5.8 shows the baseline performance measures for the entire I-66 network in terms of average vehicle delay, average vehicle speed, total vehicle travel time, and total system throughput.

### 5.1.2 US-101 in San Mateo County, California

Although the I-66 corridor provided enough precedence to test various scenarios in a CAV DL setting, the project team also used a secondary case study site to supplement some of the analysis that was performed. Specifically, having a second case study site enabled understanding of any measured variability that could be attributed to differences in operational characteristics, geometric/geographic characteristics, driving behavior, demand, and so forth. The secondary case study site chosen by the study team represents the US-101 corridor located in the County of San Mateo, California, and stretches from Redwood City to the City of Burlingame. The length of the modeled US-101 freeway facility is approximately 8.5 miles, with a parallel arterial, El Camino Real (SR-82), of similar length. The model allows diversions for vehicles from the US-101 freeway to the SR-82 via seven interchanges. The extent and coverage of the US-101 corridor model is illustrated in Figure 5.9 (Booz Allen Hamilton 2016).

Figure 5.8. **Baseline performance measures for I-66 network.**
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

The US-101 freeway carries between 200,000 and 250,000 AADT, of which 15% to 25% consists of HOV-2+ vehicles. El Camino Real carries between 25,000 and 50,000 average daily traffic. The proposed HOV-2+ DL facility will have continuous access throughout the US-101 freeway. Currently, the HOV lanes are located at the southern portion of the freeway and end at the interchange with Whipple Avenue. The freeway has a posted speed limit of 65 mph. The model was previously utilized by the U.S.DOT to conduct an impact assessment of the DSH application using connected vehicle modeling.

As the secondary site, the US-101 case study site underwent minimum modifications for use in this project. Modifications were made to the classification of vehicle classes and coding of data collection measurements to provide the necessary inputs to the CAV applications. No modifications were made to the model in relation to the portion of the El Camino Real arterial to accommodate the DL on US-101.

5.1.2.1 Baseline System Performance

This section describes the baseline performance of the modeled US-101 corridor. For full details on the data collection and calibration process with respect to this case study site, readers are encouraged to refer to the calibration report for the San Mateo Testbed by Yelchuru et al. (2016). Figure 5.10 and Figure 5.11 show some of the observed performance measures for the base model averaged using five runs (to create statistically significant results). Specifically, Figure 5.10 shows the baseline corridor travel time as a function of p.m. peak intervals for the US-101 northbound direction. Other system-wide performance measures, such as average vehicle delay, average vehicle speed, total vehicle travel time, and total system throughput, are shown in Figure 5.11.
Figure 5.10. Baseline performance in northbound (peak direction) travel time.

Figure 5.11. Baseline performance measures for US-101.
The analysis period used was between 2:30 p.m. and 7:30 p.m. It can be seen from the figures that the peak congestion occurs between 4:00 p.m. and 6:00 p.m., as represented by the reduction in vehicle speeds or the increase in vehicle delays.

5.2 Integrate CAV Application Models

The project team reviewed several longitudinal and lateral driving behavior models that could be considered in a connected and automated environment to evaluate the feasibility of prioritized and exclusive DL usage for CAVs. For this evaluation, priority was given to freeway-based applications, given that dedicating lanes on arterials presents significant challenges in quantifying the impacts due to variability in arterial design, signalized and non-signalized operations, lack of mature CAV applications for arterials, complex V2V and vehicle-to-pedestrian interactions, and so forth. Of the freeway applications evaluated, the two highly researched applications that could potentially be deployed in a DL setting were CACC and DSH.

PTV VISSIM provides two ways to code in customized vehicle controls into simulation:

- **Component Object Model (COM).** The COM interface defines a hierarchical model in which functions and parameters of the simulator originally provided by the default models can be manipulated by programming; and

- **External Driver Model (EDM).** This Dynamic Linked Libraries (DLLs) interface can be used to define driver models such as vehicle behavior, acceleration, position within a lane, desired speed, look ahead distance, and so forth.

For this step, the research team integrated these two methods so that they could be used in conjunction to enable modeling of CAV applications. The balance of this section describes the CAV applications and the modeled features.

5.2.1 CACC

CACC has been widely researched, and several algorithms exist to provide control logic for equipped vehicles to platoon at short headways. The project team selected the VISSIM-based CACC API developed by Lee et al. (2016a) as a starting point to model the CACC application for this project because of its maturity and adaptability to the project needs.

Lee’s model, originally developed in 2014, was enhanced in 2016. Based on work by TNO (The Netherlands Organization for Applied Scientific Research), the model utilizes an Enhanced Intelligent Driver Model (E-IDM) to simulate CACC string behavior and characteristics (Schakel et al. 2010). For this study, Lee’s model was applied to three types of car-following behavior: (1) VISSIM’s default car-following model (i.e., psychophysical car-following) for non-CACC drivers; (2) the IDM for the ACC driver to represent the Leader vehicle of a CACC platoon; and (3) a customized IDM to deal with CACC longitudinal maneuvering for all the follower vehicles. Both the ACC and CACC models are based on the collision-free IDM and were implemented using VISSIM’s driver behavior API.

Figure 5.12 shows the driver behavior of vehicles that are already using CACC vehicle-following controls and how their lateral and longitudinal control is governed. It also shows the behavior of vehicles when they are joining a CACC string. These customized driver behavior algorithms are modeled as EDMs, and the switching between models is done based on contextual events through VISSIM’s COM capability.

Although Lee’s model enabled dynamic switching between driver behavior models that replicated the behavior of lead and follower vehicles in a CACC string, additional enhancements were made to define string formation and dispersion mechanisms. These enhancements were implemented
Analysis and Evaluation Approach

based on recommendations from the California Partners for Advanced Transportation Technology, which is leading the CACC research on behalf of U.S.DOT’s Exploratory Advanced Research Program. The modified CACC algorithm included the following driver behavior models:

- **Preferential Lane Logic.** When CAVs enter the system, their lane preference will be dynamically set to the left-most DL unless the static routing defines it to take the upcoming off-ramp. This logic is performed via VISSIM’s COM interface using the “Desired Lane” method.

- **String Formation Logic.** This logic enables CAVs to form platoons based on their proximity to each other. When strings are formed, the lead CAV (Leader) and the follower CAVs (Followers) get their respective EDMs assigned. For the Leader, this EDM enables it to act as an ACC vehicle. For the Followers, their respective EDMs enable them to act as CACC-equipped vehicles. EDM assignments are performed through VISSIM’s COM interface, whereas the actual vehicle behavior is controlled through EDM DLLs.

- **String Size Restriction Logic.** When vehicles join existing CACC strings, they also can use the EDMs to check if the string has reached the maximum string size. This is achieved by introducing a new vehicle type (in addition to Leader and Follower), called the String Terminator.

*Figure 5.12. CACC driver behavior logic.*
The String Terminator behaves as a CACC-equipped vehicle but does not let another CAV join the platoon. This logic also is performed through VISSIM’s COM interface.

- **String Dispersion Logic.** This logic actively checks for static routes of each vehicle in the CACC string. If a vehicle needs to exit through an upcoming ramp, it will split from the string. Leader-Follower-Terminator assignments are then reconfigured based on the new order of vehicles. This logic also is performed through VISSIM’s COM interface.

### 5.2.2 Dynamic Speed Harmonization

The team used a simplified speed-based algorithm, developed by Ma et al. in 2016, which uses a simplified space-time relationship to approximate the typical complex models used by previous approaches. The vehicles upstream of congestion are provided a speed recommendation that is a linear function of space ($x$) and temporal ($t$) speed measurements at appropriate intervals. The speed recommendation for a vehicle in space ($x$) and time ($t$) is given by:

$$ s(x, t) = \left( \frac{s_n(t) - s_m(t)}{\Delta x_{nm}} \right) x + s_i(t), $$

where $s_i(t)$ represents the speed measurement at a point ($n$) at a time ($t$), and $\Delta x_{nm}$ is the distance between points $n$ and $m$.

After preliminary tests, this algorithm was modified to include a system that propagates the speed recommendations upstream to further reduce shockwaves and improve traffic flow. The team used speed measurement stations spaced at 0.1-mile increments and mapped vehicle locations to 0.1-mile resolution. The speed recommendations were updated every 15 seconds and provided to the equipped vehicles as their desired speeds. A minimum speed recommendation was kept at 25 mph, and the application was initialized only if a congested condition was detected on the DL.

With these modifications, the final recommended speed for each vehicle space ($x$) and time ($t$) was:

$$ s(x, t) = \min \left[ \frac{25,}{25,}, s_i(t) + 5, \left( \frac{s_n(t) - s_m(t)}{\Delta x_{nm}} \right) x + s_i(t) \right] \text{ mph.} $$

A COM-based application was used to implement this DSH algorithm. The application watched for inputs from freeway sensors (data collection devices) for speeds every 15 seconds. When congestion was detected, the application calculated speed recommendations for every 0.1-mile sub-link. For each sub-link, desired speed points (similar to speed limit signs), were integrated into the network, which was updated based on the COM-based DSH application. Space-resolution of 0.1-mile was chosen based on the studies conducted by U.S.DOT under the DMA Impact Assessment Program to provide granularity. The update frequency of 15 seconds was chosen as a trade-off between the computation intensity of the algorithm and the travel time of vehicles on each sub-link. The overall implementation logic is shown in Figure 5.13.

The DSH algorithm modeled in this project was implemented as a soft-control of the vehicle speeds in the sense that the vehicle controls assume the harmonized speeds as the new “desired speed.” As vehicles receive the harmonized speeds as desired speeds, each vehicle’s dynamics model tries to maintain a speed close to the received speed. In reality, vehicles using the DSH application might be paired with vehicles whose controls assume the new speed as a strict speed.
control or with vehicles whose human drivers perceive the new speed as informational only and may choose not to follow the harmonized speed recommendations.

### 5.2.3 Combined Modeling of Applications

The project team also modeled CACC and DSH applications in combination. Whereas the CACC application tends to reduce headways locally and increase lane capacity, the DSH application aims to increase lane throughput by providing early response to downstream congestion. Together, these applications could have significant mobility improvements on DLs. To test this hypothesis, evaluations were conducted by which CAVs could form close platoons when in the DLs. Additionally, the lead vehicle of each platoon was modeled as a DSH-equipped vehicle that receives speed recommendations based on any congestion detected downstream. Figure 5.14 demonstrates the two applications working in parallel on CAV DLs.

Both the CACC and DSH applications were modeled in VISSIM using a software-in-the-loop system, as shown in Figure 5.15. The combined model included multiple internal and external driver behavior models and COM-based applications. The core of the system was an external simulation manager that controlled the VISSIM object at every time step. The simulation manager ran the simulations according to the scenario definitions in a scenario table and

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**Figure 5.13.** DSH algorithm implementation.
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

Figure 5.14. CACC and DSH working together on a platoon of CAVs.

Figure 5.15. Overall evaluation framework.
exported the measures of effectiveness to a performance measures table. (The scenario table and performance measures table are discussed further in later sections of this chapter.). The CACC and DSH modules were used to manage CAV behavior and require constant interaction with the VISSIM platform. All of the interactions between the simulation manager and the VISSIM objects were handled via COM interface, but the CAV and non-CAV behavior was assigned as external and internal driver behavior modules.

5.3 Develop Scenarios for Assessment

Once the overall evaluation framework had been developed, the next step was to define the specific scenarios to be tested. These scenarios were defined based on the research questions set forth in the analysis plan. This section discusses the various research questions that were addressed in the simulated scenarios.

5.3.1 Research Questions

To support the development of guidance about conditions amenable to dedicating lanes to CAV users, the study team framed several research questions in the analysis plan. These questions were:

1. What will be the mobility, safety, and environmental benefits to users of DLs under different market penetrations of CAV applications:
   a. When they have exclusive access to these lanes?
   b. When they share the lanes with HOV/HOT vehicles?
2. What are the economic benefits to CAV DL users when compared to GPL users?
3. What are the incremental benefits of DSH application, when implemented with CACC application?
4. What are the impacts of the following factors on CAV DLs?
   a. Low versus high demand?
   b. Continuous versus restricted access to DLs?
   c. Temporary lane closures caused due to an incident?
   d. Slow-moving vehicle on a DL?

5.3.2 Simulated Scenarios

To answer the research questions defined in the previous subsection, the project team developed a list of simulated scenarios that could be used to provide performance measures. Each scenario was defined specifically to represent variations in the traffic mix, lane dedication, test-bed network, and other factors.

The baseline simulation models were calibrated to the traffic mix identified in the corresponding case study site, and included HOVs and SOVs, with a percentage of heavy vehicles as per field conditions. For CAV test simulations, an overall percentage of vehicles was converted from normal vehicles to CAVs based on the assumed market penetration, with no increase in the actual demand. The MPR was used to represent the percentage of overall vehicles that are equipped with CAV applications such as CACC and DSH.

Three lane dedication cases were considered in the simulations:

- The base case allowed only HOVs on the DLs;
- The priority lane case allowed HOVs and CAVs to share the DL; and
- The exclusive lane case allowed only CAVs on the DLs. Table 5.2 depicts these three cases using red, yellow, and gray colors representing HOV, CAV, and GPL vehicles, respectively.
Table 5.3 shows a preliminary list of evaluation scenarios. In the table, each scenario is described in terms of the case study site, demand, market penetration, users allowed on the DLs, number of DLs, applications modeled, and any special cases. Scenarios with an N/A on the DL column represent locations with a higher MPR for which dedicating lanes would not be feasible. The baseline runs were calibrated to typical evening peak traffic conditions, and low and high demand conditions represented reductions and increases in the peak traffic by 20%.

### 5.4 Measure Performance of CAV Applications

During the simulations, the project team logged a variety of performance measures to understand how dedicating lanes can impact both network performance and individual user needs in terms of efficiency. Four categories of performance measures were logged or computed from each simulation: mobility, safety, environmental, and societal equity.

#### 5.4.1 Mobility Performance Measures

The following mobility measures were logged from the simulation:

- **Average Vehicle Travel Time.** VISSIM microsimulation can generate travel time performance measure without further modifications. A measurement of individual travel times for each vehicle across the simulation network can be refined into the individual vehicle classifications. The measurement of travel time per vehicle or average vehicle delay represent the vehicles’ “experiences.” By comparing the average travel time of vehicles between different simulations, the distortion due to variations in trip lengths can be normalized.

- **Average Travel Speed.** Vehicle speeds can be quantified in several ways. For this project, the team used average network speed, which is quantified as the ratio of VMT and vehicle-hours traveled (VHT), to account for the variability in trip distances, travel segments, vehicle characteristics, and so forth.

- **Throughput.** This performance measure was used to assess whether the DLs for CAVs increased the capacity of freeways by demonstrating whether more vehicles were able to pass through sections of the case study sites. In the scenarios modeled, the throughput was measured between consecutive on-ramps and off-ramps using cordon lines. In the simulations for this report, the throughput was demonstrated by the percentage variation in cumulative number of vehicles passing through the freeway from the base case. The team also measured throughput per lane to distinguish the impact of CAVs on DLs and GPLs.
Table 5.3. Preliminary list of evaluation scenarios.

<table>
<thead>
<tr>
<th>ID</th>
<th>Site</th>
<th>Demand</th>
<th>MPR (%)</th>
<th>DL Users</th>
<th>CAV Applications</th>
<th>Special Cases</th>
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<td>I-66</td>
<td>Typical p.m. Peak</td>
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</tr>
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</tr>
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</tr>
<tr>
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<td>CACC</td>
<td>Lane Closure</td>
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</tr>
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<td>DSH</td>
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<td>Lane Closure</td>
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<td>DSH + CACC</td>
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<td>DSH + CACC</td>
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<td>DSH + CACC</td>
<td>None</td>
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<td>CACC</td>
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5.4.2 Safety Performance Measures

Safety-based performance measures can contribute significantly to the development of guidance for dedicating lanes to CAVs. Specifically, they can help assess safety features that are required in the infrastructure when lanes are dedicated to CAVs under different conditions. For this study, two types of safety performance measures were captured in the simulation:

- **Lane Friction.** This measure is defined as the difference in travel speeds of vehicles on the DLs and GPLs. Larger lane friction (a higher speed differential between these lanes) can render lane changes into and out of the DLs unsafe and hence warrants restricted lane access or physical barriers/lateral spacing between DLs and GPLs.

- **Shockwaves and Speed Differential.** Shockwaves and speed differentials occur due to changes in capacity, and they result in either static or moving bottlenecks along a facility. The properties of the shockwaves and speed differentials experienced by individual vehicles can be analyzed by studying the speed profiles of vehicles on a spatio-temporal scale (Dowling et al. 2015). The project team captured two types of speed differentials from the simulation: (a) spatial speed differential and (b) temporal speed differential.
  
  Spatial speed differential represents shockwaves. The speed differential is quantified by calculating the speed difference between adjacent segments for each time period and taking the 95th percentile throughout the simulation. The temporal speed differential is measured by calculating the speed difference between consecutive time periods for each segment and taking the 95th percentile throughout the simulation. A segment length of 0.1 mile and a time period of 15 seconds was utilized for these measures. The average of spot speeds within a segment was used to compute the speed differential, and the speed differential was compared between samples of simulation runs.

5.4.3 Environmental Performance Measures

The research hypothesis was that both CAVs and non-CAVs would benefit from a more stable and laminar traffic flow in which the reduction in the number of vehicles accelerating and decelerating across the network directly correlates with a reduction in fuel consumption and vehicle emissions. To test this hypothesis, the team coded environmental performance measures in the VISSIM microsimulation. Using data collected at defined nodes in the network, the model generated specific energy and emissions indicators based on individual vehicle trajectories consisting of speeds and accelerations. The four performance measures generated were carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOC), and fuel consumption. These measures were generated using the VERSIT+ model, which uses statistical models for detailed vehicle categories that are calibrated based on drive cycles (Smit et al. 2007). By utilizing instantaneous vehicle trajectories, the model also represents variations in fuel consumption as a function of speed and acceleration.

5.4.4 Societal Equity Performance Measures

To distinguish the economic benefits to CAV DL users, the project team used value of travel time savings (VTTS) as the performance measure (U.S.DOT 2014). VTTS is a complex concept that expresses three principles:

- Time saved from travel could be dedicated to production, yielding a monetary benefit to either travelers or their employers;
- Time saved could be spent in recreation or other enjoyable or necessary leisure activities for which individuals are willing to pay; and
• The conditions of travel during part or all of a trip may be unpleasant for the travelers and involve tension, fatigue, or discomfort. For this study, the project team utilized average value of VTTS based on personal and business trips as per 2014 guidance. The VTTS was compared for DL CAV users and GPL users to distinguish between the economic impacts on both categories of users.

5.5 Analysis Assumptions

Effectively modeling CAVs to assess their impacts on the transportation network and study the sensitivity of parameters is a complex task given the suitability of today’s microsimulation and other analytical tools. Hence, the analysis described in this report and project makes several assumptions to effectively model the behavior and performance of CAVs. This section describes some of the key assumptions used in this analysis.

5.5.1 CAV Application Modeling Assumptions

Two CAV applications were modeled in this project—the CACC application and the DSH application. It should be noted that these applications are not standardized in any way, and other algorithms are available to model these applications and the variations within them. In addition, these applications are still in the pilot deployment and testing phase, and they are not yet readily implemented in the market. Therefore, for purposes of this project, the research team employed certain assumptions regarding these applications. For example, the team assumed a maximum of five vehicles within a CACC string. This number was chosen based on some initial parametric testing aimed at considering the optimum number of vehicles that could platoon without significant string stability issues. Based on the performance measure used, other studies have shown varying values for this optimum string size. Similarly, the DSH was modeled to have a speed resolution of 5 mph. This and other parametric assumptions may have significant impact on the findings.

The project team also assumed a simplified human-to-machine control transfer, because a full-fledged human factors study was beyond the scope of this project.

5.5.2 Demand and Capacity Assumptions

Previous studies have indicated that CACC application is likely to increase the capacity of lanes and therefore may be able to carry a higher demand through the network. Consequently, the research team elected not to put any constraints in lane capacity. Consequently, the team was able to achieve higher lane capacities when CACC was used exclusively on DLs. This higher capacity may indirectly increase the demand on the network, however, because vehicles from other parallel corridors might switch routes to maintain equilibrium. In addition, the additional lane capacity might also increase the overall network VMT, latent demand, and other indirect factors. Given that the models used in this network were microscopic, the research team did not increase the demand on the network as an indirect consequence. To assess this impact fully, the model would need to include a software-in-the-loop system with an activity-based model for the entire region, which was beyond the scope of this project.

5.5.3 Performance Measurement

Four types of performance measures were considered in this project: mobility, safety, environmental, and societal equity. The performance measures considered in each category reflect
only the direct performance of the network. For example, the team did not consider impacts due to increased VMT that might be caused by the increase in mobility performance of the network. The team also used simplified performance measures to reflect safety, environmental, and societal equity. Due to software restrictions, the analysis did not consider safety impacts such as changes in surrogate safety measures or direct crash indicators. For environmental performance, the research team did not calibrate the environmental performance models to the vehicle line-up that is reflective of the two regions modeled. Rather the team used the default model parameters. Societal equity was measured using VTTS. These calculation assumptions are discussed in more detail in Chapter 4. Long-term impacts on land use, economic measures, tolling, and other considerations were not part of this study.

5.5.4 Dedicated Lane/Geometric Assumptions

Regarding the DL configuration and geometry the study team made several assumptions to distinguish the modeling scenarios clearly. For example, the geometry of DLs was assumed to be the same for HOV and human-driven lanes in terms of lane width, curvature, access and egress distances, and other details. In reality, some of these factors could be changed or reduced based on the robustness of applications and types of vehicles allowed. Similarly, the study team used strict modeling assumptions on vehicle types and access rules for the DLs, except in certain hypothetical scenarios. For example, when CAVs had exclusive access to DLs, it was assumed that no other vehicles would enter the DLs. The models also reflected tactical driving rules while accessing DLs. For example, CAVs that had shorter travel distances on highways did not access DLs for such short distances, as would happen in real life.

As much as possible, the project team made realistic assumptions in modeling and developing scenarios to perform the evaluation within resources while answering several research questions that could inform the final guidance.
This chapter expands on the detailed analysis results produced by the simulations. This chapter organizes the analysis results in terms of the sensitivity parameters that were assessed as part of the evaluation.

6.1 Priority Versus Exclusive Access

The first set of assessments was conducted to determine whether there would be benefits or disbenefits from dedicating lanes to CAVs. The baseline results included HOV access on DLs. For the I-66 study sites, an average of 20% to 25% of the traffic consisted of HOVs utilizing the DL. Table 6.1 shows the mobility performance measures under various types of DL use. The percentages shown in the table are changes from the base case. A positive change in travel time indicates disbenefits, whereas a positive change in throughput indicates benefits.

Two scenarios of lane dedication were assessed:

• **Priority lane access, under which CAVs were allowed on the DLs in addition to the HOVs that were already allowed.**
  - As shown in Table 6.1, at lower market penetration (10%), CACC application improved the network efficiency by increasing the throughput of DLs. An increase in the average speed of vehicles on the GPLs and DLs also occurred. However, DSH application was found to reduce the network performance. Specifically, it increased the average travel time by over 41%. This result was due to unequipped vehicles cutting in front of equipped vehicles whose speeds were lower.
  - At higher market penetration (25%), dedicating lanes to CAVs and HOVs caused oversaturated DLs and undersaturated GPLs that resulted in significant gridlocks.

• **Exclusive lane access, under which only CAVs were allowed on the DLs.**
  - As shown in the table, at lower market penetration (10%), the DLs were underutilized. For example, in the base case, about 25% of vehicles were using the DLs; as a result of the simulation, this number dropped to 10%. This change caused significant increase in overall network travel time of about 90%.
  - At higher market penetration (25%), CACC applications reduced network travel time by 13%. In addition, the average speed of vehicles on the DL increased significantly when all of the vehicles were equipped with CACC.

Table 6.1 also shows environmental and safety performance measures. In general, DSH applications showed increased emissions and fuel consumptions. This result primarily reflects the goal of the application, which is to distribute congestion throughout the network so that the shockwaves are minimized. In contrast, CACC applications improved fuel efficiency when
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

implemented as exclusive lane use at MPRs higher than 25%. At lower market penetration (10%), shared lane use showed a marginal improvement in fuel consumption.

Figure 6.1 compares the performance of DSH when implemented on shared and exclusive lanes at 10% market penetration as percentage change in average throughput from the base case. When the DLs are exclusive to CAVs, simulations showed reductions in throughput when the DSH application was deployed at 10% market penetration. An average reduction in throughput of 10% was found. When the DLs were shared with HOVs, however, the reduction in throughput went down to 4%.

Regarding safety performance measures, the lane friction increases with increasing market penetration and exclusive lane access to CAVs. This increase warrants restricted access to DLs and physical barriers to increase the safety of the network. The DSH application aims to lower the probability of shockwaves in the network by harmonizing the speeds across the freeway based on downstream congestion. Figure 6.2 demonstrates the shockwave performance measures of the DSH application using speed contours. The two-colored speed contours show the spatio-temporal distribution of observed speeds in the network collected during the simulation, with the vertical axis representing time-series and the horizontal axis representing the direction of travel. Three cases are shown in the figure: (1) the base case, (2) CAVs sharing the DLs with HOVs at 10% market penetration, and (3) CAVs with exclusive access to DLs at 25% market penetration. The team also assessed an exclusive lane use scenario with 10% market penetration, but that scenario was not included in this comparison because it caused significant increase in travel time due to volume imbalance on the lanes (see Table 6.1).

As shown in Figure 6.2, the base case involves sudden slow-downs in traffic at multiple places. This situation can lead to hard braking and shockwaves. In the shared DL scenario, these slow-downs are spread across the network, thereby reducing the probability of shockwaves. During visual audits of these simulations, it was found that due to the low market penetration, unequipped HOVs were cutting in front of equipped CAVs, which were traveling at a lower average speed than the general traffic. This situation caused a 41% increase in average travel time and a 5% reduction in throughput. In the exclusive DL scenario with 25% market penetration, the slow-downs reduced dramatically. A marginal 1% increase in the network throughput also occurred, but the increase in throughput came at the expense of a 12% increase in travel time.

To summarize the comparison between the priority lane and exclusive lane cases, the best strategy depends on the market penetration. At lower market penetration, sharing lanes with HOVs likely offers more benefit, and at higher market penetration, dedicating lanes exclusively to CAVs enhances overall network mobility. In this evaluation, the lower and higher market penetration percentages were defined as the percentage of DLs (10% and 25%, respectively).

### Table 6.1. Network performance under shared and exclusive DL use.

<table>
<thead>
<tr>
<th>Mobility Performance Measures</th>
<th>Shared with HOVs</th>
<th>Exclusive CAV DLs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Travel Time (10% CACC)</td>
<td>1%</td>
<td>92%</td>
</tr>
<tr>
<td>Change in Average Speed (GPV)</td>
<td>3%</td>
<td>-31%</td>
</tr>
<tr>
<td>Change in Average Speed (DLV)</td>
<td>6%</td>
<td>-20%</td>
</tr>
<tr>
<td>Change in Overall Fuel Consumption</td>
<td>-1%</td>
<td>65%</td>
</tr>
<tr>
<td>Lane Friction (mph)</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>10% DSH</td>
<td>41%</td>
<td>73%</td>
</tr>
<tr>
<td>10% CACC</td>
<td>-28%</td>
<td>36%</td>
</tr>
<tr>
<td>25% CACC</td>
<td>26%</td>
<td>10%</td>
</tr>
<tr>
<td>25% DSH</td>
<td>-11%</td>
<td>-16%</td>
</tr>
<tr>
<td>25% CACC</td>
<td>21%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.1. Comparison of DSH performance measures with and without exclusive DL access.

Figure 6.2. Speed contours for I-66 westbound direction under shared and exclusive lane use.
6.2 Impact of Market Penetration

In this analysis, the project team reviewed the impact of market penetration on network performance when dedicating lanes to CAVs.

6.2.1 CACC

When assessing the CACC application, it was found that at lower market penetration, sharing lanes with HOVs would prevent oversaturation of GPLs. Hence, for 10% market penetration, the team considered shared lane use, whereas for higher market penetrations, only CAVs were allowed on the DLs. Figure 6.3 shows comparison of vehicle throughputs at differing levels of market penetration for the I-66 case study site. The primary axis data shown by the left-hand vertical scale demonstrates the percentage difference in throughput when compared to the base case.

All the cases showed improvement in throughput, peaking at a market penetration of 35%. This pattern occurs because of the significant volume imbalance that happens at higher levels of market penetration. The I-66 case study site has three GPLs and one DL. At 25% market penetration, this lane configuration results in an equitable distribution of demand. At 35% market penetration, the demand distribution becomes 35% for DL versus 22% for GPL, and at 45% market penetration, the demand distribution becomes 45% for DL versus 18% for GPL. Even at a higher market penetration, however, the lane dedication allowed higher throughput on DLs.

Figure 6.4 shows a comparison of maximum DL throughput that was achieved through CACC implementation at differing levels of market penetration. As shown, at 10% market penetration, sharing DLs with HOVs can improve the throughput by up to 21%, whereas not sharing...
DLs with HOVs can decrease the throughput by almost 60%. The latter result arises primarily because fewer vehicles are allowed on the DLs. When not shared with HOVs, CACC DL throughput increases as market penetration goes up. At 25% market penetration, a marginal reduction occurs in throughput, whereas at 35% and 45% market penetration, the throughput increases by up to 32% and 60%, respectively.

Figure 6.4 also shows the average travel speeds on the DL under each condition. As shown, the travel speeds are much higher when exclusive lane access is given to CACC-equipped vehicles, even when the throughput is higher. Even when CACC-equipped vehicles have exclusive DL access, the average travel speeds reduce to 54 mph when the CACC market penetration increases to 45%.

Figure 6.5 shows the environmental impacts of CACC when implemented in a DL setting at differing levels of market penetration. In the figure, the 10% market penetration scenario refers to shared DL use with HOVs. In the figure, fuel consumption is shown as a comparison to the base case, whereas emissions are shown as aggregate values of CO and NOx as reported by the emissions model.
Figure 6.5 shows that the fuel consumption and emissions reduce as a function of market penetration, with most of the benefits being received at 35% market penetration or higher.

### 6.2.2 DSH

A similar assessment was performed for DSH. Unlike CACC, the DSH application was not shown to increase the freeway throughput considerably; consequently, MPRs beyond 25% were not assessed for DL situations. The four levels of market penetration were assessed for mobility impacts, as shown in Figure 6.6. In the figure, 10% and 25% cases were implemented with DLs, whereas 50% and 100% were implemented without DLs. Additionally, the 10% scenario had a DL that could be used for HOVs and CAVs, whereas the 25% scenario had a dedicated CAV-only lane. The performance measure shown in the figure is the percentage change in throughput from the base case at 10-minute resolution.

As shown in Figure 6.6, market penetration of DSH does impact the throughput of freeways. At 10% market penetration, the figure clearly shows an average reduction in throughput, whereas at 25% market penetration, the throughput increases by nearly 1%. At 50% market penetration with no DL, throughput is again reduced, and at 100% market penetration, throughput again increases by about 1%.

As mentioned before, the primary objective of the DSH application is safety in terms of reducing shockwaves and harmonizing speeds across the freeway corridor to prevent hard braking and acceleration. To demonstrate these impacts, the project team logged simulated spatio-temporal speeds on the I-66 westbound direction, which was the DSH implementation direction. Figure 6.7 shows these speed contours at differing levels of market penetration and compared to the base case.

As shown in Figure 6.7, the base case showed large variation in speeds across both spatial and temporal axes (horizontal and vertical). When DSH was introduced in the DL at 25% market penetration, the throughput increases by nearly 1%.
penetration, however, the slow-downs scattered around the network, thereby reducing the probability of shockwaves. At higher market penetrations, without dedicating lanes for CAVs, the DSH application was able to distribute the slow-downs in the network so that there were no significant shockwaves.

6.3 Combinations of Applications

To understand how combinations of applications would impact the network performance of CAV DLs, the project team assessed combinations of CACC and DSH applications at 25% market penetration. The applications were combined so that the Leader of every CACC string on the DL would receive and respond to DSH recommendations of desired speeds. Figure 6.8 shows the three cases compared for this evaluation and the throughput difference under different applications for the I-66 case study site.

As shown in the figure, the three cases compared were DSH implemented at 25% market penetration, CACC implemented at 25% market penetration, and both applications implemented at 25% market penetration. The figure shows that both DSH and CACC applications improved the overall freeway throughput. The DSH improved the throughput by about 1%, and the CACC
improved the throughput by about 2%. The throughput improvements were assessed under the same overall demand. The combination of DSH and CACC showed similar benefits as the CACC-only case, with an average throughput improvement of over 2%.

Figure 6.9 shows the other performance measures for 25% market penetration of DSH, CACC, and both applications together. As shown, the DSH application increased the travel time and fuel consumption when compared to the base case. This increase occurred because the application reduced the speed of the equipped vehicles in response to slow-downs that existed downstream. This reduces the probability of shockwaves. Unlike the DSH application, the CACC application reduced the total travel time by 13% and fuel consumption by 15%. In addition, the CACC application caused an increase of over 25% in the speed of equipped vehicles. When both the CACC and DHS applications were combined, the travel time and fuel consumption were reduced by 13% and 16%, respectively.

Figure 6.10 shows the performance of the combination of CACC and DSH applications under two levels of market penetration (10% and 25%) when CAVs have exclusive access to the DL. The bar plots shown on the primary axis demonstrate the difference from the base case in vehicle throughput.
throughout the freeway. As shown, at 10% market penetration, there is a significant reduction in throughput, averaging 9%. This result occurs primarily because fewer vehicles have access to the DL when compared to the base case, in which about 25% of HOVs used the DL. At 25% market penetration, however, there is an increase in average throughput on the freeway lanes, averaging 2%. This increase occurs because, in comparison to the base case, an equal number of vehicles can utilize the DLs, and the vehicles on the DLs travel at harmonized speeds and with closer headways.

The project team also analyzed the safety benefits of combining CACC with the DSH application, in terms of reduction in the probability of shockwaves. Figure 6.11 compares speed contours when DSH is implemented at 25% market penetration on an exclusive DL.

When compared to the base case, the DSH application was able to reduce the shockwaves by dispersing concentrations of slow-downs on the network, as shown in the spatio-temporal speed contours in Figure 6.11. Additionally, when CACC was also implemented, there were no more slow-downs in the network and there were significant improvements in environmental savings. For example, the DSH-only scenario increased fuel consumption by nearly 20% over the base case, whereas the combined DSH and CACC scenario reduced fuel consumption by more than 16% over the base case.

6.4 Impact of Demand

To assess the impact of demand on the benefits of CAV applications when deployed on DLs, the project team tested the I-66 case study sites with three demand levels:

- Normal demand, representing the typical p.m. peak traffic volume for the I-66 case study site;
- Reduced demand, representing a 20% reduction in typical p.m. peak traffic volumes for the study site; and
- Increased demand, representing a 20% increase in typical p.m. peak traffic volumes for the study site.

The normal demand case was calibrated to field-observed volumes and speeds, whereas the cases with reduced and increased demand were hypothetical cases derived from the calibrated normal demand case.
6.4.1 CACC

The impact of reduced and increased demand was assessed in relation to the CACC application at 10% market penetration. As was found in the previous analysis, to avoid disparate lane utilization, sharing lanes with HOVs was warranted at 10% market penetration. Therefore, this analysis compared scenarios of reduced and increased demand with the normal demand scenario assessed at 10% market penetration when the DLs were shared with HOVs.

Figure 6.12 compares the performance of CACC on a shared DL (with HOV) at 10% market penetration under normal and reduced demands.

In Figure 6.12, the bar graphs represented by the primary axis show time-dependent differences in vehicle throughput from the baseline when CACC is implemented. The baseline throughputs are shown using line graphs represented by the secondary axis. Under normal demand, the CACC showed average throughput benefits of up to 1%. Under reduced demand, however, the negative impacts were offset by consistent marginal positive impacts.

Similarly, Figure 6.13 shows a comparison of the performance of CACC on a shared DL at 10% market penetration under normal and increased demands. Under increased demand...
conditions, the improvement in throughput was even higher, with benefits between 3% and 4% at any given time.

The percentage benefits for each scenario are demonstrated in relation to the base case at the respective demand levels, not at the normal demand.

6.4.2 DSH

A similar analysis was conducted for the DSH application at 10% market penetration with shared DLs with HOV vehicles. Figure 6.14 shows this comparison of the performance of DSH on a shared DL (with HOV) at 10% market penetration under normal and reduced demands. The DSH application reduced the throughput under normal demand from 2% to 6%. This reduction occurred primarily because the downstream congestion reduced the

Figure 6.12. Impact of reduced demand on CACC application at 10% market penetration.

Figure 6.13. Impact of increased demand on CACC application at 10% market penetration.
speeds of equipped vehicles over the entire freeway to reduce shockwaves. However, when there was reduced demand, the DSH application had marginal impact, because there were no congested areas in the network.

Figure 6.15 compares the performance of DSH on a shared DL at 10% market penetration under normal and increased demands. Under increased demand conditions, the DSH showed an increase in throughput of up to 1.5%. This result occurred primarily because the increased demand reduced the overall speed of unequipped vehicles as well.

Conclusively, the DSH application provided better throughput when the demand was higher than typical. This outcome reflects the fact that the heterogeneity of travel speeds of different types of vehicles is reduced when there is higher congestion.
6.5 Impact of Access Restrictions

One of the research questions aimed to compare the impacts of dedicating lanes to CAV users when access restrictions to the DL exist. This section describes the impacts of continuous versus restricted access to DLs using the primary case study site, the I-66 corridor. All other sections of this report consider continuous (no physical barrier) access to the DLs.

To model restricted lane access to DLs, the research team considered a scenario of exclusive DL access to CAVs at 25% market penetration. The results for this analysis, along with four performance measures analyzed, are shown in Figure 6.16. The two situations analyzed involved CAVs using CACC applications and CAVs using both CACC and DSH applications.

To model restricted DL access, the I-66 model and the CACC API were modified. Modifications to the I-66 model included lane-change restrictions for the left lane except for the sub-links that were placed before or after each interchange. The locations of these restrictions were representative of field conditions. Modifications to the CACC API included changes to the preferential lane logic (described in the section on CACC in Chapter 5). These changes enabled a CAV to move to the DL only if its built-in static routes allow for being on the freeway for at least two interchanges. Additionally, the string dispersion logic was modified to look for exit points based on the built-in static routes.

Figure 6.16. Impact of continuous and restricted lane access, assessed using 25% market penetration of CAVs.
Several performance measures were collected during the simulation, but the following performance measures were highlighted to develop conclusions about DL access settings:

- **Change in Average Network Travel Time.** This measure showed the network-wide mobility impacts of CACC and the CACC+DSH combination as a comparison with the base case—HOV DLs with continuous access. When CAV DLs had restricted access, there was a reduction in travel time savings in comparison to the base case with continuous access to CAV DLs. As noted earlier, this result occurred because the restricted access discouraged some users with shorter trips from using the DLs. Additionally, the users of the DL needed to exit early to help them navigate their predefined routes.

- **Change in CAV:Non-CAV Speed Ratio.** This measure showed whether the CAVs achieved more mobility at the expense of non-CAVs. The ratio was calculated as the ratio of average spot speeds of CAVs (either in CACC-mode or not) and non-equipped vehicles. As shown in Figure 6.16, in the CACC-only case, the CAVs had over 46% more speed than non-CAVs when access was restricted and only 42% more speed when access was continuous. When CACC-equipped vehicles received DSH recommendations as well, the continuous access scenario had a higher CAV:Non-CAV speed ratio than it did under restricted access. This result occurred because of the presence of CAVs making shorter trips on GPLs. These shorter-trip CAVs received harmonized speed messages, which are generally lower than the speed limit.

- **Change in Travel Speeds of General Purpose Lanes.** This measure indicated whether the GPLs had higher speeds or lower speeds compared to the base case. Under the CACC-only case, there was a (marginal) increase in the speeds of GPL vehicles when there was continuous access, owing to the lesser number of vehicles on GPLs due to the switch to DLs. Under restricted access, however, a reduction in travel speed occurred in the GPLs. This reduction in speed might have occurred because fewer CAVs use DLs owing to the entry/exit limitations causing a higher volume on GPLs. When CACC was implemented with DSH, the restricted access scenario demonstrated more benefits than continuous access. Restricting access also helped the DSH application by reducing cut-ins in front of slower DSH-equipped vehicles.

- **Increase in DL Throughput.** This measure indicated whether the throughput of the DLs increased due to the CAV applications. In the CACC-only scenario, providing continuous access increased the throughput by 6%, whereas the restricted access scenario reduced the throughput by almost 8%. When CACC was paired with DSH, the throughput of DLs remained the same as the baseline in both the continuous access and restricted access scenarios.

Given scope limitations, only 25% market penetration was used in these scenarios. Higher MPRs (such as 35% or 45%) would likely provide even higher benefits to GPLs.

### 6.6 Hypothetical Scenarios

The analysis plan for this project also outlined research questions that require developing hypothetical scenarios for modeling and simulation. These scenarios were designed to answer the following two research questions:

- What is the impact of an incident-related temporary lane closure?
- What is the impact of a slow-moving vehicle on the DL?

Although these scenarios are highly probable, they were not part of the original baseline model or the baseline data collected from the field. The primary case study site, I-66, was utilized for this analysis.

#### 6.6.1 Impact of Incident-Related Temporary Lane Closure

Traffic incidents on roadway facilities represent a common form of static bottleneck and typically result in operational deterioration due to one or more lane closures. In this project, traffic
incidents were modeled in the simulation network to observe the effects of a static bottleneck on freeway operations on I-66. The location and duration of the modeled incident was developed using historical data and empirical observations derived from the Transportation Technical Report: Interstate 66 – From US Route 15 in Prince William County to Interstate 495 in Fairfax County, published in February 2013 (Virginia DOT, Virginia DRPT, and FHWA 2013). Figure 6.17 shows the location, direction, and peak-hour period for the commonly observed traffic incidents that occur on I-66.

The incident location shown in Figure 6.17 was selected based on the distance from either end of the simulation model boundary limits to maximize the capture of the static bottleneck’s operational impacts. For modeling purposes, the incident location was not located within close proximity to the network upstream location, which would impede significant numbers of vehicles from entering the network, and it was not located at the downstream location, where a significant, unrelated bottleneck could occur due to facility capacity issues. The location chosen for modeling allowed the researchers to better isolate the effects of the incident itself. The peak hour was also limited to the p.m. peak in the westbound peak direction where the heavy congestion forms. Traffic and incident data within the simulation boundaries for October 2016 on I-66 was provided by the Virginia DOT. This incident data indicated the average incident in the westbound direction during the p.m. peak hour lasted for approximately 32 minutes. The modeled traffic incident was based on a combination of information from the technical report and I-66 incident data, as follows:

- **Location:** I-66 westbound, West of VA-123 before the Jermantown Road overpass;
- **Lane Closure:** Right-most lane (1 lane) was closed;
- **Duration:** 32 minutes; and
- **Start Time:** 4:30 p.m.

This scenario was modeled with both CACC and DSH DLs at 10% market penetration. The DL was shared with HOVs in both cases, and the incident condition was compared to the situation without the temporary lane closure, as shown in Figure 6.18.

In Figure 6.18, the percentages show the differences in vehicle throughput between the CACC and DSH scenarios and the base case. In the base case “with incident” scenario, throughput was significantly less than in the base case “without incident” scenario. Significant differences can

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**Figure 6.17. Commonly occurring traffic incidents on I-66.**
be seen in the benefits obtained from both CACC and DSH DLs. For the CACC application—represented in the figure as (a) and (b)—dedicating lanes to CACC-equipped vehicles in addition to HOVs, improved vehicle throughput by up to 1% with or without a temporary lane closure. With regard to the DSH application—represented in the figure as (c) and (d)—the incident worsened the vehicle throughput by up to 10%, as opposed to just 6% for the case without incident. It should be mentioned that the lane closure was modeled on the right lane of the freeway, whereas the DL was modeled on the left lane of the freeway. As a result, the impacts represented in this section are primarily due to the additional strain placed on the open GPLs.

### 6.6.2 Impact of a Slow-Moving Vehicle on the DL

When slower vehicles are on the DL, they are expected to cause noticeable degradation in the operational performance for vehicles traveling on the DL (i.e., “moving bottlenecks”). To assess the impact of CACC applications on CAV DLs responding to moving bottlenecks, the project
team modeled a scenario to replicate this situation. Such a situation could arise from many factors, such as a slow driver, a heavy vehicle that cannot perform at a faster speed, a maintenance vehicle performing maintenance, and so forth. In a scenario with CACC-equipped vehicles with exclusive access on the DLs, the CACC performance could be metered by a slower moving lead vehicle.

Traffic data provided by the Virginia DOT from spot-speed detections indicated the speed distribution by lane type during the p.m. peak hour for October 2016, as shown in Table 6.2. The values represent average, minimum, and maximum speeds obtained from Virginia DOT detectors in the field and represent spot speeds at different segments of the corridor for every hour. Data from RITIS also indicated recorded speeds up to a maximum of 68 mph for the same period as the spot-speed data.

Limited information was available on current slow-moving vehicles operating on the existing HOV lane during peak hours; therefore, the following moving bottleneck parameters were modeled:

- **Frequency:** One slow vehicle every 30 minutes;
- **Desired Speed of Slow Vehicle:** 45 mph (10 mph below posted speed limit);
- **Lane Utilization:** Left-most lane (existing HOV lane);
- **Entry Location:** I-66 westbound direction at I-495; and
- **Exit Location:** I-66 westbound past US 29.

Figure 6.19 shows a comparison between a moving bottleneck scenario and a scenario without a moving bottleneck. In both scenarios, the CACC application was modeled in CAVs at a 25% MPR. CAVs had exclusive access to the DL.

<table>
<thead>
<tr>
<th></th>
<th>General Purpose Lane</th>
<th>HOV Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>30.7 mph</td>
<td>38.0 mph</td>
</tr>
<tr>
<td>Minimum</td>
<td>17.3 mph</td>
<td>18.7 mph</td>
</tr>
<tr>
<td>Maximum</td>
<td>58.5 mph</td>
<td>62.2 mph</td>
</tr>
</tbody>
</table>

Table 6.2. Speed distribution on I-66 by lane type for p.m. peak hour.

Figure 6.19. Impact of moving bottlenecks on CACC dedicated lanes.
Figure 6.19 shows the difference in vehicle throughput with respect to the baseline scenario in two situations: (a) without the moving bottleneck and (b) with the moving bottleneck. The figure also shows the base throughput (without CACC) under the same circumstances. As shown, the base throughput with a moving bottleneck is significantly lower than the base throughput without the bottleneck. The CACC application is able to improve the throughput without the bottleneck by up to 3%. When there are moving bottlenecks, however, the improvement in throughput due to the CACC application is up to 4.5%. The research team made two observations about this difference:

- The baseline measurement with the bottleneck had lower throughput than the baseline measurement without the bottleneck, and
- The CACC application was able to maintain a streamlined traffic flow even with the slow-moving vehicle.

Figure 6.19 should not be considered to confirm that the presence of a moving bottleneck is better than not having a moving bottleneck. Rather, it appears that the percentage savings are better because the moving bottleneck has caused a significant reduction in the baseline throughput. In other words, it appears the CACC application mitigates the reduction in throughput.

6.7 Impact on US-101 Corridor

The project team also utilized a secondary case study site to assess the impact of the CACC application. Owing to scope limitation, the US-101 study site was used only for a subset of scenarios that were analyzed and modeled for the I-66 corridor. Specifically, the US-101 case study site was used for two types of sensitivity analysis—market penetration and demand conditions. This section describes the results for the US-101 corridor scenarios.

6.7.1 Sensitivity Toward Market Penetration

The US-101 corridor case study site was used to study the impact of CACC market penetration on overall improvement in system efficiency. Four scenarios were analyzed and compared to the base case, which represented a typical p.m. traffic peak between 3:00 p.m. and 7:00 p.m. The four scenarios were:

- **10% CACC + HOV.** In this scenario, CACC has 10% market penetration in the system, and the CACC-equipped vehicles share the DLs with HOV vehicles;
- **25% CACC.** In this case, CACC has 25% market penetration in the system, and the CACC-equipped vehicles have exclusive access to the DLs;
- **50% CACC/No DLs.** In this case, CACC has 50% market penetration in the system, but no lanes are dedicated to the CACC-equipped vehicles;
- **100% CACC/No DLs.** In this case, CACC has 100% market penetration in the system, but no lanes are dedicated to the CACC-equipped vehicles.

Two performance measures were used to demonstrate the impact of market penetration: network-wide reduction in travel time and increase in overall throughput. The observed performance is shown in Figure 6.20.

As shown in Figure 6.20, both mobility performance measures increased as market penetration went up. For example, the travel time reduction increased from a marginal 0.5% at 25% market penetration to more than 6% at 100% market penetration. The increase in throughput grew from almost 0% at 10% market penetration to 10% at 100% market penetration. It should be noted that the model used by the project team had a fixed time-varying demand throughout the analysis time period. In other words, even though the CACC application increased the
theoretical throughput of the lanes, the actual number of vehicles released into the simulation was constrained by the “present-day” demand. Analysis at a macroscopic scale is required to understand the impact on the demands on transportation systems with the advent of CAV technology.

### 6.7.2 Sensitivity to Demand

To study the impact of varying demand on the performance of CACC, the project team also modeled a scenario with higher-than-typical peak demand. This scenario was developed using a fully calibrated model that represented typical p.m. peak demand by increasing the volume in increments of 20%. As in the previous section, three market penetration scenarios were assessed:

- 10% market penetration of CACC-equipped vehicles that shared the DLs with HOVs,
- 25% market penetration of CACC-equipped vehicles that had exclusive access to the DLs, and
- 50% market penetration of CACC-equipped vehicles without any DLs.

The results, in terms of reductions in travel time and increases in throughput, are shown in Figure 6.21.

As shown in Figure 6.21, for the typical p.m. peak demand, both performance measures improved as a function of market penetration of CACC. For example, network-wide benefits

![Figure 6.21. Impact of demand on CACC application.](image)
were seen in terms of reductions in travel time as well as increases in throughput when CACC market penetration was greater than 25%. With higher demand, however, the research team observed much greater benefits even at a lower market penetration. For example, at 10% market penetration, sharing of the DL between HOVs and CACC-equipped vehicles reduced the travel time of all vehicles by up to 1.3%.

### 6.7.3 Comparison of US-101 Corridor Results to I-66 Corridor Results

The project team compared the results obtained from the US-101 case study network to those obtained from the I-66 case study network. The two corridors differ significantly in terms of traffic patterns, roadway geometry, entry-exit configurations, and vehicle types. The study team compared the percentage impacts of CACC on the two networks using the scenario of 25% market penetration and exclusive DL use. The results of the comparison appear in Figure 6.22.

Figure 6.22 shows improvement in vehicle throughput as a bar graph (primary axis) and baseline throughput as a line graph (secondary axis). The benefits from US-101 were smaller than those demonstrated in the I-66 network; however, the baseline throughput was similar in both networks. This comparison indicates that the differences in roadway geometry had a significant impact on the results obtained for the CACC application, as did the driving parameters in the two networks.

### 6.8 Analysis of VTTS

As indicated in Chapter 2, the team developed a simplified VTTS analysis to compare the benefits to users of DLs versus users of GPLs. VTTS is a complex concept that undertakes economic analysis on reducing travel times. The researchers’ simplified approach was developed to at least inform general guidance on whether dedicating lanes to CAV users produces economic benefits to either category of users.

For this analysis, the study team used the simplified VTTS approach to quantify travel time savings for DL users over GPL users over a 1-year period using average observed speeds for DLs and GPLs as computation drivers. The term *computation driver* represents the parameter that
drives the computation to compare the economic benefits of one category of users over the other. The following assumptions were used in this analysis:

- **Computation Driver**: Average observed travel speeds of DL ($v_{DL}$) and GPLs ($v_{GPL}$);
- **Average Trip Distance on Freeway**: 12 miles ($s_{average}$);
- **Number of Commute-Trips per Year**: 500 (250 working days with a.m. and p.m. commute);
- **VTTS for Personal Travel**: $12.30/hour ($VTTS_{personal}$); and
- **VTTS for Business Travel**: $24.10/hour ($VTTS_{business}$).

Using these assumptions, the research team computed the annual savings per DL user as follows:

$$Annual\ Savings\ per\ DL\ User = \Delta t_{trip} \times 500 \times \frac{VTTS_{personal} + VTTS_{business}}{2},$$

where $\Delta t_{trip} = \text{the\ difference\ in\ travel\ time\ between\ a\ DL\ user\ and\ a\ GPL\ user,}$ and $\Delta t_{trip}$ is computed as $s_{average} \left(1 \over v_{DL} - 1 \over v_{GPL}\right)$.

Based on this analysis, the research team computed the annual savings per DL user under differing market penetrations of the CACC application. Although CACC DL users might also receive additional savings from fuel and maintenance, these benefits were not considered in this evaluation. The DSH application also was not part of this evaluation. DSH produced marginal travel time savings and therefore was not expected to produce any economic benefit to users apart from a reduction in surrogate factors such as prevention of secondary crashes.

Figure 6.23 compares the annual VTTS savings per DL user based on the above model and assumptions for a variety of market penetrations. The savings shown in the figure are for all DL users, not for CAV users alone. In other words, the savings shown include the scenarios under which HOVs also were allowed on the DL.

As shown in Figure 6.23, the greatest benefit for DL users was shown at 10% CACC with exclusive DL access. Under this scenario, the DLs were undersaturated and the GPLs were oversaturated; therefore, the benefit to DL users in terms of travel time was very high when compared to the GPL users. The 25% CACC scenario formed an ideal case of equitable lane-volume distribution (wherein both GPLs and DLs were saturated at the same level) but CACC streamlined the flow of traffic through the DLs and hence reduced their travel time.

![Figure 6.23. Annual VTTS savings estimated per DL user (CAV user and/or HOV user) under CACC DL scenarios.](image-url)
A key exercise in exploring the potential for DLs or exclusive lanes for CAVs is to review and document the current environment of regulatory and legislative affairs specific to CAVs and how that might impact the implementation of DLs. As part of that exploration, understanding the lessons learned from other instances of dedicating lanes is instructive. In particular, it can be helpful to consider the type and magnitude of expected societal benefits that have produced the policy justification for dedicating one or more lanes to a subset of road users.

7.1 DL-Specific Policies and Scenarios

Existing DL scenarios include HOV lanes (Figure 7.1), HOT lanes, truck-only lanes, motorcycle/bicycle-only lanes, and bus/transit-only lanes. On controlled-access high-speed facilities, the most common restricted lane scenario is HOV DLs (FHWA 2017b). This chapter reviews the laws and regulations regarding existing DLs.

7.1.1 HOV Facilities

Currently, policy for HOV/HOT lanes is loosely set at the federal level and allows authorities with jurisdiction over those facilities to set more specific restrictions, determine minimum carpool requirements, and define vehicle exemptions. At the broad policy level, the federal motivation for HOV lane dedication is to provide incentives to increase vehicle occupancy so that the number of vehicle-miles of travel can be minimized for the given level of person-miles of travel. The federal policy gives states the ability to incentivize certain types of behavior depending on the goals of the specific facility, such as throughput maximization, generation of tolling revenue, inducement of mode shift, or environmental sustainability. As a result, across states there are varying vehicle allowances and identification and monitoring methods.

Many jurisdictions exempt other vehicles, including motorcycles, charter buses, emergency and law enforcement vehicles, low-emission and other green vehicles, and/or SOVs paying a toll. Section 166 of Title 23 in the United States Code (U.S.C.) contains provisions for operating HOV facilities. Section 1411 of the Fixing America’s Surface Transportation (FAST) Act, which was signed into law in December 2015, includes the most recent amendments to these HOV regulations. The current policy states that the public authorities that have jurisdiction over the HOV facility can establish the occupancy requirements of vehicles so long as the minimum number of occupants is “no fewer than two” (23 U.S.C. § 166).

The policy specifies the following vehicle class exceptions to the occupancy requirement:

- Motorcycles and bicycles;
- Public transportation vehicles and over-the-road buses;
• HOT vehicles;
• Low-emission and energy-efficient vehicles (defined therein) until September 30, 2025; and
• Other low-emission and energy-efficient vehicles (defined by the EPA) through September 30, 2019.

In addition to variability in occupancy requirements, the ability to exempt certain vehicles based on their propulsion system also exists in several locations. The provision to allow low-emission vehicles to utilize HOV lanes was first introduced in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users Act (SAFETEA-LU), enacted in 2005. Language in this authorization bill allowed the U.S. Environmental Protection Agency (EPA) to define the single-occupant, low-emission, and energy-efficient vehicles permitted to use HOV lanes. The Moving Ahead for Progress in the 21st Century Act (MAP-21) replaced SAFETEA-LU in 2012 and extended relevant provisions.

MAP-21 also mandated that HOV facilities that allow low-emission and energy-efficient vehicle exemptions (regardless of the number of those vehicles using the lanes) submit an annual report that demonstrates the HOV facility meets performance standards. The performance standards are based on minimum operating average speed over a specified time period. If degradation of the facility speed is reported, the agency must submit a remediation plan to FHWA. The remediation plan must include ways the agency will bring the facility into compliance, including increasing the occupancy requirement, varying the toll charges for HOT lanes, discontinuing exemptions, or increasing available capacity of the facility. These policies are indicative of a federal desire to provide enhanced access for certain types of vehicles but not at the expense of overall system performance.

The FAST Act extended the ability of public authorities to offer HOV/HOT access for low-emission and energy-efficient vehicles, such as hybrid electric vehicles, through 2019. Alternative fuel vehicles (AFVs) and plug-in electric vehicles (PEVs) may continue to be granted free or discounted access to HOV/HOT lanes through 2025. At the end of 2019 and 2025, the respective vehicle classes will not be able to use HOV/HOT lanes for free unless the vehicles adhere to the occupancy requirements. These “sunset” rules were put into place based on the assumption that use of AFVs and PEVs would increase over time, but the rules may be revisited as the conclusion dates approach.

More importantly to this research, the specific models of vehicles that qualify for exemption vary from state to state, and are informed by local vehicle purchase trends and technology.
advancements. This variation has been discussed widely within the industry as a challenge for auto manufacturers and vehicle owners alike, and would be a definite consideration for review in terms of dedicating lanes for CAV usage or adding exemptions for CAVs to access HOV lanes.

7.1.2 Motorcycles and Bicycles

Motorcycle-only lanes do not exist on general purpose roads and highways in the United States, but several Asian countries have DLs for small vehicles such as motorcycles and scooters due to their popularity. In the United States, motorcycles often are permitted to use HOV lanes regardless of the number of passengers on the motorcycle. This policy is meant to increase safety for motorcyclists by reducing the amount of travel in start-and-stop traffic conditions (U.S.DOT 2017). If states determine that safety is a risk for motorcycles to use the HOV facilities due to specific operating conditions, however, they can choose to override this provision of federal law.

7.1.3 Buses

Bus lanes typically exist on urban streets, where high levels of traffic may cause delays, and in corridors with bus rapid transit, where maximizing bus speed and reliability is a priority so that buses can provide a more competitive quality of service compared to private passenger vehicles (Ryus et al. 2016). Many of the earliest highway bus-only lanes were converted to HOV lanes in an effort to maximize use (FHWA 2016b). Consequently, carpools became the dominant user group on most these projects during the 1970s and 1980s.

Not all bus-only lanes were converted back to general purpose lanes, however; New York City offers Select Bus Service on some dedicated lanes (Figure 7.2), and one facility that continues to have a high volume of bus-only traffic is the New Jersey I-495 Exclusive Bus Lane (XBL), a 2.5-mile contra-flow bus lane that operates during a.m. peak hours and averages more than 1,850 daily buses (PANYNJ n.d.). The XBL services a major component of the commuter traffic traveling across the Hudson River via the Lincoln Tunnel. Most of the buses that traverse this lane are bound for the Port Authority Bus Terminal, the nation’s largest bus terminal, which is accessible by exclusive ramps on the eastern side of the Lincoln Tunnel.

Another example of bus-only lanes, the San Francisco Municipal Transportation Agency (SFMTA) received approval from the FHWA in June 2017 to expand a pilot of red-painted,
dedicated transit-only lanes in downtown San Francisco. Red transit-only lanes were installed on three streets in 2014, and have since been found to reduce delays, collisions, and transit-lane violations in those corridors (Rodriguez 2017). SFMTA will report back to FHWA regarding the success/lessons learned for the 50 additional painted streets to inform future federal legislation (Dovey 2017).

### 7.1.4 AFVs

As mentioned previously, AFVs are allowed as a stated exemption on many HOV lanes to provide an explicit incentive for people to choose AFVs over less efficient and more polluting conventionally fueled vehicles. “Low-emission and energy-efficient vehicles” are defined in 23 U.S.C. § 166 in accordance with the EPA, but the law permits public authorities to implement more stringent definitions to better manage the performance of their HOV lanes. States may determine the specific vehicle models to exempt from HOV or HOT lane restrictions, the identification method for eligible vehicles, and the number of permits or exemptions allowed. There is no “national standard” when it comes to eligibility. As a result, many different definitions and approaches now exist.

The identification method for eligible vehicles varies from state to state, with some using special license plates or decals that limit eligibility to in-state registered vehicles. Registration fees for decals and license plates also vary and may include annual or one-time fees. North Carolina and New Jersey require no identification for eligible vehicles, however, which means qualified out-of-state vehicles may also use the HOV lanes in those states. New Jersey does require eligible drivers to register HOT transponders if they want to receive a 10% toll discount.

Non-financial incentives for AFVs are low- or no-cost measures that states can use to support AFV market growth. HOV lane access has been a popular incentive with consumers. In a 2013 survey of California drivers, for example, 59% of those surveyed stated HOV lane access was extremely important or very important in their decision to purchase a PEV (ZEV PITF 2014). The study noted that, in California metropolitan areas, a direct correlation exists between HOV lane access and daily VMT in HOV lanes. Respondents who faced a longer mileage commute often ranked the HOV lane access as their chief reason for purchasing a PEV (ZEV PITF 2014).

### 7.1.5 Truck-Only Lanes

Many states prohibit trucks from using the far-left lane of a highway to improve throughput and safety. Similarly, climbing lanes separate slow-moving heavy trucks on segments of highway that have steep grades. Interchange bypass lanes separate trucks from passenger vehicles at highway interchanges by routing trucks around major interchanges some distance away from where passenger vehicles join the highway. These truck-only lanes serve the combined policy goals of reducing potentially unsafe interactions between light and heavy vehicles in locations with complicated maneuver patterns and helping to smooth and speed up traffic flow for the light duty vehicles.

In California, two sections of I-5—one in Los Angeles County and the other in Kern County—include designated truck-only lanes. On these sections of the highway, trucks are required to travel in the designated lanes and passenger vehicles are encouraged to stay in the main travel lanes. The truck lanes in Los Angeles County are meant to separate slower truck traffic from general traffic on a section of grade. The truck lane in Kern County shifts truck merges farther downstream from automobile merges where SR-99 joins the freeway going southbound.
The New Jersey Turnpike provides an example of a separated roadway where, during a stretch along the corridor, three lanes traveling in each direction of the 12-lane toll road are reserved for passenger cars only and the other three lanes are open to all cars, trucks, and buses (N.J. Turnpike Authority n.d.). The designated lanes are intended to improve operations and safety by separating the heavy and light vehicles, and to provide flexibility for HOV and variable tolling during peak hours.

Financing remains a key issue in implementing truck-only lanes. In many cases, tolls would need to be charged to fully fund the facility, and questions remain as to whether truckers are willing to pay the additional costs for use of designated lanes. The argument also is made that both trucks and passenger vehicles benefit from truck-only lanes, so both sets of lanes should pay a toll; however, the relative cost burden for each group is more difficult to determine. Operationally, trucks place more wear and tear on roadway surfaces than passenger vehicles do, so maintenance costs may be higher on the truck-only lanes and the lanes may need to be closed more frequently for pavement repair. Roadway design features such as ramp curvature, overpass/underpass height, and crash barriers differ for trucks and cars, and the relative costs of these design features also would need to be considered in a truck-only lane situation. Currently, because of these considerations, truck-only lanes remain economically challenging and often are politically difficult to implement.

### 7.2 CAV-Specific Regulatory and Legislative Affairs

In the past 5 years, there has been a flurry of activity in the policy, regulatory, and legislative arena specific to CAVs. This section reviews and documents the current environment of regulatory and legislative affairs specific to CAVs, and how that might impact the implementation of DLs, including at both the federal and state levels, as well as how this may impact dedicating lanes for CAVs. In order to achieve political progress on lane dedication for CAVs, it will be necessary to have well-supported and clearly defined definitions of the policy goals that will be served and of the magnitude of the expected benefits to be gained.

#### 7.2.1 Current State of Legislative Affairs—State Level

As CAV development and testing pick up momentum, each year brings new legislative activity around the nation. Regardless of party or location, policymakers are questioning whether additional regulatory or legislative action will be needed.

According to the National Conference of State Legislatures (NCSL) website, in 2011 Nevada was the first state to authorize the testing of highly automated vehicles (termed autonomous vehicles in the legislation). Since then, 21 other states (Alabama, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Illinois, Louisiana, Michigan, New York, Nevada, North Carolina, North Dakota, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Virginia, and Vermont) and Washington, D.C., have passed legislation related to highly automated vehicles. Governors in Arizona, Delaware, Hawaii, Idaho, Maine, Massachusetts, Minnesota, Ohio, Virginia, Washington, and Wisconsin have issued executive orders related to highly automated vehicles (NCSL 2018).

Florida’s legislation, passed in 2012, was meant to encourage the safe development, testing, and operation of motor vehicles with automation technology on public roads of the state. Michigan’s SB 169, signed into law by Governor Rick Snyder in December 2013, allowed for the testing of highly automated cars on Michigan roads. The Michigan law included certain stipulations, such as that a licensed driver must be behind the wheel at all times and be ready to take over control.
Because this issue is evolving so rapidly, many of the “early adopters” in legislative activity have already revisited the topic and made adjustments. In 2016, Florida revised its language to expand the allowed operation of highly automated vehicles on public roads and eliminate requirements related to the testing of highly automated vehicles and the presence of a driver in the vehicle. Also in 2016, several updates to Michigan’s laws were introduced with strong bipartisan support, including the following:

- Allowing open operation of CAVs beyond testing by repealing the test only restriction;
- Allowing on-demand AV networks to link passengers and various forms of transportation with AVs;
- Allowing customers to request a ride via a network operator, which then directs a vehicle to the customer’s location and then on to a desired destination;
- Allowing vehicle platoons in which vehicles can travel together with electronically coordinated speeds;
- Establishing the American Center for Mobility, providing a research facility that will build on the intense activity already seen and providing researchers the ability to test real-world conditions in weather, road, and traffic situations; and
- Penalizing persons who hack or damage AVs to impair the technology or gain unauthorized control of the vehicle.

The 2017 legislative sessions resulted in several policy and legislative actions regarding CAVs. According to the NCSL database, 33 states introduced legislation. This number was a significant increase from 2016, when 20 states introduced legislation (NCSL 2018).

The diversity of language being recommended in the different bills introduced is vast. Bills with identical language appeared in several state legislatures (Georgia, Maryland, Tennessee, Illinois, Arizona, and Michigan), but many more bills contained individual elements that reflected a focus on unique, state-specific concerns.

A 2017 report by the Governor’s Highway Safety Association provided some valuable guidance, including a 5-point recommendation to:

- Be informed,
- Be a player in your state,
- Understand the role of states,
- Don’t rush into passing laws or establishing regulations, and
- Be flexible—this is a new game (Hedlund 2017).

This advice is valuable especially because many agencies and legislators are struggling with definitions of terms (e.g., operator versus driver, autonomous vehicle, pilot versus deployment, driverless vehicle, testing requirements and authority, and others). Because the field is so broad and evolving so quickly, definitions often are a challenge for regulatory agencies. SAE International produced a set of definitions in its J3016 document, and those definitions have been adopted in the National Highway Traffic Safety Administration (NHTSA) policy guidance (NHTSA 2017a), in draft federal legislation regarding highly automated vehicles (S.1885, the “AV START Act”), and in administrative regulations drafted by California (California DMV 2018).

It is inherently difficult to measure one state against another in terms of legislative policy because driving laws and environments are not standard from state to state. Because each state has a different format in terms of how its legislature meets (year-round, limited session duration, periodic sessions) and how its legislature operates (multiple cross-over days, different committee make-up and responsibilities), it is nearly impossible to stay abreast of the progress in real time. NCSL has worked hard to keep up, but technology, policy, and societal changes are happening quickly.
State laws concerning the testing and use of CAVs have focused largely on passenger automobiles, but some attention also has been paid to trucks. One of the applications often considered in early adoption scenarios involves truck platooning, which has numerous safety, environmental, and mobility benefits. By its nature, however, truck platooning results in a closer-than-typical following distance. Many state laws require that following distances be “reasonable and prudent” but do not set specific limits. Some states have laws that require trucks to follow at specific distances, or at a certain time gap behind another vehicle.

In 2014, the ATA documented how state laws differ with respect to definitions of “following too closely” (Scott 2014). In July 2016, the Competitive Enterprise Institute released Authorizing Automated Vehicle Platooning: A Guide for State Legislators, a report that provides suggested language for each state to adjust their laws to allow for truck platooning (Scribner 2017). The report provides both strong language that would allow a legislature to facilitate pilot tests for truck platooning, and weak language that would engage a more rigid regulatory approach to beginning truck platooning.

7.2.2 Current State of Legislation—Federal Level

The topic of CAVs is not new to the U.S. Congress, having first been addressed in MAP-21, the authorization of transportation funding enacted in early 2012. MAP-21 included elements of language that would encourage research and funding to test CV technologies. More recently, in 2015 the FAST Act included specific language meant to “accelerate deployment of connected/autonomous vehicle technologies.”

Both of those pieces of federal legislation focused in large part on authorizing funds for research, demonstration, and infrastructure-oriented pilot programs. No changes were made to vehicle safety standards or other policy/regulatory directives that would cause automakers or NHTSA to more directly guide the development, testing, and deployment of CAVs. Likewise, no language was introduced that might supersede or impact the rapidly growing “patchwork of laws and policies” being explored by the state and local governments then entering the conversation. That situation changed, however, in early 2017.

In early 2017, various members of the U.S. House of Representatives were exploring draft language for as many as 14 different bills. The Digital Commerce and Consumer Protection Subcommittee of the Energy and Commerce Committee took on the challenge of synthesizing all 14 drafts into one bill—and added the challenge of garnering bipartisan support to their effort. The resulting bill became HR 3388, titled the “Safely Ensuring Lives Future Deployment and Research in Vehicle Evolution Act” or the “SELF DRIVE Act” (U.S. House of Representatives Document Repository 2018). The House bill was sponsored by Bob Latta (R-Ohio) and Jan Schakowsky (D-Illinois), the Chair and Ranking Member of the Digital Commerce and Consumer Protection Subcommittee. HR 3388 was approved by the full House in September 2017.

Also in the fall of 2017, the U.S. Senate introduced S 1885, titled “The American Vision for Safer Transportation Through Advancement of Revolutionary Technologies Act” or the “AV START Act.” At the time of this writing, the bill had passed through committee but had not yet been brought to the full Senate floor for action. The Senate bill has several similarities to the House bill, but there are enough differences that a conference committee will be required if the Senate passes its bill.

Given the real-time activity in this sphere, it is still too early in the process to definitively identify impacts to state and local agencies or the specific impacts on dedicating lanes for exclusive or priority use of CVs and AVs. Some of the early legislative language and draft principles have
focused heavily on impacts to automakers and the automotive industry (e.g., exemptions to certain federal safety standards or required safety assessment certifications for vehicles in order to promote development). Widespread use has been made of the terms “patchwork of state regulations” in trying to unify a national picture. HR 3388 would prohibit states from imposing laws related to the design, construction, or performance of highly automated cars, but state and local agencies would still maintain their traditional responsibilities, such as licensing, registration, insurance, and law enforcement.

### 7.2.3 Current Regulatory Actions

Federal Motor Vehicle Safety Standards (FMVSS) are federal regulations that specify design, construction, performance, and durability requirements for motor vehicles and regulated automobile-related components, systems, and design features.

According to recent research released by the U.S.DOT, few barriers exist that could prevent an AV from complying with FMVSS, as long as the vehicle does not significantly diverge from a conventional vehicle design (Kim et al. 2016). That said, AVs that begin to push the boundaries of conventional design (e.g., using alternative cabin layouts, omitting manual controls) would be constrained by the current FMVSS or might not fully meet the objectives of the FMVSS. As currently written, many standards are based on assumptions of conventional vehicle designs and thus pose challenges for certain design concepts, particularly driverless concepts under which human occupants have no way of driving the vehicle.

In early 2018, NHTSA released a request for comment on removing regulatory barriers for AVs. The agency specifically seeks industry feedback/comment to identify any “unnecessary regulatory barriers to Automated Safety Technologies, and for the testing and compliance certification of motor vehicles with unconventional automated vehicles designs, particularly those that are not equipped with controls for a human driver” (NHTSA 2018). In the request for comment, NHTSA also asked for comments on the research that would be required to remove such regulatory barriers.

Current federal motor vehicle standards do not consider vehicles without human drivers. This absence of standards could inadvertently slow down the speed of innovation surrounding automation technology. However, under current law, the U.S.DOT can exempt up to 2,500 vehicles in a 12-month period from NHTSA FMVSS vehicle rules. Automakers are seeking to increase that cap. HR 3388, the SELF DRIVE Act currently being considered in the U.S. House of Representatives, makes reference to this cap and would dramatically expand the number of exemptions possible.

Beyond asking for exemptions to FMVSS, industry generally has favored a proposed regulation: FMVSS No. 150, Vehicle-to-Vehicle Communication Technology for Light Vehicles. As of 2017, in a Notice of Proposed Rulemaking, NHTSA suggested that V2V communications technology be required to be installed in all new light duty vehicles beginning in 2020 (NHTSA 2017b). This requirement would dramatically increase the possibility of CV applications and move toward solving any debate as to whether future AVs will be connected.

NHTSA has proposed this requirement based on the potential safety benefits. According to U.S.DOT literature, CV technology will prevent between 421,901 and 594,569 crashes by 2051 and reduce the costs from motor vehicle crashes by $53 billion to $71 billion. Looking at the universe of currently known applications, U.S.DOT reports estimate that up to 80% of non-impaired driving crashes could be reduced in severity or eliminated (NHTSA 2015).

More far-reaching opportunities and benefits can be created if all new vehicles come equipped with V2V communication (and as V2I capabilities develop further). Achieving the goal of a
single open, interoperable, and nationwide CV system would enable a large range of application development. Establishment of the NHTSA’s proposed regulation will help resolve technology and standards issues (e.g., network interoperability, security, privacy) before they become significant challenges, will reduce the risk for industry to invest further in vehicle-to-everything applications, and should bolster consumer confidence.

Beyond the V2V regulation, one possible regulatory issue for truck platooning is existing legal restrictions on signage and lights on platooned vehicles. Currently, the only flashing lights that can be placed on vehicles are for emergency vehicles, which require standardized indicators. Exceptions to this requirement exist, including tow trucks and school buses. Some industry experts have suggested that platooning vehicles (particularly trucks) may need an indicator light of some kind to verify that they are safely operating at a reduced headway between vehicles; however, this issue is currently regulated at the state level (Fitzpatrick et al. 2016a). For wide-scale adoption of truck platooning, if indicator lights are desired, it would be wise to consider standardization of requirements, perhaps at least on the National Highway Freight Network.

### 7.2.4 Federal Automated Vehicle Policy

In September 2016, NHTSA released *Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety*, a document that set out a proactive safety approach to bring life-saving technologies to the roads while providing innovators with the space needed to develop new solutions (NHTSA 2016). The policy was rooted in the U.S.DOT’s view that AVs hold enormous potential benefits for safety, mobility, and sustainability. In September 2017, an updated document, *Automated Driving Systems 2.0—A Vision for Safety*, was produced (NHTSA 2017a).

The first chapter of the 2017 document presents “Voluntary Guidance for Automated Driving Systems.” This chapter sets out to support the automotive industry and (to a lesser extent) other key stakeholders as they “consider and design best practices for the testing and safe deployment” of automated driving systems (ADS) (NHTSA 2017a). Acknowledging that vehicles operating on public roads are subject to both federal and state jurisdiction, and that states are beginning to draft legislation to safely deploy emerging ADS, the second chapter seeks to clarify federal and state regulatory roles by including a section on “Technical Assistance to States, Best Practices for Legislatures Regarding Automated Driving Systems.” This chapter also addresses best practices for legislatures and best practices for state highway safety officials. These sections incorporate “common safety-related components and significant elements regarding ADSs that states should consider incorporating in legislation” and offer a framework for states to develop procedures and conditions for safe operation of ADS on public roadways (NHTSA 2017a).

NHTSA’s *Automated Driving Systems 2.0* document includes considerations in such areas as applications and permissions to test, registration and titling, working with public safety officials, and liability and insurance. It does not mention of dedicated or exclusive lanes for CAVs, because infrastructure issues are outside NHTSA’s interest and jurisdiction; however, the U.S.DOT has made several public statements about developing a Version 3.0 of the guidance, pledging to include multimodal issues of importance to all the modal administrations within the U.S.DOT.

In support of the Version 3.0 update, the U.S.DOT released a request for information in early 2018 that mentioned specific interest in “Integration of ADS into the Highway Transportation System from the FHWA” (FHWA 2017c). Several responses to this request for information referred to infrastructure needs and consideration of more research on dedicating lanes for CAV. Whether the FHWA and U.S.DOT will include these topics in Version 3.0 was unknown at the conclusion of NCHRP Project 20-102(08); however, the updated guidance was anticipated to be released in late summer or early fall of 2018.
7.2.5 Individual State Barriers to Dedicating Lanes for Exclusive Use by CAVs

An important lesson learned from dedicating lanes, in particular from HOVs and the inclusion of AFVs, lies in the definitions of allowed vehicles. Legislation and regulation in progress at the federal level is making progress toward better use of definitions developed by SAE International in terms of vehicle levels of automation and related terminology. Until the federal legislation moves from concept to law, however, the legal and regulatory environment remains evolutionary and state laws and regulations vary. Individual states are at various levels of maturity in terms of understanding how their own state laws or regulations would impact the testing and use of CAVs in their jurisdictions. Given this variability, and the fact that both the technology and the legal/regulatory environment are evolving in real time, it was beyond the scope of this research to identify every possible incentive or impediment to dedicating lanes for CAV within each state.
Based on the analysis described in the previous chapters, the project team developed guidance for agencies regarding dedicating lanes to CAVs. The guidance provided in this chapter related to the operational characteristics and impacts of dedicating lanes to CAVs are representative of the scenarios that were explicitly modeled in this project, and may not be representative of a wider range of scenarios.

8.1 Shared and Exclusive DLs

For purposes of this guidance, the following definitions also will be helpful:

**Priority DLs:** Lanes on which CAVs share the access privileges with HOVs.

**Exclusive Lane Access:** Only CAVs are allowed on the DLs.

Based on the simulation scenarios, the study team found that the CAV application provides overall system benefits when the CAVs:

- Share lanes with HOVs (at lower rates of market penetration) or
- Have exclusive lane access (at a market penetration level that was at least proportional to the number of lanes dedicated to their exclusive use so that all lanes are fully utilized).

8.1.1 CACC-Equipped Vehicles

The research team’s findings suggest that, at lower MPRs (up to 10%), allowing both CACC-equipped vehicles and HOVs on the DLs improves lane utilization. Specifically, when the corridor already has an HOV DL, it makes sense to allow CACC-equipped vehicles. The CACC-equipped vehicles increase the lane capacity and lane utilization beyond what is possible in an HOV-only DL. This analysis did not consider person-throughput but only vehicle throughput, because the models used were not calibrated to a level of observed vehicle occupancy.

As the MPR increases, the benefits of dedicating lanes to CACC-equipped vehicles for exclusive use become clearer. At MPRs approaching 25% and increasing between 25% and 45%, the research suggests that dedicating lanes to CACC-equipped vehicles for exclusive use can improve system efficiency in two ways:

- By granting exclusive access for CACC-equipped vehicles to the DLs, these lanes see 100% market penetration, which improves the lane capacity to up to 3,500 vphpl.
- By improving the capacity of DLs and encouraging CACC-equipped vehicles to use DLs, the demand on the GPLs drops significantly, thereby improving overall system efficiency.
As the market penetration of CACC-equipped vehicles increases beyond 45%, mobility benefits will likely occur even without dedicating lanes to CAVs. Significantly, the project team did not model scenarios in which more than one DL was provided for exclusive use by CAVs. Other studies have shown that at higher market penetrations it becomes beneficial to dedicate additional lanes to exclusive CAV usage, maintaining a balance so that the DLs and GPLs remain well utilized (Liu et al. 2018). Figure 8.1 represents guidance on when to share and when not to share dedicated CAV lanes with HOVs, in terms of market penetration of CACC-equipped vehicles.

### 8.1.2 DSH-Equipped Vehicles

Performing a similar analysis for DSH-equipped vehicles, the research team found that the DSH application does not increase lane capacity. The analysis suggests that the presence of DSH-equipped vehicles reduces lane throughput but improves overall safety by reducing the speed differential and shockwaves. By harmonizing speeds, the DSH application could potentially reduce the “snail” effect.

### 8.2 Expected Benefits and Disbenefits from Dedicating Lanes to CAV Users

As discussed in Chapter 2 of this report, this research also considered factors affecting the expected benefits and disbenefits to various stakeholders from dedicating lanes to CAV users on a priority basis, shared basis, or exclusive basis. This section describes the assessment of the performance measures and sensitivity parameters discussed in Chapter 2, based on the modeling and simulation analysis performed.

#### 8.2.1 Market Penetration

For purposes of this report, market penetration has been defined as the percentage of the overall vehicle population that is equipped with CAV technology and applications. The impact of market penetration was assessed both with and without DLs for CAV applications. The analysis suggests that mobility benefits increase with increasing market penetration with the CACC application, and that safety benefits increase with increasing market penetration with the DSH application. The rest of this section presents specific guidance for expected benefits to differing stakeholders.

##### 8.2.1.1 CACC-Equipped Vehicles

The research team assessed the impact of CACC applications with MPRs up to 45% and found that the DL throughput increased to up to 3,400 vehicles per lane per hour. For market penetrations greater than 45%, although no lane was dedicated to CAV users in the analysis, there were overall benefits. Similarly, the benefits due to DSH application included reduction in speed differentials and shockwaves, which in turn improved roadway safety. Table 8.1
Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles

illustrates the benefits and disbenefits to users of DLs and GPLs when CACC-equipped vehicles have shared or exclusive access to DLs. The actual increase in person-throughput would differ from the vehicle throughput, because CACC-equipped vehicles might be SOVs, whereas the baseline DL usage was exclusive to HOVs. Additionally, the analysis of differing levels of market penetration assumed the same percentage of HOVs as the base case, given the lack of indicators regarding change in vehicle occupancy due to changes in DL policies.

**Benefits to Users of DLs and GPLs.** The mobility benefits to users of DLs manifest as an increase in travel speed. As market penetration increases, the throughput increases. In the scenarios examined, throughput increased from an average of 2,100 vphpl in the baseline case to 3,400 vphpl at 45% market penetration, representing a system operator or societal benefit rather than an individual user benefit. The travel speeds on the DLs also remain high, but reduce gradually as market penetration increases and more equipped vehicles “choose” the DLs. Based on the research, however, the travel speeds on the DLs can be expected to remain higher than the travel speeds on the GPLs even at higher MPRs. As far as emissions and fuel consumption are concerned, the study suggests that the users of the facility can save an average of 16% fuel at 25% market penetration. At higher market penetrations (e.g., 35% and 45%), these savings increase to almost 40%, primarily due to reductions in delays and stops.

Although there are benefits to users of DLs at all levels of market penetration, the impacts on GPL users differ based on market penetration. At a lower market penetration (10%), the analysis suggests that significant disbenefits accrue to GPL users when CACC-equipped vehicles receive exclusive access to DLs because the DL is underutilized while the GPLs are overburdened. When the DLs are shared with HOVs, however, there is a slight benefit to GPL users in terms of mobility. At higher MPRs (e.g., greater than 25%), significant benefits accrue to GPL users in addition to the benefits to DL users.

As shown in Table 8.1, at lower levels of market penetration, sharing DLs or providing exclusive DL access provides slight and significant mobility benefits to DL users. Under exclusive lane use, however, GPL users see a significant reduction in their travel speeds. This pattern suggests that it is ideal to share DLs with HOVs at lower levels of market penetration. At higher MPRs (e.g., 25% to 45%), exclusive DLs for CACC-equipped vehicles improves the mobility

<table>
<thead>
<tr>
<th>Lane Use Type (CACC-Equipped Vehicles)</th>
<th>Stakeholder Group</th>
<th>Lower Market Penetration (10%)</th>
<th>Higher Market Penetration (25% to 45%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Travel Speed</td>
<td>Energy/Emissions</td>
<td>Travel Speed</td>
</tr>
<tr>
<td>Shared Dedicated Lanes</td>
<td>DL Users</td>
<td>Slight Increase</td>
<td>No Change</td>
</tr>
<tr>
<td></td>
<td>GPL Users</td>
<td>Slight Increase</td>
<td>No Change</td>
</tr>
<tr>
<td>Exclusive Dedicated Lanes</td>
<td>DL Users</td>
<td>Significant Increase</td>
<td>Slight Reduction</td>
</tr>
<tr>
<td></td>
<td>GPL Users</td>
<td>Significant Reduction</td>
<td>Significant Increase</td>
</tr>
</tbody>
</table>

Table 8.1. Benefits and disbenefits of dedicating lanes to CACC-equipped vehicles to both DL and GPL users.
and environmental performance of both sets of users. At still higher market penetration levels, dedicating additional lanes for use by the CACC-equipped vehicles provides additional benefits when the number of dedicated lanes is well matched to the market penetration so that all lanes are well utilized.

**Benefits to Owners and Operators of the Facilities.** Owners and operators of the facilities also achieve benefits when CACC-equipped vehicles are allowed or provided exclusive access to DLs. For example, the modeled scenarios provided evidence of improved throughput of the system in a DL setting as well as reduced energy use and emissions. In addition, the following lane dedication scenarios provided benefits for DL users and GPL users from an equity standpoint:

- At lower market penetration levels, shared DLs between HOV vehicles and CACC-equipped vehicles increased travel speeds on both the DLs and GPLs.
- At higher market penetration levels, exclusive DLs for CACC-equipped vehicles increased travel speeds on the DLs, because all vehicles in the DL were CAVs; exclusive DLs for CACC-equipped vehicles also increased travel speeds on the GPLs, because the demand on the GPLs was reduced.

### 8.2.1.2 DSH-Equipped Vehicles

Similarly, Table 8.2 demonstrates the benefits and disbenefits to users of DLs and GPLs when DSH-equipped vehicles have shared or exclusive access to DLs. Unlike the CACC scenarios, DLs did not cause a significant increase in throughput for the DSH application; therefore, they were used only up to 25% CAV market penetration. (For higher MPRs the research team assessed scenarios without DLs.)

As shown in the table, shared DLs caused a slight reduction in speed differential and shockwaves when the DSH market penetration was lower (10%). This reduction was seen among both DL users and GPL users. In the case of exclusive DLs, it appeared that only the DL users received the benefits. At lower levels of market penetration, the GPL users experience significant disbenefits. At higher levels of market penetration, however, GPL users experience no significant benefit or disbenefit. No statistically significant change was found in the energy consumption or emissions.

<table>
<thead>
<tr>
<th>Lane Use Type (DSH-Equipped Vehicles)</th>
<th>Stakeholder Group</th>
<th>Lower Market Penetration (10%)</th>
<th>Higher Market Penetration (25%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed Diff./ Shockwaves</td>
<td>Energy/ Emissions</td>
<td>Speed Diff./ Shockwaves</td>
</tr>
<tr>
<td>Shared Dedicated Lanes</td>
<td>DL Users</td>
<td>Slight Reduction</td>
<td>No Change</td>
</tr>
<tr>
<td></td>
<td>GPL Users</td>
<td>Slight Reduction</td>
<td>No Change</td>
</tr>
<tr>
<td>Exclusive Dedicated Lanes</td>
<td>DL Users</td>
<td>Slight Reduction</td>
<td>Slight Reduction</td>
</tr>
<tr>
<td></td>
<td>GPL Users</td>
<td>Significant Reduction</td>
<td>Significant Increase</td>
</tr>
</tbody>
</table>
As far as system-wide benefits are concerned, there is some benefit when DSH-equipped vehicles share the DLs with HOVs at lower market penetration, and when DSH-equipped vehicles have exclusive lane access in the case of higher market penetrations. For market penetrations higher than 25%, safety-related benefits are demonstrated when no DLs are used.

### 8.2.2 Impact of Combination of Applications

Two CAV applications—CACC and DSH—were assessed in this project. The CACC application aims to improve the mobility of freeway lanes by coordinating the maneuvers of vehicles and driving them closer together so that they act as a string with virtual connectivity. The DSH application aims to harmonize the speeds across the freeway, thereby reducing sudden speed changes to reduce shockwaves and increase safety. When implemented together, the modeling included CACC strings as a platoon of vehicles in which the lead vehicle received “harmonized” speed recommendations in response to downstream congestion. The combination of applications produced both safety and mobility benefits when compared to the baseline.

### 8.2.3 Impact of Demand

The impact of dedicating lanes to CACC-equipped vehicles and DSH-equipped vehicles was assessed using varying demand conditions for the I-66 and US-101 corridors. Table 8.3 shows how the percentage change in average system throughput due to CAV DLs is impacted by changes in demand levels. A “lower than peak” scenario was not simulated for the US-101 testbed, and the two cases represent a 0.2-fold increase or decrease in typical peak demand.

As shown in the table, the performance of the CACC application in terms of percentage change in throughput improved with increased demand beyond typical demand. With reduced demand, however, the performance remained unchanged. The DSH application, which typically reduced the throughput when implemented, slightly increased the throughput under higher demands.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Corridor Used for Analysis</th>
<th>Change in Average Vehicle Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower than Peak Demand</td>
</tr>
<tr>
<td>10% Market Penetration of CACC (Shared DL)</td>
<td>I-66 Northern Virginia</td>
<td>Slight Increase</td>
</tr>
<tr>
<td></td>
<td>US-101 San Mateo, California</td>
<td>N/A</td>
</tr>
<tr>
<td>25% Market Penetration of CACC (Exclusive DL)</td>
<td>US-101 San Mateo, California</td>
<td>N/A</td>
</tr>
<tr>
<td>50% Market Penetration of CACC (No DL)</td>
<td>US-101 San Mateo, California</td>
<td>N/A</td>
</tr>
<tr>
<td>10% Market Penetration of DSH (Shared DL)</td>
<td>I-66 Northern Virginia</td>
<td>No Change</td>
</tr>
</tbody>
</table>

Table 8.3. Impact of demand on benefits from CACC and DSH DLs.
When CACC was assessed for the US-101 corridor, increasing traffic beyond typical peak traffic did not cause further increase in throughput. This result was primarily due to the fact that the US-101 traffic density was already approaching saturation at typical peak traffic conditions.

### 8.3 Guidance on Access Restrictions

As described in Chapter 2, access points or restrictions influence the design of DLs for CAVs. Restricting access to DLs serves two purposes: (1) it delineates CAVs from other users, increasing safety in situations of high lane friction, and (2) it reduces the overall disturbances in the flow of traffic on the DLs by concentrating these disturbances to a reduced number of access points. Restricting access to DLs also can have some apparent disadvantages: (1) DL users need to manage their exit points from the GPLs, allowing ample time for the vehicles to cross over the GPLs to the designated entries to the DLs, and (2) CAV users who need to use the DL for short distances are discouraged from using it because of the limited availability of entry and exit points. Based on this project’s comparison of system performance during continuous and restricted access scenarios (as described in Chapter 6), the following guidance statements can be made:

- Mobility benefits increase when there is continuous access to the DLs. This result occurs because even vehicles taking shorter trips can utilize the DLs.
- Speed differentials between DLs and GPLs increase with restricted access to DLs. DLs with exclusive access for CAVs will have a much higher travel speed than GPLs. Average travel speeds on GPLs reduce significantly when there is restricted access to DLs. This result occurs because the demand on GPLs will be higher when compared to continuous access, as vehicles taking shorter trips cannot use the DLs.

The analysis conducted for this study did not include scenarios with higher levels of market penetration (i.e., 35% to 45%) by users utilizing DL with restricted access. Additional research is warranted to further this analysis. Moreover, other studies have found significant differences in the way drivers behave in weaving sections (in the case of restricted access dedicated lanes), and this behavior needs to be further studied to conclude whether these findings can be generalized.

### 8.4 Guidance on Lane Separation Barriers

This analysis used lane friction as the performance measure to develop guidance regarding lane separation barriers. Lane friction is defined as the difference in travel speeds between vehicles on the DLs and vehicles in the GPLs. More lane friction (a higher speed differential) between DLs and GPLs can render lane changes into and out of DLs unsafe, and therefore warrants the use of restricted lane access or physical barriers/lateral spacing between DLs and GPLs. Based on the observed average lane friction, the research team categorized the scenarios into four groups (see Figure 8.2):

- **High Market Penetration of CAV with shared DLs with HOVs.** This group demonstrated the lowest lane friction, and does not warrant lane separation barriers or restricted lane access.
- **Low Market Penetration of CAV with shared DLs with HOVs.** This group also demonstrated relatively low lane friction.
- **High Market Penetration of CAV with Exclusive DLs.** This group showed medium lane friction, where the average speeds of the DL and the adjacent GPL differed by 10 mph to 15 mph. According to Best Practices: Separation Devices Between Toll Lanes and Free Lanes (Hlavacek et al. 2007), this level of lane friction does not warrant physical separators, but rather buffer-separated double solid lines.
• Low Market Penetration of CAV with Exclusive DLs. This group showed the highest lane frictions, on the order of 30 mph. This result warrants the need for physical separators for both enforcement and safety purposes.

This guidance is based on the modeling-based analysis that was performed in this project. For more detailed design considerations, additional field data collection and alternative analysis are proposed.

8.5 Findings on Economic Equity

The project team also conducted a simplified VTTS analysis to compare the benefits that DL users will see. This evaluation used the national average VTTS values, averaged between business purpose and personal trip purpose. Annual savings were computed based on these average values and other assumptions highlighted in Chapter 6. In general, the DL users saved more travel time than the GPL users. GPL users saw fewer (and sometimes no) travel time benefits when compared to the DL users. The intensity of this mismatch appeared to depend on market penetration. The DL users received maximum benefits under 10% market penetration when CAVs had exclusive lane access to the DLs. Under 25% market penetration, however, DL users with exclusive lane access also demonstrated some annual economic savings. For market penetrations higher than 25%, there was no significant difference in travel time savings between DL and GPL users. Please note that there may be other scenarios outside of our analysis space that could potentially provide greater travel time savings for both DL and GPL users.

8.6 Regulatory and Policy Guidance

Consideration of definitions for dedicating lanes requires an agreed-upon framework of decisions. Will the lanes be restricted to vehicles based on their class, type, amount of automation, or connectivity? Will the levels of technology installed in the roadway or roadside influence such restrictions? Having clear definitions of differing types of functionality will be crucial for enforcement in allowing vehicles to operate in DLs of any type, and crucial in determining the potential HOV/HOT exemption eligibility of specific vehicles.

The challenge that exists today is the overlap in functionality and difficulty in differentiating between a vehicle capable of automatically handling a dynamic driving task and a vehicle that is actually operating in such a mode. Human drivers will be able to select the mode of usage of a vehicle that is equipped with an ADS, and that could include differing levels of automation at different times and under different operating conditions. States will need to decide whether it is important to impose restrictions on which types of automation should be used, at which times, and in which DL locations. It also will be important to harmonize these state decisions with the federal rules that govern the requirements on HOV and HOT lanes when the CAV DLs are coincident with HOV or HOT lanes.
As they begin to contemplate dedicating lanes for CAVs, state and local DOTs, metropolitan planning organizations, and infrastructure owners and operators are trying to determine what CV infrastructure needs to be deployed, where to deploy it, and when to deploy it. Furthermore, these agencies are struggling with the issue of how to fund and/or finance this deployment. They also are trying to prepare for the future of AVs and asking the question: what roadway infrastructure (e.g., pavement markings, signing, etc.) will be needed to optimize the performance of the AV safety systems? These infrastructure owners and operators want to know what infrastructure can be provided to enhance the performance and safety of vehicles with low-level automation (i.e., automated braking and lane departure systems) as well as highly automated vehicles.

Discussion about how to answer the “road readiness” question is increasingly common within agencies, as is the recognition that the future will reflect a balance between proactive implementation and reactive adjustments. Because differing vehicle developers will use differing combinations of sensors, with differing levels of sophistication, it is not feasible at present to specify a single level of infrastructure specifications that can ensure suitability for use by ADS. Therefore, initial decisions on the types of vehicles that can be given DLs will most likely be based on vehicle types and levels of automation, because those definitions are the most mature. As this issue evolves, the research team suggests revisiting the guidance provided by this study and determining whether roadway definitions will have a significant or minimal impact on the allowance of DLs for CAVs.

Some designation of roadways with respect to the quality of lane markings and signage could be important for future efforts to license CAVs for broader public use. With SAE International Level 4 and Level 5 systems, considering whether detailed digital maps are available for roadways will likely be important. It also will be important to identify roadway geometric limitations and turning radius restrictions on maps for trucks. Therefore, some consideration of roadway characteristics will likely come into play.

To avoid compounding the patchwork of vehicle definitions that has resulted from current policy for low-emission and energy-efficient vehicle exemptions to HOV facilities across different states, it would be wise to begin addressing CAV DLs by focusing on the creation of a standard set of vehicle definitions as prescribed by the industry. This focus is currently reflected in SAE International’s SAE J3016: Recommended Practice (SAE International 2018). Presumably, SAE J3016 will be adapted to follow any changes should industry evolve its thinking.

Currently, the classification scheme in SAE J3016 only represents the division of functions between the driver and the driving automation system; it does not attempt precise classifications of the Operational Design Domain (ODD) elements, which will be much more complicated. Future standardization efforts may define some representative ODD clusters as well, but this task will be challenging because there are so many dimensions to the ODD and these will depend on the capabilities of different sensing technologies and information-processing approaches that various vehicle developers will choose to adopt. Standards to define the roadway infrastructure characteristics also are likely to be rather general, along the lines of Interstate Highway design standards, rather than highly prescriptive, because the local geographical constraints will vary widely across the country. The developer of each driving automation system will have to determine on which specific roads their system is capable of driving safely, and those are the roads that will be included within its ODD. Already, Level 2 automation systems such as the GM Super Cruise system are configured so that they can be engaged only on the freeways that GM has approved for its use.

Given the current state of the industry, Levels 3, 4, and 5, defined in SAE J3016 and adopted in the 2017 NHTSA policy as Automated Driving Systems, would be logical initial break-points for dedicating lanes based on vehicle levels of automation.
For the foreseeable future, the large majority of CAVs that could potentially benefit from dedicated lanes will be at the lower levels of automation, with SAE Level 1 and Level 2 driving automation systems, so there is no reason to discriminate among levels of automation in determining which vehicles should have access to the DLs. Rather, the important criterion for DL access should be the use of connectivity, because the concentration of connected vehicles in the DL is the fundamental way of gaining benefits. For example, vehicles without any automation but with V2V communication capability can serve as the Leaders for CACC-equipped Follower vehicles, helping to accelerate the benefits from CACC during the period when the market penetration of CACC-equipped vehicles remains low. Level 4 vehicles without connectivity have the potential to actually degrade highway throughput and traffic flow stability, whereas Level 1 vehicles using CACC could significantly improve these performance measures.

Admitting connected vehicles to the dedicated lanes by use of their communication devices (and assessing any needed user fees) will be straightforward, as the process is directly analogous to the use of electronic tolling tags as the means of admission to HOT lanes today. Additional considerations would come into play if levels of driving automation functionality and connectivity were to become the basis for implementation of dedicating lanes. For example, the methods of identification would also need to be standardized across states to reduce complexity for law enforcement and avoid the patchwork of definitions currently seen with AFV use in HOV/HOT lanes. Some complexities also would be associated with determining the conditions in which the ADS should be engaged. An ADS may be engaged or disengaged by a human driver at any time, and in some cases the local conditions are likely to deviate from the minimum ODD conditions for use of some specific ADS; consequently, those ADS will not be capable of operating continuously.

Additional reasons why identification of ADS as the pre-screening criterion for dedicating lanes would be problematic include:

- Because Level 3, Level 4, and even Level 5 vehicles can still have the human driver engaged in certain situations, it can be unclear whether a human driver or ADS is operating the vehicle in a lane that is theoretically dedicated to AV operations; and
- Given that vehicle identification in relation to vehicle automation has not yet been addressed in a significant way, enforcement officials and systems cannot easily identify whether a vehicle is actually being operated under human or automatic control (other than via the vehicle communication system indicating its real-time status).

In the face of these uncertainties, developing policies for operations, management, and enforcement presents several technical and institutional challenges that have not yet been addressed. Much like the uncertainty surrounding HOV/HOT enforcement (i.e., identifying vehicle occupancy), attempting to monitor and enforce vehicle automation is not an immediate consideration by the vehicle industry at this stage of CAV evolution.

### 8.7 Guidance Regarding Updating Laws and Regulations

Attempting to establish any kind of regulatory or legislative foundation while operating in a state of constant change and high uncertainty brings with it many challenges. As a result, any policy, regulatory, or legislative actions that are taken should be incremental in nature, incorporating graduated approaches to change and flexibility through moderation. It is suggested that agencies not attempt to solve every eventuality in one action; rather, it will be productive to consider pilot programs and small increments of change as agencies navigate through this fast-evolving environment.
Public opinions are still being formed and are at a volatile stage as the boundaries between imagination and reality become more clearly defined in the public mind. The initial “hype” period will likely yield to a more realistic assessment of opportunities and risks, especially in light of the early 2018 crash of an automated Uber vehicle (Bliss 2018). Surveys of public opinion have already displayed wide divergence on the desirability and safety of automation of road vehicles. Dedicating lanes to AVs brings in the added dimension of distributional equity and may risk being perceived as introducing elite “Lexus Lanes,” so it is important to tread carefully and build public consensus about the broader societal desirability of dedicating CAV lanes before implementing actions.

Various operational and policy issues remain unaddressed, truck platooning issues loom large, and questions about exemptions for CAVs in HOV/HOT lanes are still unclear. For all vehicles, a rich understanding of state laws that might restrict or inhibit the testing or use of ADS comes with the territory. For trucks, a keen understanding of current laws related to following distances is important. As federal laws and regulations mature, it will be important to revisit this topic regularly. Currently, the stage is being set for future precedent; now, more than ever, it is important to respect flexibility.
This project expanded the current spectrum of understanding with respect to dedicating lanes to CAVs, but unknowns remain that will require further research to understand how different applications impact managed lane facilities. This chapter suggests specific research directions that may need to be undertaken in the near future.

9.1 Granular Energy and Environmental Impact Assessment

The energy and environmental measures used in this project are simplified microscopic models that do not consider vehicle-specific calibration parameters in the modeled regions. To build on the results of this research, future efforts could include a more granular investigation of performance measures. The assessment of environmental impacts could be expanded with the adoption of MOVES to estimate the energy consumption and criteria pollutant emissions based on vehicle trajectories.

9.2 Expansion for More Test Scenarios

The scenarios assessed in this research were selected to maximize the opportunity to address the uncertainty of dedicating lanes for CAVs on freeways. These scenarios were chosen as a building block to address the most common question encountered about committing a lane to CAV usage. To expand the number of possible scenarios, the following scenarios could be explored:

- Varying speed limits;
- Different heavy vehicle composition in traffic flow;
- Increasing the number of dedicated CAV lanes; and
- Higher levels of market penetration on restricted access DLs.

Adding these scenarios to the scenarios assessed in this research project will yield a larger number of study-based considerations and permutations. Selection of scenarios and considerations for further study could be prioritized based on the overall anticipated impact and facilitation to the mass deployment of CAVs. The scenarios to be examined should be defined to address the uncharted transition from initial CAV deployment to full market penetration.

9.3 Dedicating Lanes for CAVs on Arterials

Previous studies regarding CACC applications have focused primarily on freeway traffic management. The majority of past efforts to identify the operational, safety, and environmental impacts of CACC and similar CAV applications limited themselves to uninterrupted traffic flows or relatively high-speed facilities (i.e., facilities with design and posted speeds greater than 45 mph).
A few studies, such as eco-approach and departure, glidepath, and eco-speed control, have focused on low-speed arterial facilities with various intersection control types (Hao et al. 2015, Altan et al. 2017, and Kamalanathsharma et al. 2015). None of these studies looked at dedicating arterial lanes to CAVs, however, because doing so would have posed a more complicated set of deployment challenges, especially associated with accommodating turning movements. Such research will require a closer assessment of the various types of controlled and uncontrolled traffic interruptions. The following traffic flow interruptions have been identified as the most common types:

- Road intersections (signalized and unsignalized);
- Pedestrian midblock crosswalks;
- Transit stops and loading/unloading zones along the curbside;
- On-street parking; and
- Driveways.

Roadway geometric design along arterials also differs to support low-speed functionality and various vehicle mode operations. These geometric designs also need to be accounted for when considering the practicality and possible inclusion of dedicated CAV lanes:

- Dedicated bicycle lanes, and
- Center turn lanes (e.g., two-way left-turn-lanes).

Additional research into the impacts of CAV applications on DLs on collectors and minor arterials, with and without intersections, may be warranted.

### 9.4 Dedicating Lanes to Connected and Automated Trucks

Current standard practice allowing roadway facility owners and operators to dedicate lanes to heavy vehicles like trucks is mostly limited to truck climbing lanes. These lanes are used for short distances in certain areas to improve safety, ease congestion, and prevent delays by facilitating the passing of trucks and other slow-moving vehicles whose speeds drop due to sustained steep grades. Truck climbing lanes typically have not been designated as restricted for use by heavy vehicles, but other (lightweight) vehicles generally have avoided using them because they are occupied by slower moving vehicles.

Creating a DL for connected and automated trucks could bring various operational, environmental, safety, economical, and societal impacts. Additional studies are warranted that could review these impacts and provide guidance to agencies who operate major trucking routes. The following scenario variations could be considered when developing an analysis framework to expand considerations for connected and automated truck DLs:

- Percent of heavy vehicles in traffic;
- Restriction to trucks with/without payloads;
- Parallel use with truck climbing lanes; and
- Mixed use between connected and automated vehicles and trucks.

Macroscopic modeling of exit-to-exit automated freight movements also could help determine operational and economic aspects of freight optimization.

### 9.5 Modeling Higher Levels of Automation

The completed research task for this project included the demonstration of the CACC and DSH CV applications under the scenarios designed to address the identified research questions, which mostly fell under SAE J3016 Level 1 or Level 2 of automation (SAE International 2016b).
Meanwhile, the industry is moving fast to achieve higher levels of automation. A more near-term application of AVs, called “automated highway driving,” is a combination of ACC and lane centering for use on freeways (SAE International 2016b). Automated highway driving does not require continuous supervision by a human driver. The traffic performance of such systems is likely to be nearly indistinguishable from the performance of the Level 1 and Level 2 systems that have been modeled in this research. Although small differences in lane changing and merging behaviors may occur, the impacts of these small variations could either improve traffic flow or make it worse, depending on the level of sophistication of the specific automation system.

9.6 Unified Definitions for CAV and Related Terminology

Because the definitions of automated vehicle types are more mature, using the SAE J3016 definitions as a basis for allowing and enforcing CAVs in DLs is a logical starting point. Nonetheless, it is suggested that attention to the ODD capabilities issue be further researched and considered early in the adoption cycle of any DL scenario.
This report documents the research conducted under Task 8 of NCHRP Project 20-102, which aims to assess the impacts CAVs on state and local transportation agencies. The project aimed at developing guidance on identifying and describing conditions amenable to dedicating lanes for CAV users. To assist in identifying the conditions and parameters that can make or break a case for dedicating lanes to CAV users, the project team conducted simulations to analyze two CAV applications, CACC and DSH, based on two case study sites—I-66 in Northern Virginia and US-101 in San Mateo County, California. The modeling and simulation activity helped the project team (1) identify parameters that are sensitive to dedicating lanes to CAV users and (2) identify expected impacts under various conditions of lane dedication, market penetration, demand conditions, combined deployment of applications, and so forth using virtual computer-based models.

To conduct this research, the team started with a comprehensive literature review to identify:

- The types of stakeholders benefited (or disbenefited) when dedicating lanes to CAVs,
- Factors influencing these benefits, and
- The potential measures of the performance.

Specifically, the research team identified three types of stakeholders: (1) DL users, (2) GPL users, and (3) facility owners and operators. The following factors also were identified as influencing the benefits and disbenefits to these stakeholders:

- CAV market penetration, representing the percentage of vehicles in the traffic mix with CAV capabilities;
- Roadway geometry, including access/egress features, lane attributes, number of lanes, and so forth;
- Enforcement intensity, which restricts unallowable categories of users to enter the DLs;
- Toll collection attributes, such as whether non-CAV vehicles can use the DLs, for a fee;
- Operation hours, such as dynamic operations or peak-hour operations;
- CAV technology, which represents the type of applications allowed on vehicles using these lanes; and
- Functional types, which dictate the type of vehicles allowed on the DLs.

The review also documented performance measures specific to mobility, energy and environment, safety, and societal benefits that might be achieved by users and non-users of such DLs.

This step was followed by research on various CAV applications. Several CAV applications exist in the research industry today, and assessing all of them was beyond the scope of this study. As a result, the study team down-selected two CAV applications, CACC and DSH, along with
suitable modeling techniques for use in this project. The applications were selected based on three factors:

- Suitability to DLs,
- Suitability to the CAV/AV environment, and
- Adaptability to simulation models.

Specific modeling frameworks that could represent each of these applications also were selected, based on several criteria.

The project team utilized modeling and simulation-based analysis to evaluate potential benefits and parameter sensitivity of CAV applications on overall traffic efficiency and safety. Having identified multiple modeling-based test sites to which the team had access, the research team narrowed the field of candidates to nine case study sites that were then evaluated and ranked based on the following characteristics:

- Overall site characteristics (e.g., geography, operational conditions, modes, presence of managed lanes, and so forth);
- Managed lane characteristics (e.g., geometry, allowed users, operating rules, access point configurations, and so forth); and
- The feasibility of modeling CAV applications for the site.

As a result of this evaluation, the team selected two case study sites: the I-66 corridor in Northern Virginia and US-101 corridor in San Mateo County, California.

The project team then conducted simulation-based analysis to evaluate the impacts of CAV DL applications under different sensitivity parameters. Primarily, the simulations studied the impacts of:

- Priority lane use (where CAVs were permitted on HOV lanes), versus exclusive lane use (where CAVs had exclusive access to DLs);
- Rates of market penetration of CAV/AV users, assessed under a DL case and a non-DL case;
- A combination of CAV applications;
- Varying demand and changing operational conditions on the CAV DL benefits;
- Access restrictions to the DL under exclusive CAV lane situations; and
- Hypothetical scenarios, such as incident-related lane closures or moving bottlenecks.

In addition to the more operational analysis based on modeling and simulation, the project team also conducted a literature review to identify the laws and regulations regarding dedicating lanes to a specific category of users. It was found that, historically, lanes have been dedicated to HOVs, motorcycles and bicycles, buses, AFVs, and trucks.

Consequently, the project team developed specific guidance for agencies on operational characteristics and impacts, as well as regulatory and policy guidance for states and local agencies on conditions amenable to dedicating lanes to CAVs. This guidance is summarized as follows:

- For CACC DLs, it is advisable to have shared DLs with HOVs at lower levels of market penetration (10%), exclusive DLs at medium levels of market penetration (20% to 45%), and no DLs for higher levels of market penetration (greater than 50%).
- For lower levels of market penetration of CACC:
  - Under shared DL conditions, slight mobility benefits may result for both DL users and GPL users; and
  - Under exclusive DL conditions, significant mobility and energy/environmental benefits to DL users may result, at the expense of GPL users.
• For higher levels of market penetration of CACC:
  – Under exclusive DL conditions, moderate to significant mobility and energy/environmental benefits to DL users may result, and slight to moderate benefits to GPL users.

• For lower levels of market penetration of DSH:
  – Under shared DL conditions, slight safety benefits may result for both DL and GPL users; and
  – Under exclusive DL conditions, slight safety benefits may result for DL users, and significant safety benefits may result for GPL users at the expense of GPL users’ mobility performance.

• For higher market penetration of DSH:
  – Under exclusive DL conditions, moderate to significant improvement in safety and slight improvement in energy/environmental performance may occur for DL users; GPL users would remain unaffected.

• Combining DSH-enabled vehicles with CACC-enabled vehicles will improve safety in addition to mobility and energy/environmental performance.

• CACC DLs can provide mobility benefits (in terms of throughput improvement), particularly when the corridor is subject to peak or higher than peak demand.

• Mobility benefits are more significant when there is continuous access to the DLs because even vehicles taking shorter trips can utilize the DLs.

• Speed differentials between DLs and GPLs increase with restricted access to DLs. DLs with exclusive CAV access will have a much higher travel speed than the GPLs.

• Average travel speeds on GPLs reduce significantly when access to DLs is restricted. This reduction in speed occurs because the demand on GPLs will be higher with a restricted access DL compared to a continuous access DL. Depending on the placement and convenience of access points, even eligible vehicles may not use the DLs for shorter trips.

• Lane friction (the speed differential between the DL and adjacent GPLs) informs guidance on when barrier separated lanes are warranted:
  – High MPRs of CAVs with shared DLs with HOV demonstrated the lowest lane friction; this scenario does not warrant lane separation barriers or restricted lane access.
  – Low MPRs of CAVs with shared DLs with HOV also demonstrated relatively low lane friction.
  – High MPRs of CAVs with exclusive DLs showed medium lane friction, whereby the average speeds of the DL and the adjacent GPL differed by 10 to 15 mph. According to Best Practices: Separation Devices Between Toll Lanes and Free Lanes (Hlavacek et al. 2007), this level of lane friction does not warrant physical separators, but rather buffer-separated double solid lines.
  – Low MPRs of CAVs with exclusive DLs showed the highest lane friction, on the order of 30 mph. This level of lane friction warrants physical separators for both enforcement and safety purposes.

This guidance must be used in conjunction with the type of analysis that went into developing these statements. Scenarios may exist outside the scope of the analysis performed during this project that could potentially enhance or change this guidance.
Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AADT</td>
<td>Annual Average Daily Traffic</td>
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<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
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<td>ADS</td>
<td>Automated Driving System</td>
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<tr>
<td>AFV</td>
<td>Alternative Fuel Vehicle</td>
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<tr>
<td>AMS</td>
<td>Analysis, Modeling, and Simulation</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
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<tr>
<td>ATDM</td>
<td>Active Transportation and Demand Management</td>
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<tr>
<td>AV</td>
<td>Automated Vehicle</td>
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<tr>
<td>BOS</td>
<td>Bus on Shoulder</td>
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<tr>
<td>BSM</td>
<td>Basic Safety Message</td>
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<tr>
<td>CACC</td>
<td>Cooperative Adaptive Cruise Control</td>
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<tr>
<td>CalSTA</td>
<td>California State Transportation Agency</td>
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<tr>
<td>CAMP</td>
<td>Crash Avoidance Metrics Partnership</td>
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<tr>
<td>CAV</td>
<td>Connected and Automated Vehicle</td>
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<td>COM</td>
<td>Component Object Model</td>
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<tr>
<td>CV</td>
<td>Connected Vehicle</td>
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<td>DDT</td>
<td>Dynamic Driving Task</td>
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<td>DL</td>
<td>Dedicated Lane</td>
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<tr>
<td>DLL</td>
<td>Dynamic Linked Libraries</td>
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<tr>
<td>DLV</td>
<td>Dedicated Lane Vehicle</td>
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<tr>
<td>DMA</td>
<td>Dynamic Mobility Application</td>
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<tr>
<td>DSH</td>
<td>Dynamic Speed Harmonization</td>
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<td>DSRC</td>
<td>Dedicated Short-Range Communication</td>
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<tr>
<td>EDM</td>
<td>External Driver Model</td>
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<td>E-IDM</td>
<td>Enhanced Intelligent Driver Model</td>
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<tr>
<td>ESH</td>
<td>Eco-Speed Harmonization</td>
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<tr>
<td>ETL</td>
<td>Express Toll Lane</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>FAST</td>
<td>Flexible Agent-Based Simulator of Traffic</td>
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<td>FMVSS</td>
<td>Federal Motor Vehicle Safety Standards</td>
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<tr>
<td>GEH</td>
<td>Geoffrey E. Havers Statistic</td>
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<tr>
<td>GKT</td>
<td>Gas-Kinetic Traffic</td>
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<td>GPL</td>
<td>General Purpose Lane</td>
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<tr>
<td>GPV</td>
<td>General Purpose Lane Vehicle</td>
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<tr>
<td>HIA</td>
<td>Here-I-Am</td>
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<tr>
<td>HOT</td>
<td>High Occupancy Toll</td>
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<tr>
<td>HOV</td>
<td>High Occupancy Vehicle</td>
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<tr>
<td>I2V</td>
<td>Infrastructure-to-Vehicle</td>
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<tr>
<td>IDM</td>
<td>Intelligent Driver Model</td>
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<tr>
<td>MIXIC</td>
<td>MIcroscopic Model for Simulation of Intelligent Cruise Control</td>
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<tr>
<td>MOVES</td>
<td>Motor Vehicle Emission Simulator</td>
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<td>MP</td>
<td>Market Penetration</td>
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<tr>
<td>MPR</td>
<td>Market Penetration Rate</td>
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<tr>
<td>ODD</td>
<td>Operational Design Domain</td>
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<tr>
<td>PeMS</td>
<td>Performance Measurement System (Caltrans)</td>
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<tr>
<td>PEV</td>
<td>Plug-in Electric Vehicle</td>
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<tr>
<td>RITIS</td>
<td>Regional Integrated Transportation Information System</td>
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<tr>
<td>SIM</td>
<td>Safety Impact Methodology</td>
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<tr>
<td>SOV</td>
<td>Single Occupancy Vehicle</td>
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<tr>
<td>SPaT</td>
<td>Signal Phase and Timing</td>
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<tr>
<td>TMC</td>
<td>Traffic Management Center</td>
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<tr>
<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle-to-Infrastructure</td>
</tr>
<tr>
<td>VAD</td>
<td>Vehicle Awareness Device</td>
</tr>
<tr>
<td>VHT</td>
<td>Vehicle-Hours Traveled</td>
</tr>
<tr>
<td>VMS</td>
<td>Variable Message Sign</td>
</tr>
<tr>
<td>VMT</td>
<td>Vehicle-Miles Traveled</td>
</tr>
<tr>
<td>VTTS</td>
<td>Value of Travel Time Savings</td>
</tr>
<tr>
<td>XBL</td>
<td>Exclusive Bus Lane</td>
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</table>
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Abbreviations and acronyms used without definitions in TRB publications:

A4A Airlines for America
AAAE American Association of Airport Executives
AASHTO American Association of State Highway Officials
AASHTO American Association of State Highway and Transportation Officials
ACI–NA Airports Council International–North America
ACRP Airport Cooperative Research Program
ADA Americans with Disabilities Act
APTA American Public Transportation Association
ASCE American Society of Civil Engineers
ASME American Society of Mechanical Engineers
ASTM American Society for Testing and Materials
ATA American Trucking Associations
CTAA Community Transportation Association of America
CTBSSP Commercial Truck and Bus Safety Synthesis Program
DHS Department of Homeland Security
DOE Department of Energy
EPA Environmental Protection Agency
FAA Federal Aviation Administration
FAST Fixing America’s Surface Transportation Act (2015)
FHWA Federal Highway Administration
FMCSA Federal Motor Carrier Safety Administration
FHWA Federal Highway Administration
FRA Federal Railroad Administration
FTA Federal Transit Administration
HMCAR Hazardous Materials Cooperative Research Program
IEEE Institute of Electrical and Electronics Engineers
ISTEA Intermodal Surface Transportation Efficiency Act of 1991
ITE Institute of Transportation Engineers
NASA National Aeronautics and Space Administration
NASAO National Association of State Aviation Officials
NCFRP National Cooperative Freight Research Program
NCHRP National Cooperative Highway Research Program
NHTSA National Highway Traffic Safety Administration
NTSB National Transportation Safety Board
PHMSA Pipeline and Hazardous Materials Safety Administration
RITA Research and Innovative Technology Administration
SAE Society of Automotive Engineers
SAFETEA-LU Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP Transit Cooperative Research Program
TDC Transit Development Corporation
TRB Transportation Research Board
TSA Transportation Security Administration
U.S. DOT United States Department of Transportation