
CAV TRAFFIC SIMULATION LITERATURE REVIEW

Prepared by:



November 9, 2019

TABLE OF CONTENTS

| | |
|--|-----------|
| Executive Summary | 1 |
| List of Acronyms | 5 |
| 1. Introduction | 7 |
| 1.1 Requirement..... | 7 |
| 1.2 Task Order Objective. | 7 |
| 1.3 Literature Review Project Overview..... | 7 |
| 1.4 Overview of Current Activities in CAV | 9 |
| 1.5 Organization of This Report..... | 11 |
| 2. CAV Penetration Rates | 13 |
| 2.1 CAV Penetration Rates in the Literature | 13 |
| 2.2 Summary of other State Studies Involving CAV and Impacts..... | 17 |
| 2.3 CAV Adoption Scenarios in Published Planning Efforts | 18 |
| 2.4 Section 2 References | 21 |
| 3. Effects of CAV Technologies on Traffic Modeling | 23 |
| 3.1 Overview of CAV Technologies Impacting Microsimulation | 23 |
| 3.2 Impact of CAV on Traffic Operations | 25 |
| 3.2.1 Capacity | 26 |
| 3.2.2 Reduction or Increase in Congestion..... | 34 |
| 3.2.3 Traffic Stability..... | 35 |
| 3.2.4 Travel Time | 36 |
| 3.3 Impact of CAV on Society | 39 |
| 3.3.1 Safety Improvements Based on Vehicle Crash Reduction..... | 40 |
| 3.3.2 Mode Choice, Vehicle Ownership and Shared Mobility | 42 |
| 3.3.3 Value of Travel Time | 44 |
| 3.3.4 Increased Fuel Efficiency and Related Emissions Reduction..... | 45 |
| 3.4 Section 3 References | 46 |
| 4. Traffic Simulation as a Tool for CAV Analysis: State of the Practice | 50 |
| 4.1 Overview of CAV Analysis Tools | 50 |
| 4.2 Incorporating CAV Characteristics and Impacts into Travel Modeling..... | 51 |
| 4.2.1 Travel Demand Models..... | 53 |
| 4.2.2 Traffic Simulation Modeling | 55 |
| 4.3 Overview of past Work on Model Use for States or Regional Agencies | 56 |
| 4.3.1 Vissim Customization..... | 57 |

| | | |
|--|--|-----------|
| 4.3.2 | TransModeler Customization | 63 |
| 4.4 | Section 4 References | 69 |
| 5. | Addressing Risk and Uncertainty in CAV Modeling | 71 |
| 5.1 | Recent Examples Treating CAV Uncertainty..... | 71 |
| 5.2 | Visioning and Strategic Planning | 71 |
| 5.3 | Scenario Planning | 72 |
| 5.4 | Exploratory Modeling and Analysis | 73 |
| 5.5 | Section 5 References | 74 |
| 6. | Recommendations | 75 |
| Appendix A: Overview of the Current State of Connected and Automated Vehicles (CAV) (the Big Picture of CAVs) | | 80 |
| 1.0 | Introduction | 80 |
| 2.0 | SAE Levels of Automation..... | 82 |
| 3.0 | Connected and Automated Vehicle Technologies..... | 83 |
| 4.0 | Impacts of Automated Vehicles..... | 85 |
| 5.0 | Pilots, Deployments, Tests..... | 87 |
| 6.0 | Regulatory and policy issues related to CAV Testing and Implementation | 91 |
| 7.0 | CAV Implementation Uncertainty and the Importance of Safety. | 92 |
| 8.0 | CAV Infrastructure and Agency Needs and Readiness. | 93 |
| 9.0 | The Private Sector..... | 94 |
| APPENDIX B. Literature search annotated CAV reference list..... | | 97 |

LIST OF TABLES

| | |
|---|------|
| Table 1. Typical Penetration Rates from the Literature..... | 16 |
| Table 2: CV/AV Adoption Scenarios for 2035 | 19 |
| Table 3: Candidate Scenarios and Penetration Rates | 21 |
| Table 4: AVs Freeway Capacity Improvement | 26 |
| Table 5: Research into Modeling of CACC..... | 31 |
| Table 6: Research Studies on Impacts of Automation on Traffic Flow Stability, Congestion, and Travel Time | 37 |
| Table 7: Vissim CAV Use Cases..... | 58 |
| Table 8: Vissim Parameter Ranges..... | 59 |
| Table 9: Example Use of Vissim to Test CAV..... | 63 |
| Table 10: TransModeler Automation Level Use Cases..... | 71 |
| Table 11 : Increases in Capacity by CAV Technology..... | 75 |
| Table 12: Candidate Scenarios and Penetration Rates..... | 7682 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1: CAV Spreadsheet..... | 8 |
| Figure 2: Automated Vehicle system and Levels of Automation..... | 10 |
| Figure 3: CAV Literature Review Flow Chart..... | 12 |
| Figure 4: Diffusion Process of AVs for Individuals and TNCs | 14 |
| Figure 5: Automated Vehicle Adoption Scenarios in Iowa | 18 |
| Figure 7: Truck and Private Car Automation Adoption Scenarios | 20 |
| Figure 9: Approach to varying CAV capability..... | 27 |
| Figure 10: Safety Distances per CAV Capability | 27 |
| Figure 11: Theoretical and Simulated (Pipeline) Capacity for a Homogenous Freeway Segment | 28 |
| Figure 12: Pipeline capacity with CACC operation strategies | 29 |
| Figure 8: On-Ramp Capacity Improvement with CACC Market Penetrations | 30 |
| Figure 13: Traffic Analysis Tools..... | 52 |
| Figure 14: TF Resource - Autonomous Vehicles: Modeling Frameworks | 52 |
| Figure 15: Activity-Based (Left) and Trip-Based (Right) Travel Demand Model Improvements..... | 53 |
| Figure 16: Added Platooning Logic | 62 |

EXECUTIVE SUMMARY

Driverless cars have been of interest to futurists and technologists for many decades. With 21st century advances in computer hardware, communications systems, and innovative software development, there has been keen interest in applying those technologies to automating the driving function. Automated vehicles (AV) are vehicles that may be driven using varying combinations of human and machine decision making and control. Connected vehicles (CV) rely on wireless communication systems to exchange data among vehicles (Vehicle-to-Vehicle or V2V) and/or between the vehicles and the roadway infrastructure (Infrastructure-to-vehicle or I2V, and Vehicle-to-Infrastructure or V2I). When the automation and connectivity capabilities are combined in the same vehicles, they can be considered connected automated vehicles (CAV).

Expectations for the higher levels of automation (Levels 4 and 5 on the SAE J3016 Levels of Driving Automation) among the general public and politicians have been unrealistically elevated by media accounts that amplify the overheated marketing rhetoric of some industry spokespeople. Cooperative research, analysis, testing, and limited deployments have helped advance CAVs, even as the public maintains skepticism about full automation. Highly-publicized accidents in some of the demonstrations have fueled the skepticism while causing the developers, researchers at universities, and governments at all levels to focus their efforts on moving forward with CAV implementation while assuring safety and mitigating potential negative impacts of CAVs. Industry experts understand that the technical challenges of automating driving under the full range of roadway, traffic and environmental conditions (SAE Level 5) is far beyond the state of the art and will remain so for the foreseeable future. Thus, a very gradual rollout of automated driving features and an even more gradual expansion of the market penetration of these features among the vehicles on the road are expected.

In recent years, there have been many research papers and research reports relating to the technologies and potential impacts of CAVs. In completing the literature search and review for this project, CDM Smith prepared a multi-tab spreadsheet to provide overview information about each document included. Each document entry includes a summary of the contents as well as categorizations of key words related to the document. To make the spreadsheet easier to use, each document was assigned to one tab. For example, there are tabs for documents related to the congestion impacts or software/modeling among others (See Appendix B).

CAV Penetration Rates. There are many references that include assumptions about the timing and extent of technology adoption that may occur as CAVs are deployed. The assumptions and adoption rates are discussed in this report along with how those assumptions relate to modeling and analysis of CAV impacts.

Shladover and Greenblatt (2017) noted that CAV impact estimates are very sensitive to assumptions about the extent of usage of AV technologies, and noted three uncertainties related to market penetration:

- Pace of technological maturity
- Rate of inclusion of technology in new vehicles and retirement of old vehicles
- Extent of use of technology by consumers

Even after the initial highly automated driving applications become available for public use, their use is likely to grow gradually. The vehicles will be expensive for the foreseeable future because of the complexity of the needed sensor and software systems, and not all of the components will be available in mass production quantities. Advanced automotive technology features enter the market as options on a few high-end vehicles, but it can take decades from the first introduction until they become standard features on all new vehicles. This process took over 30 years for automatic transmissions, and about 25 years for power steering and air conditioning.

The average age of vehicles on the road in the U.S. today is around 12 years, which means that many vehicles are older than that, so even after all new vehicles are equipped with an advanced feature it will take a few more decades for the fleet to turn over so that the large majority of the vehicles in public use are equipped, sold, and used. Most past CAV research and projected penetration rates have been based on past technology implementations, expert knowledge of CAV technologies and projection methods, and analytical modeling. Gordon, Kaplan et al (2018) postulated several reasons why penetration rates and AV ownership may take longer to occur.

- Private ownership will continue, decreasing interest in shared AVs
- VMT will increase with AVs
- AV penetration may be slowed by political and regulatory issues
- Accidents may slow evolution of AV technology

Recommendation. To address the uncertainty of CAVs implementation rates, set up the simulations so that the market penetration level is an adjustable parameter and then vary that parameter to do sensitivity studies.

Impacts of CAV Technologies. Based on the findings of the studies reviewed in this project, most of which are speculative surveys or modeling analyses, impacts of CAVs are:

- CAVs have the potential to improve the capacity of the highway due to the shorter time headways which they can maintain in a platoon or string and the more stable vehicle-following dynamics. However, this is highly dependent on the market penetration rate, traffic volume, traffic management strategies, and the automated system capability.
- CAVs are expected to decrease the congestion considering the higher capacity which would be achieved due to the shorter time headways maintained by these vehicles. However, the mitigation in congestion is unlikely to occur with low penetration rates of CAVs.
- CAVs and AVs can reduce the travel time due to their behavior: smaller headways, and accurately tracking the speed profile of the lead vehicles. Moreover, dedicating a lane for CAVs allows for a higher possibility for platooning.
- AVs and CAVs can significantly increase safety and decrease the possibility and severity of accidents by eliminating human error, smoothing the traffic, and preventing shockwave formation and consequently stabilizing the traffic. However, literature lacks evidence-based

research resulting from field test experiments since CAVs are not yet deployed widely on the road network, and the existing simulation studies have been founded on dubious assumptions that cast significant doubt on the validity of their results.

- Most of the research that has been done to study the impact of AVs on travel behavior is based on data from stated preference surveys analyzed using discrete choice models methods.
- Based on analysis in the literature, AVs do not decrease vehicle ownership compared to regular vehicles.
- Value of travel time may be reduced as an impact of AVs, since travelers may be involved with other tasks than driving. However, this may not necessarily increase the productivity of the travelers during the trip, as some travelers are willing to continue watching the road when riding with an AV.
- It is expected that CAVs will reduce fuel consumption and emission due to their smoother driving behavior and also reduced congestion. Because of CAVs' situational awareness about surrounding vehicles, they are less likely to frequently accelerate or decelerate hard which increases emissions. On the other hand, the enhanced comfort provided by CAVs could potentially increase the VMT and consequently fuel consumption and emissions.

Recommendation: Research into various traffic impacts should continue with models until those impacts can be measured in field tests or initial operational implementation, which should be given priority.

Traffic Simulation of CAVs. Numerous evaluations have been completed for strategic-level decision making by states and MPOs in advancing awareness and preparation for CAVs. They have used a variety of tools and techniques, including Vissim and TransModeler described in this report, and forms of scenario planning to examine different assumptions about technologies and adoption rates of CAVs. Four state/regional studies were summarized: Austin (scenarios addressing capacity including mode shift to high-occupancy AVs), Puget Sound (examining roadway capacity with metropolitan data), Florida (corridor-focused using regional data), Iowa (corridor-focused on I-80); all successfully used scenarios with different technology or adoption rates and calculated expected vehicle miles traveled.

- Because Ohio Department of Transportation has used both Vissim and Transmodeler in previous transportation planning studies, the study team looked at the two models and what has been discussed about adjusting those models to analyze CAVs. Vissim is a traffic simulation model focused on the microscopic (individual vehicle, sub-1 second timescale) simulation of vehicles. Vissim has been used in several past cases to test the sensitivities of CAV technology. Some additional functionality, found in the literature, has been added of Vissim for CAVs. TransModeler is a traffic simulation software developed by Caliper Corporation, a member of the study team and co-authors of the report. The software is capable of simulation at multiple resolutions – macroscopic, mesoscopic, and microscopic – but is principally used for microsimulation for planning, design, and engineering. TransModeler was modified for use in a Federal Highway Administration (FHWA) project and was used to analyze Jacksonville FL regional data.

Recommendation: Industry and government should summarize completion of the PTV-identified modifications that would allow Vissim to model the impacts of CAVs. TransModeler adjustment as

documented in an FHWA report should also be reviewed and built upon. In addition, there should be comparisons with the PTV changes and those identified by the tfresource wiki, and additional model improvements made as appropriate, while involving stakeholders in the analyses. It is important to not duplicate effort and for the modeling community to collectively move forward with model improvements.

Risk and Uncertainty in CAVs. CAVs introduce deep uncertainty that has the potential to be disruptive and transformational. CAVs, if or when they come to pass, may fundamentally alter the way the public perceives and experiences travel, with ripple effects on how traffic flows and how land uses are developed in response to changes in traveler behavior. Techniques for managing CAV uncertainty in transportation planning include scenario planning tools and Exploratory Modeling and Analysis (EMA) for exploring the possible futures with CAVs. Scenario planning involves making assumptions about those variables whose values are uncertain and modeling a variety of future conditions to better understand what outcomes are possible.

EMA seeks to structure the approach to scenario planning in a systematic way that uses sensitivity analysis to explore patterns in model results to reduce the range and number of asserted model input values and scenarios. Whereas scenario planning can produce a picture of a relatively small number of possible futures, it does not necessarily illuminate the relationship between the different assumptions and possible futures. EMA seeks to uncover the patterns or relationships in the system to provide more guidance to decision-makers about how their decisions might shape the future.

Whatever modeling is used, it is important that stakeholders are continually involved and invested in the vision and the planning process. Involving stakeholders and paying attention to what others have done in CAV analysis will help position ODOT to manage and reduce uncertainty and to make better-informed decisions.

The FHWA study Stabler, Bradley, Morgan, Slavin, and Haque, 2018 used an integrated dynamic traffic assignment (DTA) model and activity-based model (ABM) to explore the relationships between AV adoption, traveler behavior, and the operational benefits of AVs and served as a demonstration of a framework for using EMA in regional transportation planning and of adjusting existing models, in this case TransModeler, to account for CAV characteristics.

Recommendation: The study team recommends that ODOT embrace the proposed modifications to Vissim and TransModeler included in this report and that they carefully review and take advantage of experience gained in Iowa, Florida, and other states in analyzing the applicable Ohio corridors.

LIST OF ACRONYMS

| | |
|----------|---|
| ABM | Activity Based Model |
| ACC | Adaptive Cruise Control |
| API | Application Programming Interface |
| AV | Automated vehicle |
| BSM | Basic Safety Message |
| CACC | Cooperative Adaptive Cruise Control |
| CALTRANS | California Department of Transportation |
| CAV | Connected and automated vehicle |
| COM | Component Object Model |
| CV | Connected Vehicle |
| DCE | Discrete Choice Experiment |
| DLC | Discretionary Lane Change |
| DRS | Dynamic Ride Sharing |
| DSRC | Dedicated Short Range Communications |
| DTA | Dynamic Traffic Assignment |
| DVE | Driver Vehicle Entity |
| EMA | Exploratory Modeling and Analysis |
| EIDM | Enhanced Intelligent Driver Model |
| FHWA | Federal Highway Administration |
| I2V | Infrastructure to Vehicle |
| IDM | Intelligent Driver Module |
| IT | Information Technology |
| MAAS | Mobility as a Service |

ML Managed Lane

MPO Metropolitan Planning Organization

MV Manual Vehicle

NCHRP National Cooperative Highway Research Program

NHTSA National Highway Traffic Safety Administration

ODOT Ohio Department of Transportation

OEM Original Equipment Manufacturer

PAV Private Automated Vehicle

PEL Planning and Environmental Linkage

PSRC Puget Sound Regional Commission

RFP Request for Proposal

SAE SAE International (formerly Society of Automotive Engineers)

SAV Shared Automated Vehicle

SSAM Surrogate Safety Assessment Model

TJA Traffic Jam Assist

TMC Transportation Management Center

TNC Transportation Network Company

TRB Transportation Research Board

USDOE United States Department of Energy

USDOT United States Department of Transportation

V2I Vehicle to Infrastructure

V2V Vehicle to Vehicle

V2X Vehicle to Everything

VAD Vehicle Awareness Device

VANET Vehicle Ad-hoc Network

VMT Vehicle miles travelled

1. INTRODUCTION

1.1 Requirement

The Ohio Department of Transportation (ODOT) contracted with the CDM Smith Inc. team and Caliper Corporation for a collaborative effort to improve the ability to consider impacts of connected and automated vehicles (CAV) on future transportation investments in Ohio. More specifically, ODOT asked CDMS and Caliper to provide

- (1) a synthesis of CAV research documented in the literature tailored to capturing the effects of such vehicles on performance with traffic simulation, and
- (2) the modification and enhancement of two traffic simulation models based on the findings of the synthesis to better evaluate the potential impacts of CAVs on various highway conditions.

1.2 Task Order Objective.

ODOT's objective is to prepare a report that will:

- (1) Define CV, AV, and CAV technology penetration rates
- (2) Determine effects of CV, AV, and CAV technologies on several measures of performance at various penetration rates
- (3) Identify modifications that could be implemented to Vissim and TransModeler software analysis models in order to portray CV, AV, and CAV technologies at various penetration rates
- (4) Recommend means to assess the risks of uncertainty in CV, AV, and CAV implementation on ODOT's policies and projects.

1.3 Literature Review Project Overview

Automated vehicles (AV) are vehicles that may be driven using varying combinations of human and machine decision making and control. The different allocations of driving roles between human and machine have been defined in terms of levels of automation in SAE J3016 (see more details and a diagram in the next section), and those allocations will vary depending upon the conditions in which the vehicle is driven. The usage of the terms "automated vehicles", "autonomous vehicles" or "self-driving vehicles" has not been consistent in the literature. In some cases, they refer to vehicles operating at any of the levels of automation, but in other cases they refer only to vehicles operating at the higher levels of automation, which can create considerable challenges in comparing findings across different published works. Connected vehicles (CV) rely on wireless communication systems to exchange data among vehicles (V2V) and/or between the vehicles and the roadway infrastructure (I2V and V2I). When

the automation and connectivity capabilities are combined in the same vehicles, they can be considered connected automated vehicles (CAV).

In recent years, there have been many research papers and research reports relating to the technologies and potential impacts of CAVs. Notably, the Transportation Research Board (TRB) and the U.S. Department of Transportation (USDOT) have sponsored several studies that address aspects of the ODOT objectives noted above. Many of the research papers and TRB studies have been prepared by universities such as the University of California Berkeley, Texas A&M Transportation Institute, and the University of Texas Austin, often working with teams of trucking companies, consultants, and Federal, state, and local government organizations. Of particular note is the National Cooperative Highway Research Program (NCHRP) 20-102 series of papers, the most recent being *Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles, Volume 2: Guidance* (Zmud et al, 2018). There are also some privately-funded and conducted analyses of CAV, including the Victoria Transportation Policy Institute, Bloomberg Philanthropic Group, Rand Corporation, and Ford Motor Company. The challenge in this current project for ODOT was to decide which documents to cite and how to synthesize the information in the various reports. The team concentrated on documents since 2014.

CDM Smith prepared a multi-tab spreadsheet (see **Appendix B**) to provide overview information about each document included. The tabs were for various key words in the analysis of CAV including some impacts, software, technologies, and more general AV information addressed in a document. Figure 1 shows an excerpt from the spreadsheet. Each document entry includes a summary of the contents as well as categorizations of key words related to the document. To make the spreadsheet easier to use, each document was assigned to one tab. For example, there are tabs for documents related to the congestion impacts or software/modeling among others.

Figure 1: CAV Spreadsheet

| Basic Information | | | | | | Summary of Contents | Scenario (Penetration Rate) | Impact |
|--|--|---|--|---|------|--|-----------------------------|-------------|
| Title | Published on (book/journal) | Document URL | Organization | Author | Year | | | |
| Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies | Transportation Research Part A: Policy and Practice Vol. 95 p49-63 | https://www.sciencedirect.com/science/article/pii/S0965856415300628 | University of Texas | Prateek Bansal, Kara M. Kockelman | 2017 | <ol style="list-style-type: none"> 1. This study created a simulation-based fleet evolution framework to forecast Americans' long-term (year 2015–2045) adoption levels of CAV technologies. The simulation runs eight different scenarios based on 5% or 10% annual drops in technology prices and 0%, 5%, or 10% annual increments in Americans' willingness to pay. 2. Results show that the privately held light-duty-vehicle fleet will have 24.8% Level 4 AV penetration by 2045. In the study an annual 5% price drop and constant willingness to pay values (from 2015 forward) are assumed. This share jumps to 87.2% if one uses a 10% annual rate of decline in prices and a 10% annual rise in willingness to pay. | Multiple | |
| Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore | Transportation Research Part A: Policy and Practice 113: 125–136. | https://www.sciencedirect.com/science/article/pii/S096585641730681X | Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University | Yu Shen, Hongmou Zhang, and Jinhua Zhao | 2018 | <ol style="list-style-type: none"> 1. This article details a simulation of an integrated autonomous vehicle and public transportation system. 2. Under the simulation's set of assumptions on AV operation costs and dispatching algorithms, the results show that the integrated system has the potential of enhancing service quality, occupying fewer road resources, being financially sustainable, and utilizing bus services more efficiently. | Multiple | Traffic Per |

The spreadsheet was designed to be a continually-useful tool, so that additional documents can be added as desired. The team found in its work that new documents came to light almost every day in this fast-changing field. The Excel spreadsheet allows additional tabs to be created in the future, for future projects with a different or more detailed focus.

In its research, the team also found that a number of the documents contained literature searches (for example Zmud et al. 2018 cited above and *Connected and Automated Vehicle Concept Dimensions and Examples*, Shladover and Greenblatt UCal Berkley for USDOE 2018). Since this project focuses on

modeling of CAVs for state transportation network investment, the team did not attempt to include all documents about CAV, so the search and documents in the spreadsheet do not necessarily duplicate the searches in past studies. Many reports and documents discuss the need to modify models, or the potential impacts of CAVs derived from such activities. However, few of the documents found have actually dived into what modifications are needed to the various models. Mahmassani, Elfar, Shladover et al, 2017 developed high level requirements for analyzing the impacts of CAVs. RSG and Caliper collaborated on a report for USDOT (Stabler, Bradley, Morgan et al., 2018) and two presentations in 2017 and 2018 about model modifications they did in a CAV study in Jacksonville, FL. (Bradley, Slavin, and Morgan, 2017) and (Bernardin, 2018). Zmud et al. 2018 had separate chapters on adaptation of trip-based models, disaggregate/dynamic models, and strategic models to analyze the impacts of CAVs.

It is also important to note the relevant Travel Forecasting Resource AV wiki ([http://tfresource.org/Content/Charrette: Autonomous Vehicles](http://tfresource.org/Content/Charrette:AutonomousVehicles)). Created by a group under the Travel Demand Forecasting Committee of the Transportation Research Board, the wiki provides useful information and insights into needed adaptations of existing transportation planning models, including several state or regional studies that addressed automated vehicles in their planning. Since ODOT has expressed an interest in making this project report a living document that it can update as time goes along, the agency may wish to merge new information into the existing wiki or create its own updating process. In any case, the team found the wiki to be helpful.

1.4 Overview of Current Activities in CAV

Driverless cars have been of interest to futurists and technologists for many decades. With 21st century advances in computer hardware, communications systems, and innovative software development, there has been keen interest in applying those technologies to automating the driving function. Cooperative research, analysis, testing, and limited deployments have helped advance CAVs, even as the public maintains skepticism about full automation. Highly-publicized accidents in some of the demonstrations have fueled the skepticism while causing the developers, researchers at universities, and governments at all levels to focus their efforts on moving forward with CAV implementation while assuring safety and mitigating potential negative impacts of CAVs. Every day new articles and reports about CAVs appear in the popular and trade press. Figure 2 provides the Society of Automotive Engineers and Federally-accepted definitions of the five levels of automation and the definition along with some additional information about the respective roles of the human driver and the automated technologies. This 2018 version of the SAE levels took the SAE task force that developed the definitions at least six months to reach agreement on the precise wording in this new chart to minimize the likelihood of misunderstandings.

Figure 2: Automated Vehicle system and Levels of Automation



SAE J3016™ LEVELS OF DRIVING AUTOMATION

| | SAE LEVEL 0 | SAE LEVEL 1 | SAE LEVEL 2 | SAE LEVEL 3 | SAE LEVEL 4 | SAE LEVEL 5 |
|--|---|--|--|--|--|---|
| What does the human in the driver's seat have to do? | You are driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering | | | You are not driving when these automated driving features are engaged – even if you are seated in “the driver's seat” | | |
| | You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety | | | When the feature requests, you must drive | These automated driving features will not require you to take over driving | |
| What do these features do? | These are driver support features | | | These are automated driving features | | |
| | These features are limited to providing warnings and momentary assistance | These features provide steering OR brake/acceleration support to the driver | These features provide steering AND brake/acceleration support to the driver | These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met | This feature can drive the vehicle under all conditions | |
| | <ul style="list-style-type: none"> • automatic emergency braking • blind spot warning • lane departure warning | <ul style="list-style-type: none"> • lane centering OR • adaptive cruise control | <ul style="list-style-type: none"> • lane centering AND • adaptive cruise control at the same time | <ul style="list-style-type: none"> • traffic jam chauffeur | <ul style="list-style-type: none"> • local driverless taxi • pedals/steering wheel may or may not be installed | <ul style="list-style-type: none"> • same as level 4, but feature can drive everywhere in all conditions |
| Example Features | | | | | | |

Source: <https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles>

CAVs are developing rapidly, and according to a TRB-sponsored 2018 study (Zmud et al, 2018) published in December 2018, manufacturers and shared fleet operators are involved in at least 17 shared automated vehicle (SAV) pilots in eight states in current deployment. In June 11, 2019 remarks before an Uber-sponsored event in Washington DC (Etherington, TechCrunch June 11, 2019), the Secretary of Transportation noted that there are more than 1,400 “self-driving cars, trucks and other vehicles” are currently in testing by more than 80 companies across 36 U.S. states, plus DC itself. (But it is important to recognize that none of 17 SAV deployments or other on-road tests is actually operating without constant supervision by a safety driver, so although they are aiming for Level 4 automated driving, they are actually being operated at Level 2). Many states have taken steps to adjust their regulatory and policy structure to accommodate the pilots. The Federal government has issued guidance, most recently as AV 3.0, to help facilitate CAV development while maintaining public safety. Because of the central role the automobile plays in transportation in the U.S., a very gradual rollout of automated driving features and an even more gradual expansion of the market penetration of these features among the vehicles on the road should be expected. Industry experts understand that the technical challenges of

automating driving under the full range of roadway, traffic and environmental conditions (SAE Level 5) is far beyond the current state of the art and will remain so for the foreseeable future.

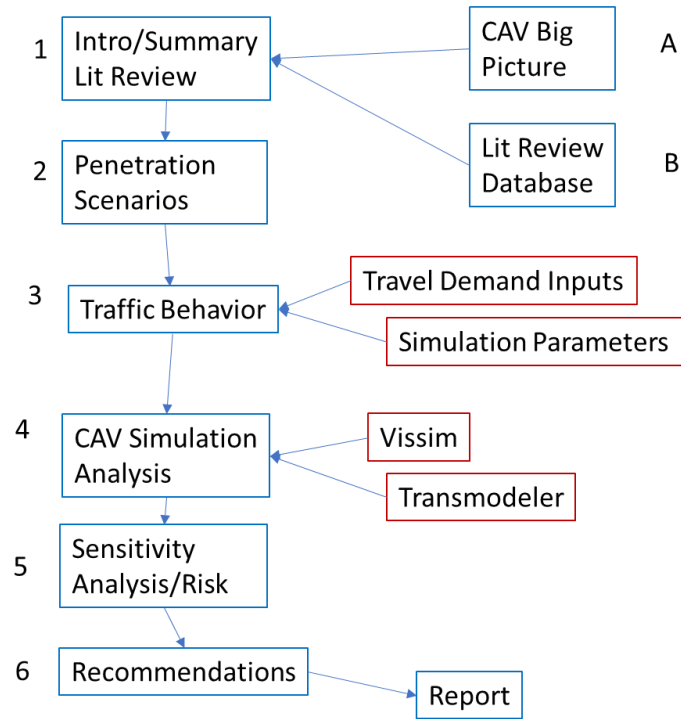
While pilot testing is important to prove CAV technologies and introduce the public to CAV capabilities, the testing is not sufficient for states and MPOs to plan for widespread CAV implementation. Planning requires traffic, economic, and demographic data and models of trips by various modes based on assumptions about the future. According to Zmud et al 2018, the basic tenet of CAV planning and modeling is uncertainty of implementation of this new and evolving technology. As time passes, the relevancy of current data becomes less. Therefore, predictive modeling is more valid for the shorter term, while exploratory modeling is useful for long-term planning. In any case, current models built around current modes and vehicles with drivers cannot adequately analyze CAVs. Therefore, updates to modeling and forecasting tools will be necessary to more appropriately account for the expected impacts of automated vehicles (AVs) and connected vehicles (CVs). (Zmud et al. 2018) These modeling updates are the subject of Sections 4 and 5 of this report.

The TRB effort, other research, as well as this current project for ODOT are aimed at identifying changes that are needed in traffic analysis models to address the impacts of CAV.

1.5 Organization of This Report

Figure 3 shows the flow and relationship among the various sections of this report. Supporting the Executive Summary and overview information in this section are two documents included in the appendices: the “Big Picture” overview of CAVs and the spreadsheet of documents found during the literature for this project. Section 2 covers the importance of analyzing multiple penetration rates of CAV. Section 3 deals with the impacts of CAV on modeling, by looking at traffic behavior and some of traffic demand modeling inputs that would be needed for models. It also notes potential output ranges (based in part on various CAV penetration rates) of impact parameters that can become inputs to the simulation models in the next section. Section 4 looks at the simulation models and what changes or additions are needed to analyze CAVs. The output of section 4 is the changes and/or settings needed in models, especially Vissim and TransModeler. Section 5 includes reasonableness checks and the kinds of sensitivity or risk analysis needed to interpret the simulation results. Section 6 contains recommendations from the team to help move CAV analysis in simulation modeling forward.

Figure 3: CAV Literature Review Flow Chart



2. CAV PENETRATION RATES

Most studies of the future of CAV agree on one thing: there is uncertainty as to when there will be widespread implementation of automated vehicles that are capable of operating at the higher levels of automation. Indeed, Stabler, Bradley, Morgan et al (2018) listed penetration rate as the highest priority assumption – and uncertainty – to include in modeling of CAVs. That report noted that simulating the effect of AVs on the network requires predicting whether each auto trip is made in a conventional vehicle or AV. State transportation plans usually look 30 or more years in the future.

Shladover and Greenblatt (2017) noted that impact estimates are very sensitive to assumptions about the extent of usage of AV technologies, and noted three uncertainties related to market penetration:

- Pace of technological maturity
- Rate of inclusion of technology in new vehicles and retirement of old vehicles
- Extent of use of technology by consumers

Even after the initial highly automated driving applications become available for public use, their use is likely to grow gradually. The vehicles will be expensive for the foreseeable future because of the complexity of the needed sensor and software systems, and not all of the components will be available in mass production quantities. Advanced automotive technology features enter the market as options on a few high-end vehicles, but it can take decades from the first introduction until they become standard features on all new vehicles. This process took over 30 years for automatic transmissions, and about 25 years for power steering and air conditioning (all of which were simpler and less expensive than higher levels of automation).

The average age of vehicles on the road in the U.S. today is around 12 years, which means that many vehicles are older than that, so even after all new vehicles are equipped with an advanced feature it will take a few more decades for the fleet to turn over so that the large majority of the vehicles in public use are equipped (and just because they are equipped provides no guarantee that the vehicle owners will actually choose to use the feature). A significant portion of the population is likely to remain resistant to automation even after it is widely available and affordable, so it is not realistic to expect the disappearance of human-driven vehicles, even in the long term. The question this raises is: When will this gradual growth occur and what effect will that have on the future? This section highlights some of the research and observations about CAVs that are found in the literature.

2.1 CAV Penetration Rates in the Literature

Talebian and Mishra (2018) provide a comprehensive overview of past research on adoption rates of technology innovations including CAVs. They note that research and projected rates have been based on past technology implementations, expert knowledge of CAV technologies and projection methods, and analytical modeling, such as those described later in Section 4. Their particular research was on the

Theory of Diffusion in which communications among peers and through social networks and advertising over time helps increase adoption rates of any technology.

Gordon, Kaplan et al (2018) in their analysis based on past technology adoption take issue with some other researchers who predict that the introduction of AVs will mostly take place through the shared economy and reduce the proportion of private vehicle ownership. Based on the introduction of computers, smart phones, and similar products, the authors take a position that private ownership of AVs is likely to continue for a long period of time (a number of decades), leading to higher vehicle miles travelled (VMT) than some other researchers estimate. The authors used a threshold model that showed for numerous older technologies that Individuals learn about technologies from trend-setters, but then make the decision about whether to adopt themselves. The personal decision is influenced by differences in a person needs and circumstances as well as external events such as accidents. We saw this with the Three Mile Island accident that slowed nuclear power expansion and, more recently, with the AV fatal accident in Chandler, Arizona. The authors found that more cars are likely to be purchased by individuals than TNCs, at least for many decades. Geographic dispersion of the population, even with some cities showing a resurgence in their population, tends to favor AV use. In addition, auto companies are likely, as they have in the past, to produce multiple models and versions of AVs to appeal to the various types of car buyers. And there will be new users of AVs such as the disabled or young. The authors identified several reasons why penetration rates and AV ownership may take longer to occur.

- Private ownership will continue, decreasing interest in shared AVs
- VMT will increase with AVs
- AV penetration may be slowed by political and regulatory issues
- Accidents may slow evolution of AV technology

Figure 4: Diffusion Process of AVs for Individuals and TNCs

Source:

Zmud et al, 2018 included a chapter on uncertainties associated with CAVs that will affect the ability to predict when CAVs will be widely deployed. The uncertainties they listed include:

- The cost of the technology will certainly drive the rates of adoption.
- Whether the technology is used in privately held vehicles or through private corporations supplying fleet services will drive the rate of market penetration.
- On-road testing of CAVs continues, but actual usage safety statistics and experience will drive public attitudes about the technology.
- Comfort and convenience, in addition to cost, will drive consumer preferences regarding AVs.
- Roadway and parking infrastructure will need to be adapted to CAVs.
- Government policy and traffic laws, including tests of liability in the court system, will undoubtedly drive market penetration scenarios.
- The technology will certainly advance and change, and features will be added or subtracted on the basis of cost effectiveness in the market.

The Zmud report emphasized the uncertainty about CAV development. Their review of the literature, which was corroborated by the study team for this current report, found high uncertainty in published deployment scenarios. They defined three “eras” during which varying but increasing rates of CAV penetration will occur:

1. CAVs are developed and tested.
2. Consumers begin to adopt CAVs.
3. CAVs become the primary means of transport.

They went on to note that the industry does not have enough information to provide exact timing and details for the start and end of these eras. They state on page 12 that “There will be a long period of time (perhaps three to four decades or more) with a mix of human-driven vehicles and CAVs on the roadways.” While acknowledging that “this is not a consensus view,” the authors include a number of expectations and general forecasts of what will occur within each era. See page 12 in the Zmud report.

Table 1 includes penetration rates from several documents included in the team’s literature search. The table includes comments about uses made of, or conclusions reached, in the research documentation.

Table 1. Typical Penetration Rates from the Literature

| Document | Penetration Rates or Scenarios | Comment |
|-------------------------------------|---|---|
| Kockleman 2017 | 8 scenarios related to price, willingness to pay, government regulations | Used survey results to look at demand side of AVs. Simulated adoption rates into 2045 as people become more used to AV technologies. No consideration of technological realities that will constrain the supply side (when the AV systems of varying capabilities will actually become available). |
| Workforce 2018 | Scenarios related to private AV ownership versus shared use. Level 5 automated trucking 100% in 2045. Level 4 trucking 100% in 2031. | Emphasis was on the impact of AVs on jobs gained or lost from automation and geographic dislocation, but unfortunately the analysis was based on assumptions about the levels of automation in trucking that do not adequately address the reality of technological constraints. There is too much unrealistic optimism in the timeframes chosen. |
| RSG EMA Modeling 2018 | 3 levels of AV penetration with changes in level of AV ownership and types of household trips, and amount of shared use. | Used data for Jacksonville FL and included modifications to Daysim and TransModeler software. Included analysis of dedicated lanes for AVs. Levels of AV penetration were arbitrary a priori assumptions. |
| Bernardin 2018 | 80% CAV, 50% shared and 100% CAV, 65% shared | Used data from Burlington VT and adjustments to traffic modeling software. Increased VMT at 80%, but decrease at 100%. But unfortunately based on arbitrary assumptions about percentages of CAV and shared vehicles. |
| Litman 2018 | Scenarios about prices of AVs, increases in the amount of travel, and amount of shared use | Includes discussion of impacts on planning of implementation of AVs over the decades |
| Stanek, Huang, Milam, and Wang 2017 | AV percentages of 0, 10, 30, 50, 70, 90, and 100 percent in modeling. Defined parameters to define impacts of AVs on travel behavior. | Used data from a California interchange and an oft-congested California highway segment. Arbitrary assumptions about different levels of market penetration in different future years. |
| I-80 Study in Iowa 2017 | Early AV Adoption (20% in 2025), Rise of the AVs (50% in 2030), Limited AV Adoption (20% in 2040), and AV Domination (85% in 2050) | Arbitrary assumptions about different levels of market penetration in different future years. Results applied to planning of future roadway enhancements on I-80. |

A study team observation is that most of the above and other studies that address variations in market penetration percentages, chose a wide range of hypothesized market penetration levels, without underlying analyses to consider the mechanisms of market growth and the constraints on rate of market growth. This is a significant limitation in virtually all the published literature that cites a range of market penetrations for CAVs or AVs because there is no scientific data available to show when the more advanced CAV features will be introduced to the market, nor how quickly their shares of new vehicle purchases or actual usage on the road will grow.

Studies that rely on analogies to the information technology (IT) industry and the growth of markets such as mobile phones fail to account for the fundamental differences between mobile phones and vehicles in terms of capital costs, product development cycle length, and durability of the product itself. Studies of the rate of change in the vehicle market have shown that major high-cost automotive features such as automatic transmissions and air conditioning took several decades to advance from market introduction on a few premium vehicles to becoming standard equipment on all new vehicles. Even after automotive features dominate the new vehicle market, it takes additional decades for the vehicle fleet to turn over so that they dominate the population of vehicles on the road (for example, the average age of vehicles on the road in the U.S. is about 12 years). These factors were accounted for in the report by Shladover and Greenblatt, 2018 which showed a very large range of uncertainty between the optimistic and pessimistic predictions of the usage of a variety of CAV features in the years 2030 to 2050.

2.2 Summary of other State Studies Involving CAV and Impacts

This is not an exhaustive list, but rather is a sampling of four that have been documented. Readers are encouraged to look up more details about these state studies.

- **Michigan** – Included in RSG presentation (Bernardin, 2018). Statewide flow modeling using AirSage and advanced trip-based passenger models. Statewide model being updated in 2018 to include CAVs. Both private and shared AVs included in analysis for mode share and trip length. Michigan is also home to automakers and their AV activities and significant testing programs and facilities.
- **Puget Sound** – discussed in tfresource wiki. Puget Sound Regional Council (PSRC) analyzed four CAV-related scenarios using their activity-based model system. They did not define CAV technology or penetration rates directly, but made assumptions about road capacity, time in vehicle, parking costs, and shared-use AVs through ride-sharing companies.
- **Texas** – discussed in tfresource wiki. Dealt with the Capital Region in Austin and used a four-step trip-based modeling system. Researchers at Texas A&M defined six scenarios of increasing lane capacity, based around assumptions of CAV use and impact and shifts of transit trips to shared use AVs. These scenarios were compared with the most recent regional transportation plan for the area with a 2040 forecast. The wiki write-up noted that the changes imposed on network capacity and modal trip tables do not directly represent CAV impacts, but mimic the potential impacts that may result. Further, the study is meant to show the sensitivity in the models to changes in variables that are expected to be significant for CAV travel behavior and did not directly model CAV impacts.
- **Iowa** – documented in study about AV impacts on I-80. Used Planning and Environmental Linkage (PEL) Study process to model potential future impacts, especially quality of peak traffic service, traffic safety and travel time reliability. Iowa initiated an AV initiative in conjunction with its state universities to “develop a platform for connecting and guiding AVs based on high-definition (HD) dynamic mapping, predictive travel modeling and a cloud-based communications

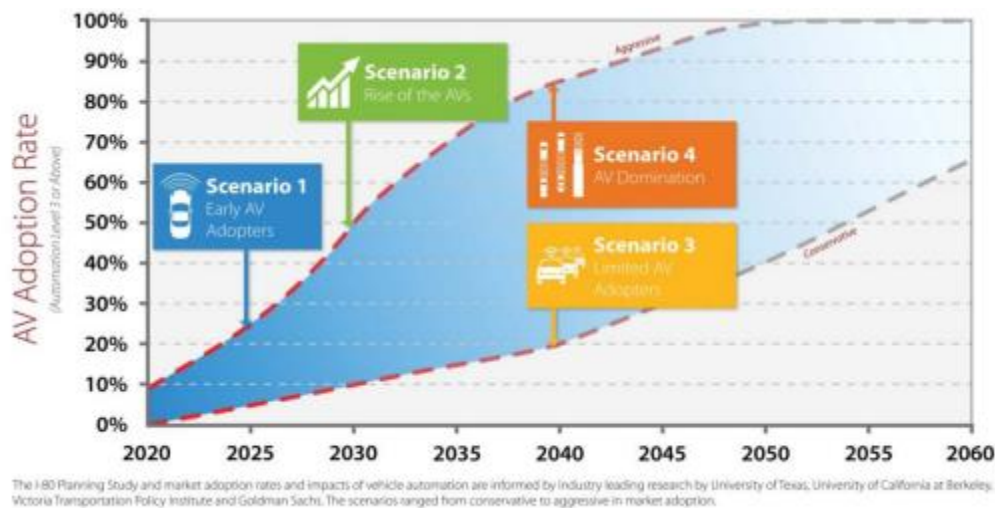
network.” The initiative defined 4 implementation scenarios for AVs. Information in a graphic of penetration rates is included below.

2.3 CAV Adoption Scenarios in Published Planning Efforts

This section discusses some of the approaches that have been taken to modeling future CAV scenario approaches in published planning efforts.

As noted in the table in an earlier subsection, the state of Iowa, with consultant HDR, in its study of the I-80 corridor used four scenarios to represent different AV penetration rates (Interstate 80 Planning Study (PEL) Iowa DOT, 2017). From its review of literature, Iowa DOT and HDR concluded that AV technologies can lead to major improvements in safety, accessibility and capacity. As a result, the level of AV technology adoption (Level 3 and above) was selected as a key factor in the scenario planning, along with 3 other key factors: millennial travel behavior, smart truck parking, and aging population. In terms of AV adoption rates, scenarios 1, 2, and 4 assumed “aggressive” adoption whereas scenario 3 was “conservative.” The adoption rate for scenario 1 assumed 20% adoption of AVs in 2025, scenario 2, 50% in 2030, scenario 3, 20% in 2040, and scenario 4, 85% in 2040. It should be noted that adjustments for the impacts of AVs were made in the analysis tools based on modeling results in the literature, specifically in number of trips, vehicle miles traveled, roadway capacity and crash frequency. The scenarios are shown in Figure 5.

Figure 5: Automated Vehicle Adoption Scenarios in Iowa



Source: Iowa DOT and HDR, Interstate 80 Planning Study June 2017

For FHWA, ICF has studied the impacts of the adoption of AVs. They created six adoption scenarios to which they applied scenario planning exploratory modeling techniques to look at the impacts variations in AV penetration rates for 2035. The scenarios and the ICF analysis techniques were discussed in a September 2018 presentation to the Association of Metropolitan Planning Organizations (Twaddell, 2018). Table 2 describes the scenarios and the various technology adoption rates in each scenario. ICF made assumptions about the extent of adoption of vehicles with Automation Level 2, 3, and 4, and in two of the scenarios assumed increases in shared use vehicles for increased mobility as a service. The

ICF work included increased truck platooning in some scenarios, but they are not shown in the table since the primary focus of the current report is CAVs.

Table 2: CV/AV Adoption Scenarios for 2035

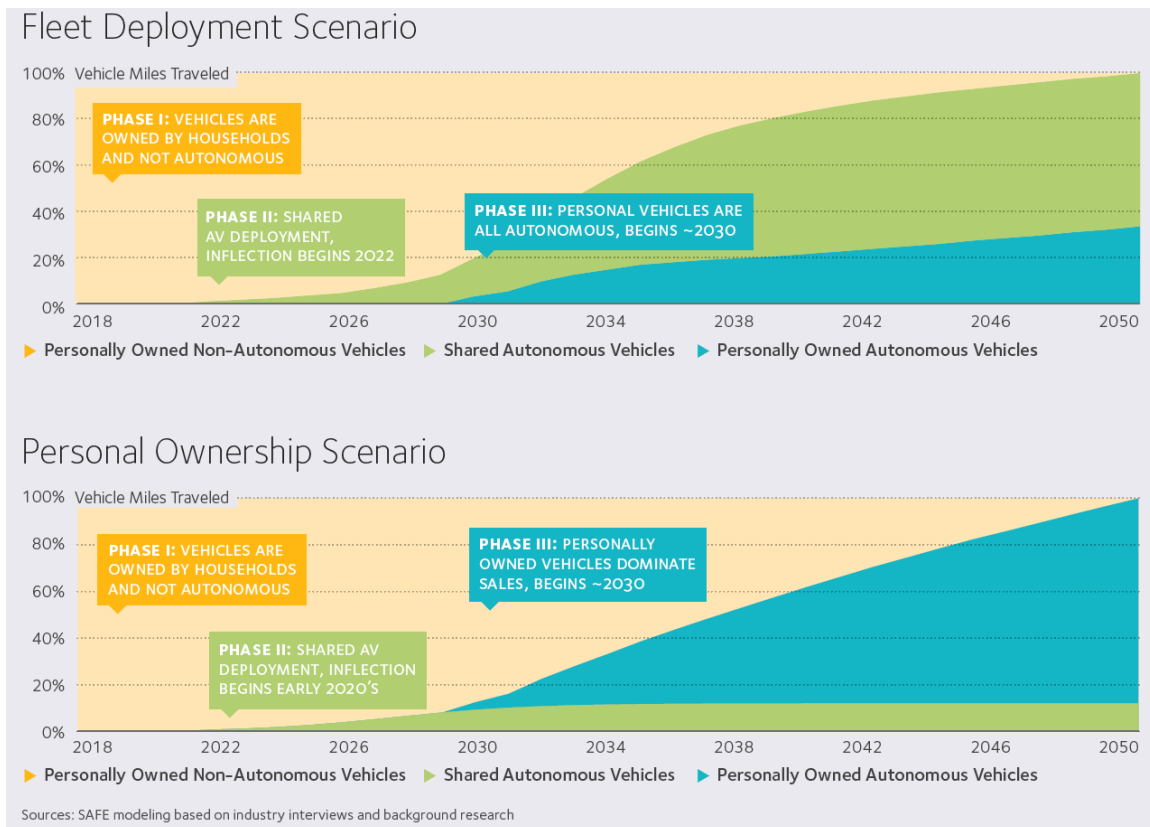
| Scenarios and Parameters | Slow Roll or Baseline | Niche Service Growth | Ultimate Traveler Assist | Managed Automated Lanes | Competing Fleets | Automated Integrated Mobility |
|--------------------------|--|---|--|---|---|--|
| Subtitle | Minimal Plausible Change | High CV/AV in Certain Cases | Ultra connectivity | AV Lane Networks | Automated TNC Fleets Compete | Automated Mobility as a Service |
| Scenario Description | <i>Minimal change beyond currently available technology and investments already in motion including advances in safety technology, TSMO, and mobility services</i> | <i>Innovation proliferates, but only in special purpose or Niche applications</i> | <i>CV technology progresses rapidly, but AV adoption stagnates</i> | <i>AV travel is consolidated to a large-scale lane network with significant consumer adoption; certain lanes become integrated with CVs and AVs</i> | <i>TNC-like services proliferate rapidly, but compete with each other and do not operate cooperatively Level 4 AV is safe for most trips.</i> | <i>On demand shared services proliferate and integrate with other modes via cooperative data sharing, policies, and infrastructure</i> |
| Level 2 adoption | 30-40% | 30-40% | 30-40% | 30-40% | 70% | 70% |
| Level 3 adoption | NA | NA | NA | 20% | 70% | 70% |
| Level 4 adoption | NA | Some campuses | NA | available but rare | 70% | 70% |
| V2X adoption | 40% | 40% | 85% | | 75% | 75% |
| Private Ownership | Continues | Continues | Continues | Continues | Reduced in cities and suburbs | Reduced in cities and suburbs |
| Mobility as a service | 5-20% | | 5-20% | 5-20% | Increased TNC w/o central management | Increased TNC w/ public role |
| EV Use | NA | NA | NA | NA | Increased, especially w/ TNC | Increased, especially w/ TNC |

Source: CDM Smith derived from information in Twaddell presentation to Association of Metropolitan Planning Organizations, September 28, 2018

Amitai Bin-Nun, Alex Adams, and Jeffrey Gerlach (2018) *America's Workforce and the Self-Driving Future: Realizing Productivity Gains and Spurring Economic Growth* is a compilation of AV-related impact analysis that explores the impacts on jobs in the U.S. as AVs are implemented, including new

transportation-related jobs as well as jobs lost to advancing technology and how AVs are used – and the timeframe in which that implementation occurs. Figure 6 was drawn from the report’s discussion of truck and private car automation. The figure and the analysis contrast private ownership with shared use of AVs in fleets, but both analyses were based on unrealistically optimistic assumptions about the maturity of the technology needed to support the higher levels of automation.

Figure 6: Truck and Private Car Automation Adoption Scenarios



Source: Amitai Bin-Nun, Alex Adams, and Jeffrey Gerlach (2018) *America’s Workforce and the Self-Driving Future: Realizing Productivity Gains and Spurring Economic Growth*

Liu, H., Kan, et al (2018c) used several penetration rates to analyze the effect of CAVs on roadway capacity. This study assessed the traffic impacts at each possible market penetration. The report found that penetration rates lower than about 60% did not result in much road improvement, but that 100% penetration increased capacity by 90%. As will be discussed in subsequent sections of this report, and as noted from several sources cited earlier in this section, additional research is needed to incorporate AV characteristics into traffic modeling. What is clear from the literature cited is that there are multiple factors that influence the timeline for full AV implementation.

After reviewing the documents above, along with many others found in the course of the literature search, the study team developed Table 3 to display and briefly describe eight scenarios that ODOT may wish to analyze in the three road projects currently being considered (Ohio Turnpike, U.S. 33 corridor, and the Ohio River bridge crossing in Cincinnati). The eight scenarios start in the near term, building on the current and anticipated pilot implementations throughout the U.S. and in countries such as Japan,

China, the United Kingdom, and the European Union. The later scenarios have an analysis date of 2050 and include different penetration rates, as well as assumptions about proliferation of mobility as a service.

Table 3: Candidate Scenarios and Penetration Rates

| Scenario | Target Year | Penetration Rate | SAE Level 3 Rate | SAE Level 4-5 Rate |
|----------------------------|-------------|------------------|------------------|--------------------|
| Pilots proliferate | 2025 | 5% | 4% | 1% |
| Private AVs | 2030 | 10% | 6% | 4% |
| Shared and private AVs | 2035 | 20% | 10% | 10% |
| More AVs, some Level 5 | 2040 | 50% | 25% | 25% |
| More MAAS and more Level 5 | 2045 | 80% | 16% | 64% |
| More Level 5 | 2045 | 100% | 10% | 90% |
| No more Manual Vehicles | 2050 | 100% | 5% | 95% |
| Widespread MAAS | 2050 | 100% | 0% | 100% |

Source: CDM Smith

Table 3 could be considered a starting point. Scenarios need stakeholder input, so ODOT should carefully review potential scenarios with local and regional officials involved with the location being analyzed. An option ODOT may wish to consider adding to the scenarios where automated vehicles are increasing and manual vehicles are decreasing is connected trucks. The connected truck scenarios could apply truck platooning and other freight improvements that have positive economic benefits and could favorably affect passenger CAV operations on shared roadways. The remainder of this report will address progress toward modeling CAVs to determine the impact they may have on transportation in the future. Meanwhile, scenarios such as the one discussed in this section can provide the inputs of penetration rate at specific future dates that are needed in travel demand models so that CAVs and their uncertainties can be simulated.

2.4 Section 2 References

- Stabler, Bradley, Morgan et al 2018 Volume 2: Model Impacts of Connected and Autonomous/Automated Vehicles (CAVs) and Ride-Hailing with an Activity-Based Model (ABM) and Dynamic Traffic Assignment (DTA)—An Experiment FHWAHEP Report 18081 April 2018
- Talebian and Mishra (2018) *Predicting the adoption of connected autonomous vehicles: A new approach based on the theory of diffusion of innovations* University of Memphis
- Shladover and Greenblatt (2017) Connected and Automated Vehicle Concept Dimensions and Examples Lawrence Berkeley National Laboratory USDOE December 2017
- Stanek, Huang, Milam, and Wang 2017 Measuring Autonomous Vehicle Impacts on Congested Networks Using Simulation Nov 2017
- Gordon, Kaplan, Zarwi, Walker, Zilberman *The Future of Autonomous Vehicles: Lessons from the Literature on Technology Adoption*, U Cal Berkeley for CALTRANS June 2018
- Bansal and Kockelman (2017) *Forecasting Americans' Long-Term Adoption of Connected and Autonomous Vehicle Technologies* University of Texas Austin

Amitai Bin-Nun, Alex Adams, and Jeffrey Gerlach (2018) *America's Workforce and the Self-Driving Future: Realizing Productivity Gains and Spurring Economic Growth* Securing America's Energy Future June 2018

Vince Bernardin 2018 *Scenario Modeling and EMA for CAVs* RSG September 14, 2018

Liu, H., Kan, X. (David), Shladover, S. E., Lu, X. Y., & Ferlis, R. E. (2018c). Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities. *Transportation Research Part C: Emerging Technologies*, 95(December 2017), 261–279.
<https://doi.org/10.1016/j.trc.2018.07.027>

Iowa DOT and HDR. *Interstate 80 Planning Study* (PEL) June 2017

Twaddell, Hannah (2018) *Scenario Planning for Connected and Automated Vehicles* ICF September 26, 2018

3. EFFECTS OF CAV TECHNOLOGIES ON TRAFFIC MODELING

3.1 Overview of CAV Technologies Impacting Microsimulation

A variety of CAV systems and technologies exist in vehicles being manufactured today, such as blind spot monitoring and lane keeping assistance. Other CAV technologies have been demonstrated but have yet to be widely deployed, including vehicle to infrastructure (V2I) technologies. Still other technologies are discussed in the literature but exist only in concept. Because CAV are not operational and do not operate in mixed traffic situations, there is little driver behavior or operational information available from tests and demonstrations. As a result, modeling and analysis are needed with assumptions about how CAVs would behave in operation. In addition, Zmud et al (2018) noted for TRB that some preliminary attempts at modeling have been made with existing trip-based and activity-based (AB) models, but the results have been somewhat unsatisfying, posing questions instead of answering them.

This discussion summarizes the connected vehicle and automated vehicle technologies that are:

- most prominent in the research and as such are supported by enough literature to form relatively clear ideas about how they may operate, and
- supported in the literature review by traffic modeling and analysis.

Lacking a substantial body of research based on field testing, the research with a traffic modeling component offered the best opportunity to learn how CAV systems are expected to operate when deployed in the field. Undoubtedly, other CAV strategies not discussed in this report will emerge, while some that are described will fade from the CAV picture.

To facilitate this summary, an attempt has been made to categorize the various CAV technologies that are present in the research literature. One broadly recognized categorization of CAV technologies is that based on the mode of communication on which they rely: vehicle-to-vehicle (V2V) or V2I. The former describes the exchange of wireless information between vehicles, while the latter describes the exchange of information between vehicles and road infrastructure, such as traffic signal controllers and road message signs. Vehicle to Everything (V2X) communication describes technology that can communicate with a range of other entities, including vehicles, infrastructure, pedestrians, and cyclists.

The technologies summarized below are discussed in no particular order, and an attempt has been made to specify the communication category with which they are best identified, though some technologies do not necessarily strictly rely on one mode of communication or may be supported by more than one mode.

Cooperative-Adaptive Cruise Control (CACC) aims to establish reduced following headways or distances within clusters (or strings) of vehicles, thus facilitating the maximization of the roadway's capacity and minimizing the ripple effect from downstream incidents. CACC relies on the combination of Adaptive

Cruise Control (ACC) and V2V communications to enable cooperation between vehicles and reduce the delay in response times between vehicles (Liu, Kan, Shladover, Lu, & Ferlis, 2017).

Speed Harmonization is a cooperative vehicle-highway system strategy whereby vehicle speed recommendations are dynamically adjusted with the goal of reducing temporal and spatial variations in traffic speeds or mitigating bottleneck congestion using V2I technology (Hale, et al., 2016). V2V technology can also be employed in a speed harmonization strategy to supplement V2I data (Ghiasi, Lia, Ma, & Qu, 2018).

Advanced lane detection technologies, once fully evolved and matured, will be able to detect the lane in which a vehicle is traveling and inform automated vehicles about which lanes are most advantageous given a known path and current traffic conditions, opening the door to a range of CAV strategies designed to mitigate the effects of merging and weaving or to improve traffic flow generally. Where transportation management centers (TMCs) have lane-level traffic condition information available, that can be communicated to CAVs and used to support decisions that the more highly automated vehicle automation systems make about which lane is most suitable to use. An example from the literature of such an application is Advanced Lane Management Assist (ALMA) (Gordon, 2018).

Intelligent Traffic Signals utilize CAV technology using both V2V and V2I infrastructure for cooperative intersection management. Cooperative methods include time slots and space reservation, trajectory planning, and virtual traffic lights (Chen & Englund, 2016). Nearer-term applications of cooperative traffic signal systems can provide smoothing of vehicle trajectories to reduce energy consumption and emissions and reduce delays at signalized intersections by broadcasting signal phase and timing (SPaT) messages that the vehicle speed control systems can use to optimize each vehicle's speed profile.

Traffic Jam Assist (TJA) allows automated control of lateral and longitudinal movements by the vehicle using vehicle sensors, but the driver must continually monitor operations with hands on the steering wheel. TJA can typically be engaged up to a specific speed threshold. For example, the Level 2 TJA system analyzed in Dogan, et al., (2017) operated up to 50 km/h in freeway environments only (not arterials). TJA exists in some vehicles today and do not rely on V2V or V2I communication, but one can imagine that through V2V or V2I, TJA systems may be made more intelligent and adaptive to traffic conditions.

Queue Warning systems broadcast the queued status of vehicles to nearby vehicles (V2V) or from the infrastructure to approaching vehicles (V2I) with the purpose of determining where queues are located, the estimated duration of the queue, the estimated queue length, and an appropriate response to this information. The main purpose of a Queue Warning system is to reduce the likelihood of rear-end collisions at the back of the queue. While Speed Harmonization strategies try to manage speed prior to congestion queue forming, Queue Warning strategies try to manage vehicles after congestion has already formed queues (Balke, Charara, & Sunkari, 2014).

In a future with ever-increasing proportions of connected vehicles, connected vehicle **Dynamic Route Guidance** systems, which provide route guidance based on current traffic conditions, can be improved with data transmitted by CAVs, most likely through V2I communication.

T-DISP is a **Dynamic Transit Operations** connected vehicle application prototyped by the USDOT and its partners as part of the Connected Vehicle Program that will match travelers' trip requests with available services based on vehicle availability and other real-time data. The traveler will receive several candidate trip plans that will include routing information, instructions for each trip segment, and potentially additional information for other services pertaining to the trip, such as parking information. A transportation information center would be responsible for processing incoming data, most likely via V2I communication, and dynamically scheduling and dispatching trips (Bettisworth, Hassol, Maloney, Sheridan, & Sloan, 2015).

Dynamic Ridesharing, a connected vehicle technology which matches rides on demand and in real time, can also take advantage of automated vehicle technology. For example, Farhan, Chen, & Zhang (2018) analyzed the use of Shared Autonomous Electric Vehicles for dynamic ridesharing services and first/last mile connection services and estimated a reduction in VMT by about 36%. The USDOT also has a Dynamic Ridesharing application called D-RIDE, which allows users to set near-term carpool trips and will allow users to reach areas not served by transit (Bettisworth, Hassol, Maloney, Sheridan, & Sloan, 2015). V2I communication will likely make it possible to obtain and monitor information about ridesharing vehicles and their location and availability in real time.

The application of connected vehicle technology on **Managed Lanes** can also be used to better match supply (capacity) and demand. Connected vehicles using the managed lanes can produce real-time traffic information, such as travel time or price variability and transmit this information to other vehicles whose drivers will be making the decision about whether to use the managed lane (Lou & Vadlamani, 2017). V2V and V2I communications both have the potential to support CAV applications in managed lanes.

3.2 Impact of CAV on Traffic Operations

The areas of impact of CAVs on traffic operations were categorized by Zmud et al, 2018 as follows:

- Transportation cost
- Transportation safety
- Vehicle operations (including capacity changes, congestion, and other traffic impacts)
- Energy use and related emissions
- Personal mobility and convenience (including shared, owned, or rented vehicles)

Because the traffic operations categories need to be accounted for in traffic analysis modeling, the list does not include wider potential societal impacts of CAVs such as land use, employment, or regional economics. Zmud et al, 2018 points out that transportation cost is a very uncertain impact area. Costs of vehicles that include highly automated technology will need to be recouped by OEMs, so the cost per vehicle is likely to increase. However, the cost per trip may decline if fleet services of AVs prevail in the market. Thus, the overall transportation cost to the consumer is uncertain and is most likely tied to vehicle ownership versus distributed vehicle ownership, vehicle club membership, or ridesharing.

The safety impacts of CAVs include an expected reduction in crashes, which should increase the utility of AVs, which would increase their market share. Improved reliability would also increase the utility of the

network performance itself by encouraging users to travel farther as trip and tour planning becomes more consistent.

The impacts of CAV operational characteristics are perhaps the most discussed in the industry to date. Much research has focused on the impact of connecting vehicles through DSRC into platoons of vehicles. The overall impact of better connected and more automated vehicles would be to increase capacity, dramatically shorten headway space and thereby improve coordinated acceleration and vehicle throughput, although operations that involve platoon formation and dissolution may decrease capacity (Zmud et al, 2018). This section discusses these and other impacts in more detail.

3.2.1 Capacity

Several studies exploring the operational impacts of CAVs estimate that deployment of CAVs in traffic in significant numbers may have a positive effect on capacity, increasing that capacity as the portion of CAVs increases.

Zmud et al, 2018 noted that CAVs are expected to improve traffic flow and total throughput capacity on freeways. This would be because of CAV's ability to use close headway spacing and coordinated speed control to form platoons. In a mixed traffic stream of CAVs and manually operated vehicles, fewer gains in capacity are expected as platoons form and dissolve and weaving occurs. Some speculation about exclusive use of managed lanes for CAVs exists. Using a physical separation from manually operated vehicles could enable CAVs to take advantage of capacity-enhancing operation.

Mahmassani, 2016 looked at following distances and capacity improvements with CAVs at various penetration rates. The paper differentiated CVs from AVs and assumed CAVs could follow at 73 feet, whereas Manual Vehicles (MVs) would need 146 feet. Table 4 is derived from Vovsha and Vyas, 2018 and postulates a doubling of lane capacity at full penetration of AVs. The study team emphasizes that the timing of such full penetration of CAVs is very uncertain and no specific date is included in Vovsha and Vyas, 2018. There is no field test or operational data that can substantiate the model findings in Table 2 of doubling capacity with 100% AVs.

Table 4: AVs Freeway Capacity Improvement

| Manual Vehicle | Connected Vehicles | Automated Vehicles | Average Lane Capacity (vehicles/hour) |
|----------------|--------------------|--------------------|---------------------------------------|
| 100% | 0% | 0% | 1800 |
| 50% | 50% | 0% | 2057 |
| 50% | 0% | 50% | 2400 |
| 0% | 50% | 50% | 2880 |
| 0% | 100% | 0% | 3600 |
| 0% | 0% | 100% | 3600 |

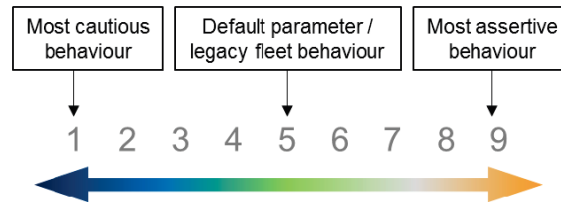
Source: Vovsha and Vyas 2018 presentation at MAG Activity-Based Model Peer Review, from Mahmassani 2016

An Aimsun microscopic traffic simulation of an isolated signalized intersection with both MVs and AVs was conducted to understand the extent to which the traffic dynamics change as automated vehicle penetration rate varies (Bailey, 2016). The behavioral models of the AVs were obtained from Enhanced Intelligent Driver Model (EIDM) proposed by (Kesting, Treiber, & Helbing, 2010) while the default car-

following model implemented in Aimsun, which is based on the Gipps model was used for MVs. An increase in network capacity and a decrease in average delay were observed as automated vehicle penetration rate was increased.

A Vissim microsimulation study was conducted with different driving behaviors for CAVs, to adapt to different driving styles of drivers, ranging from cautious to assertive behavior. For instance, more assertive drivers may maintain shorter gaps compared to cautious drivers (Atkins, 2016). Nine levels of CAV capability (driving behavior) were defined that might be set up by CAV users. (see Figure 7).

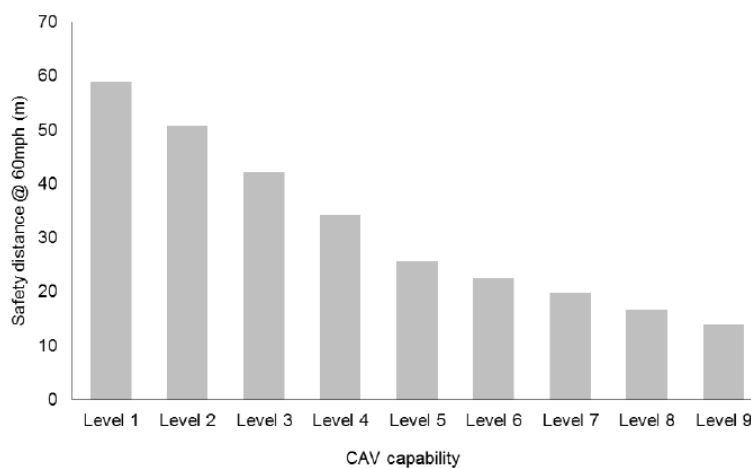
Figure 7: Approach to varying CAV capability



Source: (Atkins, 2016)

The capability levels were different in terms of obeying traffic regulations, like speed limits, safety distance, and priority rules (see Figure 8). The results showed that with enhanced longitudinal behavior (level 5-9), higher density - and consequently greater capacity - could be obtained. With increases in CAV penetration rate, the increase in capacity was greater. On the other hand, deploying more cautious vehicles (i.e. larger time gaps) resulted in lower capacity. To make it clearer, 100% of cautious (level 1) CAVs decrease the capacity by 40%. Moreover, the trade-off between penetration and CAVs capability showed that higher levels of capability can compensate for the low penetration rates. As an example, the same capacity was obtained with high penetration (75%) of a moderately assertive CAV (level 6) as compared to lower penetration (25%) of a highly assertive CAV (level 9).

Figure 8: Safety Distances per CAV Capability

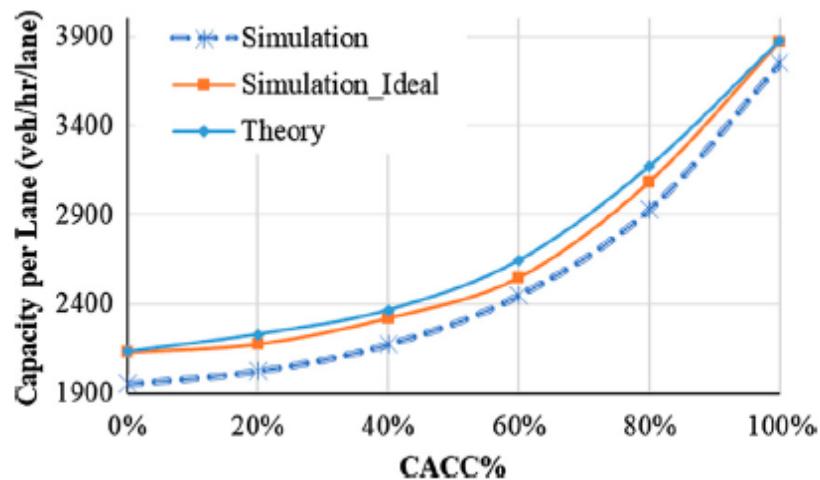


Source: (Atkins, 2016)

Although CACC is able to improve the traffic performance, the role of traffic management strategies on changing the traffic flow characteristics cannot be neglected. The effects of a CACC managed lane (ML) strategy, a vehicle awareness device (VAD) strategy and discretionary lane change (DLC) restrictions on the capacity of a simple four-lane freeway section and a 20-kilometer freeway corridor was investigated by Liu, Kan, Shladover, Lu, & Ferlis (2018a). A vehicle awareness device allows the manually-driven vehicles to communicate wirelessly with other vehicles to broadcast the real time information regarding their operation status and route choice. A vehicle equipped with the vehicle awareness device can serve as the leader of CACC vehicle strings even if it does not have CACC vehicle following capability itself. According to the analysis results, the ML and vehicle awareness device strategies are able to substantially increase the pipeline capacity of the freeway with a CACC market penetration of 60% or less. Moreover, these strategies could enhance the traffic operation at freeway on-ramp bottlenecks significantly at different CACC market penetration rates. Even for CACC market penetrations as low as 20%, these strategies led to an improvement in the overall operation of the freeway corridor. However, the positive impacts of restricting DLC is more evident when the penetration is 80% or higher.

Liu, Kan, Shladover, Lu, & Ferlis (2018c) through case studies with different road geometry and traffic complexity presented a modeling framework to depict the interactions among CACC vehicles and manually driven vehicles under various CACC operation strategies. The case study results demonstrated a quadratic relationship between the CACC penetration rate and the pipeline capacity. As shown in Figure 9 the freeway capacity was 90% higher at the 100% penetration rate compared to 0% penetration rate.

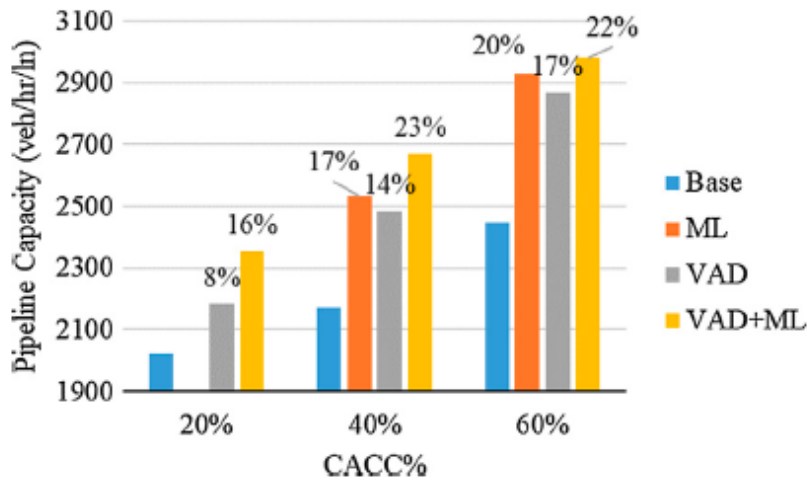
Figure 9: Theoretical and Simulated (Pipeline) Capacity for a Homogenous Freeway Segment



Source: (Liu, Kan, Shladover, Lu, & Ferlis, 2018c)

Although at lower penetration rates (between 20% and 60%) the capacity increase was not significant, the ML and VAD strategies led to improvement in capacity (from 8% to 23%) by increasing the possibility of CACC string formation. (Figure 10).

Figure 10: Pipeline capacity with CACC operation strategies



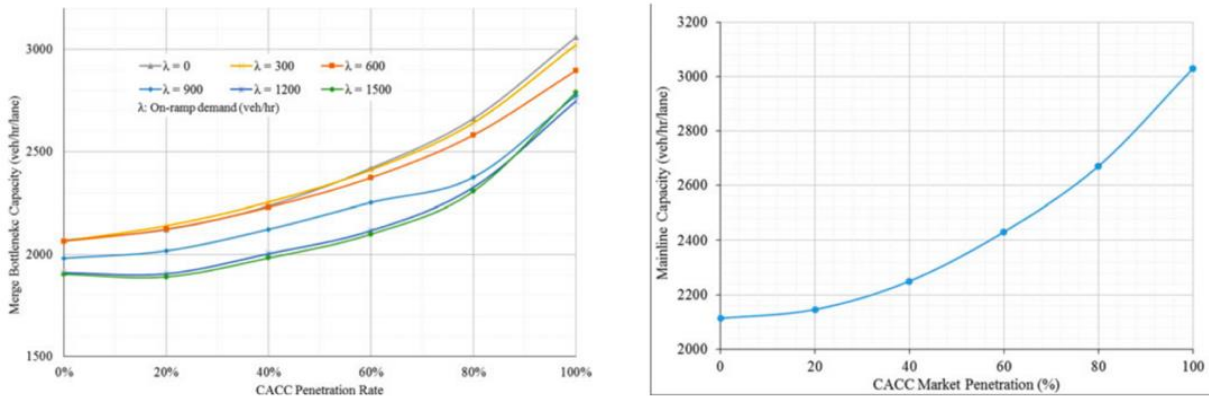
Source: Liu, Kan, Shladover, Lu, & Ferlis, 2018c

While studies such as those described above have explored the potential impacts of CACC on capacity in general terms (e.g., in “pipeline” homogenous freeway segments), few have specifically addressed the effects that closer following headways are likely to have where freeway merging and weaving activity is prevalent. Closer following headways afforded by CACC and which contribute to increases in capacity on the open road may serve to diminish lane changing opportunities, which in turn may lead to more serious congestion in critical merging and weaving areas on freeway facilities.

Liu, Kan, Shladover, Lu, and Ferlis (2018b) predict that on-ramp capacity can be improved with CACC vehicles. They investigated the impact of CACC vehicle string operation on the capacity of multilane freeway merge bottlenecks, commonly found at on-ramp merging areas on urban freeways. From field test data they derived car following models based on the selected CACC time gaps by naïve drivers and used it together with lane-changing models of CACC vehicles and manually driven vehicles, as well as a maximum CACC string length and inter-string time gap constraint to conduct the simulation experiment. It was found that as the CACC market penetration rate increases, the freeway capacity increases quadratically, with a maximum value of 3080 veh/hr/lane at 100% market penetration rate. Although the merge bottleneck caused by the disturbance from on-ramp traffic can lead to a reduction in freeway capacity by 13%, larger CACC market penetration rates still increased the bottleneck capacity quadratically. See Figure 11: for more details on both the on-ramp merge and mainline capacity results.

Figure 11: On-Ramp Capacity Improvement with CACC Market Penetrations

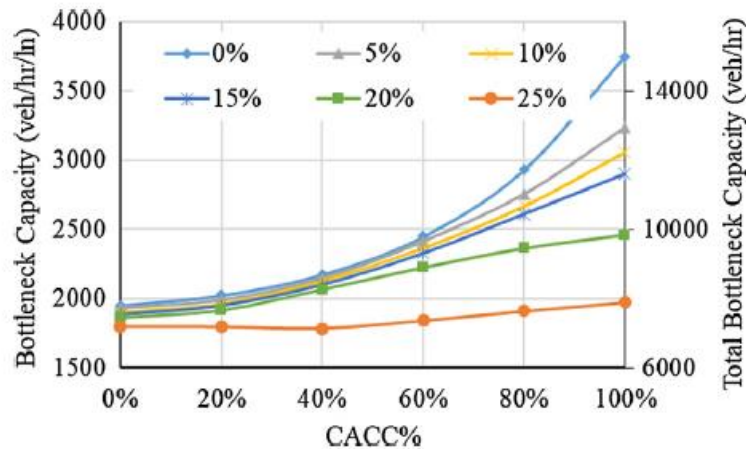
Merge bottleneck capacity vs. CACC market penetrations under varying levels of on-ramp volume (left), Mainline only capacity vs. CACC market penetrations (right)



Source: (Liu, Kan, Shladover, Lu, and Ferlis, 2018b)

When it comes to off-ramps, the analysis shows that the maximum off-ramp traffic percentage out of the mainline traffic that could exit the freeway without causing traffic congestion decreases significantly as the penetration rate increases. This is illustrated in Figure yy below.

Figure yy – Capacity Achievable at various off-ramp traffic percentages



Source: (Liu, Kan, Shladover, Lu, and Ferlis, 2018c)

The off-ramp challenge is that in locations where a substantial fraction of the congested mainline traffic volume needs to exit at the same off-ramp (such as 20% of the mainline volume on a 4-lane freeway), the lane-changing maneuvers required to get all those exiting vehicles onto the off-ramp create significant disturbances to the mainline traffic flow. This means that high volumes of exiting traffic can cause similar bottleneck problems as high volumes of entering traffic. When a CACC vehicle plans to exit, the driver needs to first turn off the CACC and manually make the lane change. Such a behavior breaks the CACC string operation and further negatively impacts the bottleneck capacity. This observation suggests that at higher penetration rates there is a need for management strategies at the

off-ramp bottlenecks. Such traffic routing strategies should be designed to try to avoid concentrating large volumes of exiting traffic at the same exit. If there is a major destination with a high demand level, it would be better to serve it with two exit ramps on both its sides, with some decent spacing between them, so that the mainline congestion effects are reduced. This emphasizes the need for developing management strategies for the off-ramp bottleneck after the CACC market penetration exceeds a certain level.

Summary

Some studies have estimated that CAVs have the potential to improve the capacity of the highway due to the shorter time headways which they can maintain in a platoon or CACC string and the more stable vehicle-following dynamics. However, this is highly dependent on the market penetration rate, traffic volume, traffic management strategies, and the automated system capability. It stands to reason that if vehicles can follow one another more closely, as CACC allows, then capacity will increase. However, none of the papers is definitive and there have been no documented field tests to quantify the potential impacts of CACC. In conclusion, at low market penetration rates CAVs appear to have no significant impact on capacity of the roads since platooning would be challenging due to the low number of CAVs. However, with the help of traffic management strategies, the possibility of CACC string formation and consequently the capacity could be increased. Moreover, CACC is not the only advanced technology implemented in vehicles. Systems such as automated merging or lane changing assistance, and speed harmonization should be deployed together with CACC to best exploit the benefits of the technology.

Although CACC is a Level 1 automation system, the results reported for its effects on traffic flow should also be relevant for higher levels of automation that combine automated car following with additional automation functions. The car following effects are expected to dominate the effects of other automation functions.

Table 5 shows some of the key research efforts that have looked at inclusion of CAVs in traffic analysis modeling.

Table 5: Research into Modeling of CACC

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|--|--|------------------------|------------------------------------|-----------------|--|
| Van Arem, Van Driel, and Visser (2006) | To what extent can CACC contribute to a better traffic-flow performance? | CACC | Four-lane highway with a lane drop | MIXIC | <p>CACC:</p> <ul style="list-style-type: none"> Increase highway capacity near a lane drop with higher than 40% CACC market penetration rates. |

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|-----------------------|---|--|--|---|---|
| Makridis et al., 2018 | To give insights on the anticipated impact of connectivity and/or automation in future transport systems. | ACC CACC | Ring road of Antwerp | Aimsun | Regarding AVs and manual vehicles (MVs), MVs outperformed AVs and AVs negatively affected the congestion and travel speed. In scenarios with MVs and CAVs, CAVs had small negative effects on capacity at low penetration rates and also when the traffic demand was low. However, at higher penetration rates and high traffic demand CAVs could improve density and average speed and also prevent bottlenecks. |
| Liu, et al., (2018b) | To show how merge capacity varies with CACC market penetration at freeway ramps merging bottleneck. | CACC | Multilane freeway merge bottlenecks | Aimsun + NGSIM oversaturated flow model | Freeway capacity and the merging bottleneck capacity both increase quadratically as the CACC market penetration increases. |
| Liu, et al., (2018a) | To explore the effects of traffic management strategies on the capacity | CACC | Simple four-lane freeway section and a 20-kilometer freeway corridor | Aimsun + NGSIM oversaturated flow model | Managed Lane, Vehicle Awareness Device and Discretionary Lane Change strategies can increase the pipeline capacity of the freeway in different levels of CACC market penetration. |
| Bailey, 2016 | To understand the extent to which the traffic dynamics change as autonomous vehicle penetration rate varies | ACC | An isolated signalized intersection | Aimsun | An increase in network capacity and a decrease in average delay were observed as autonomous vehicle penetration rate was increased. |
| Atkins, 2016 | Impacts of CAV capability and penetration rates on capacity | CACC with Autonomy-affected lateral movement | Motorway A-road Major intersection (free-flow) Major intersection (controlled) Merge and diverge Urban A-road Signalized junctions Mid-link pedestrian crossings Priority junctions Dedicated PT infrastructure | Vissim | Deploying more cautious vehicles (lower capability) resulted in lower capacity. With increase in CAV penetration rate the increase in capacity was more evident. The trade-off between penetration and capability showed higher levels of capability can compensate for the low penetration rates. |

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|----------------------|--|------------------------|---|--|--|
| Liu, et al., (2018c) | To present a modeling framework to depict the interactions among CACC vehicles and manually driven vehicles under various CACC operation strategies. | CACC | Two freeway configurations: a simple 4-lane freeway segment with an onramp and an off-ramp an 18-kilometer State Route (SR) 99 northbound freeway corridor that contains complex on-ramp, offramp and weaving bottlenecks. | Aimsun + NGSIM Oversaturated Flow Model | The results demonstrated a quadratic relationship between the CACC penetration rate and the pipeline and on-ramp capacity. In lower penetration rates (20%-60%) the capacity increase was not significant. The ML and VAD strategies led to improvement in capacity (8%-23%) by increasing the possibility of CACC string formation. Maximum off-ramp traffic percentage decreases significantly as the penetration rate increases. |

Source: Delft

3.2.2 Reduction or Increase in Congestion

An Aimsun traffic simulation study showed that CAVs may reduce or increase the congestion depending on their penetration rate (Makridis et al., 2018). The authors demonstrated some preliminary results regarding the introduction of AVs compared to CAVs in the ring road of Antwerp, Belgium under three different traffic demands: 80% 100% and 120% of the estimated peak demand based on real counts. Regarding AVs and MVs, MVs outperformed AVs since human drivers are more risk taking and drive with speeds higher than the speed limit. So, the desired time gap of AVs and their inability to predict their neighboring vehicles' movement negatively affected the congestion and travel speeds. In scenarios with MVs and CAVs, CAVs had small negative effects at low penetration rates and also when the traffic demand was low. However, at higher penetration rates above 60% and high traffic demand, CAVs could improve traffic density and average speed and also prevent bottlenecks. Regarding long term impacts of CAVs, Zhao (2017) used a conventional travel demand model for Austin, Texas to investigate the impacts of CAVs and shared automated vehicles on congestion. The findings of the study suggest that with a reduction in the value of travel time, operating costs, and parking cost, more travelers will choose AVs over regular vehicles and buses. As a result, demand for vehicle-miles traveled (VMT) around the region will increase more than 20% followed by associated congestion delays. This was found from a series of eight test scenarios for Austin's year 2020 network which were sensitive to parking cost and vehicle operating cost assumptions.

Research has been conducted to explore whether dedicating a lane to AVs may have an impact on congestion. A microscopic simulation of the city of Singapore revealed that roads leading to highways will be congested due to the fact that more AVs want to use the highways to enter to the dedicated lanes (Ivanchev, Knoll, Zehe, Nair, & Eckhoff, 2017). Another study considering dedicated lanes for AVs examined the following strategies: (a) mandatory use of the dedicated lane by AVs, (b) optional use of the dedicated lane by AVs, and (c) permitting automated operation only in dedicated AV lanes and requiring human operation elsewhere (Talebpour, Mahmassani, & Elfar, 2017). According to the results the optional use of dedicated lanes leads to a reduction in congestion. On the other hand, forcing AVs to ride only in dedicated lanes may lead to significantly increased congestion.

Summary

CAVs are expected to decrease congestion considering the higher capacity which will be achieved due to the shorter time headways maintained by these vehicles. However, the mitigation in congestion is unlikely to occur with low penetration rates of CAVs. In fact, without proper traffic management strategies, a negative impact on congestion can also be expected. Indeed, reduction in the value of travel time, operating costs, and parking cost, more travelers are likely to choose AVs over regular vehicles and buses. As a result, VMT can be expected to increase unless there is a shift to shared AVs. However, research shows that CAVs have a significant effect in mitigating congestion at high penetration rates and specially at high traffic demands. Moreover, dedicating a lane to AVs can help to improve the congestion. But this is highly dependent on the utilization policy of this lane and also the penetration rate of CAVs. If a lane is dedicated to AVs when their market penetration is too low, it will be under-utilized and the remaining general-purpose lanes over-utilized, so the number of dedicated lanes needs to be carefully matched to the population of AVs that can use those lanes.

3.2.3 Traffic Stability

Van Arem, Van Driel, and Visser (2006) examined whether CACC can improve traffic stability in a four-lane highway with a lane drop via a traffic simulation study using MIXIC, a microscopic traffic simulation model developed by the Netherlands Organization for applied research (TNO) and the Dutch Ministry of Transport, Public Works and Water Management for the study of Autonomous Intelligent Cruise Control (AICC), a concept similar to CACC. At high market penetration rates (>60%) of CACC, improvement in traffic stability and throughput was simulated. When a lane was dedicated to CACC vehicles, low CACC penetration rates (< 40%) led to a degradation of performance, demonstrated by lower speeds, higher speed variances, and a higher incidence of shockwaves. However, the study estimated that at high penetration rates (>60%) CACC may improve traffic stability by reducing speed variances, but only in high-volume flow upstream of bottlenecks. Outcomes were found to vary, however, depending on the policy relating to utilization of the dedicated CACC lanes (i.e. whether usage by CACC vehicles was optional or mandatory).

Amoozadeh, Deng, Chuah, Zhang, and Ghosal (2015) developed a platoon management protocol for CACC vehicles with three basic maneuvers - merge, split, and lane-change - based on wireless communication through Vehicular Ad-hoc Network (VANET). The authors also designed a comprehensive CACC longitudinal control system implemented in SUMO, an open-source traffic microsimulation platform developed predominantly by the Institute of Transportation Systems at the German Aerospace Center. Simulation results suggested that the protocol would be able to maintain traffic flow stability at 100% penetration rate.

Another platooning strategy was developed by Arefizadeh and Talebpour (2018). They introduced a constant time headway strategy for AV platooning which was able to track changes in speed limits. The results were compared to platoons of manual vehicles whose car following behaviors were simulated using the intelligent driver model (IDM) and Gipps models. While the simulations of non-automated vehicles resulted in shockwave formation where a drop-in speed limit occurred, platoons of AVs were able to transition stably to the new speed without any adverse effects on flow. In other words, the proposed platooning strategy was able to prevent shockwave formation and propagation.

Mahmassani (2017) studied the flow implications and traffic physics of CVs and AVs on freeways, arterials, and urban junctions. Analytical investigations showed that the stability of the vehicle string can be improved by deploying CVs into the traffic stream. Unlike AVs, the study predicted that CVs would have a positive impact on string stability at low market penetration rates, whereas at high market penetration rates, AVs were better able than CVs to improve stability. The study's simulation results suggested that oscillation and collision thresholds increase with decreasing platoon size and increasing market penetration rates for both CVs and AVs.

Summary

In conclusion, research shows that CACC-equipped vehicles can increase traffic stability and this enhancement is more evident when the penetration rate is high (>60%).

3.2.4 Travel Time

The introduction of CAV technologies such as CACC that permit short following headways is likely to reduce travel times because those shorter following headways will enable free flow speeds to be maintained at higher traffic volumes. As an example, a 9% reduction in travel times was simulated in a VISSIM microsimulation study assuming 100% market penetration (Aria, Olstam, & Schwietering, 2016).

Similar studies based on microsimulation suggest that CAVs may reduce travel time on merging roadways as well. In a study by Rios-torres and Malikipoulos (2017) using a microscopic simulation framework to explore the impacts of CAVs on travel time reduction on merging roadways, scenarios were simulated assuming 0% and 100% CAV penetration rates under low, average, and high traffic volume conditions. According to the model, a significant reduction in travel time (up to 60%) in moderate and high traffic congestion situations resulted at 100% CAV penetration.

Bailey (2016) used AIMSUN to simulate the impact that AV penetration rate may have on the average travel time experienced by vehicles at an isolated signalized intersection. Travel time was examined in scenarios varying the AV penetration rates between 0 and 100% in intervals of 10% and green phases as a function of demand rate. Demand was varied between 300 and 1800 vehicles per hour to examine the impacts in low traffic, moderate traffic, and heavy traffic. as shown in Figure X.X.

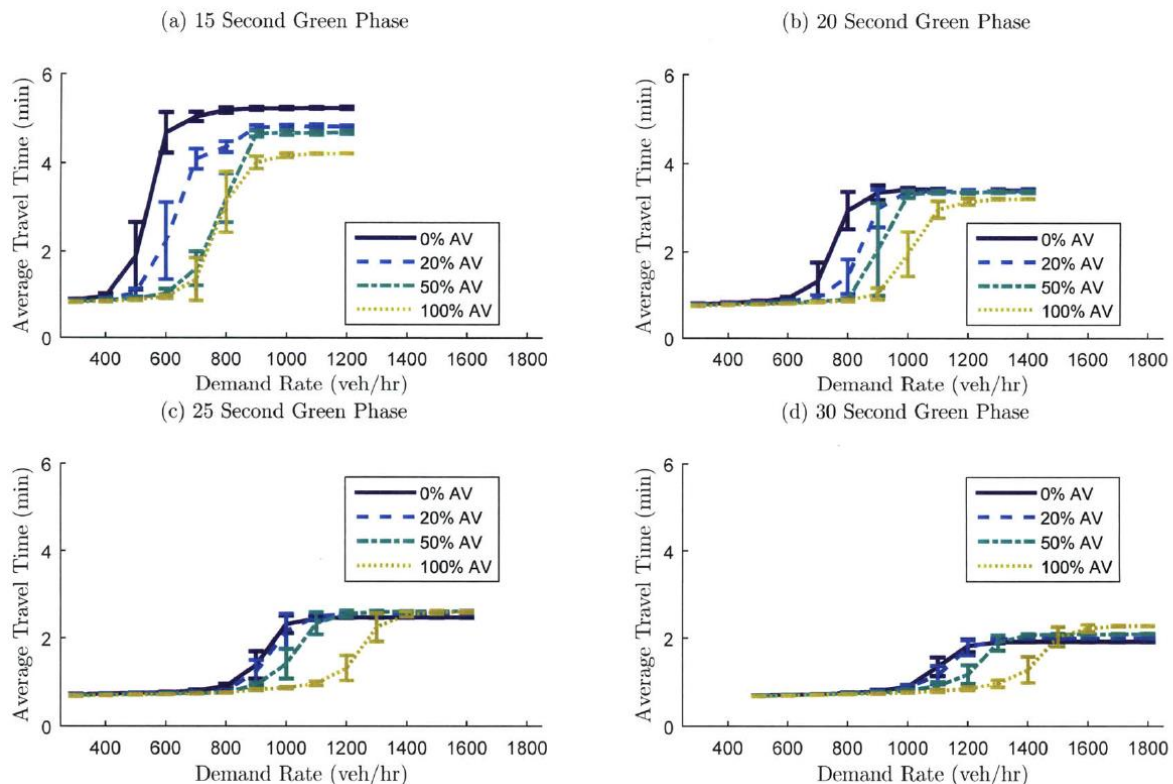


Figure X.X: Average travel times obtained for different combinations of AV penetration rate, green phase, and demand rate via microscopic traffic simulation.

The results indicated that as AV penetration increases, average travel times for vehicles decreases. Specifically, when assuming 15 seconds of green time and a demand rate of 600 vehicles per hour, travel times were reduced by 53% and 80% when AV penetration was assumed to be 20% and 100%, respectively.

Ivanchev, Knoll, Zehe, Nair, and Eckhoff (2017) conducted an analytical evaluation of AVs using a macroscopic simulation of the city of Singapore with a realistic traffic demand. The model showed a reduction in average travel time with increasing AV penetration. In addition, when it was assumed AVs would follow one another with shorter headways, travel times were further reduced. The authors also investigated the effect of a dedicated lane for AVs on travel time. The analysis suggested that implementing a dedicated lane at 40-50% AV may increase the travel times experienced by conventional vehicles in the traffic stream due to the congestion caused in the remaining lanes. However, with increasing AV penetration, travel times decreased relative to the base condition without AVs. The simulation study by Talebpour, Mahmassani, and Elfar (2017), discussed earlier, also addressed travel time reliability. See also the previously-cited Arefizadeh and Talebpour (2018) which addressed AV platooning and can also improve travel time.

Summary

In summary, research has demonstrated that CAVs and AVs can reduce the travel time due to their behavior: smaller headways, and accurately tracking the speed profile of the lead vehicles. Moreover, dedicating a lane for CAVs allows for a higher possibility for platooning. As a result, not only the travel time of CAVs will be decreased, but also the travel time of the entire vehicle fleet will be affected positively when the CAV penetration rate is equal or higher than saturating a lane. An overview of the key studies and their outcome on the CAV impacts on travel time, traffic stability, and congestion is illustrated in Table 6.

Table 6: Research Studies on Impacts of Automation on Traffic Flow Stability, Congestion, and Travel Time

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|-------------------------|---|------------------------|--|-----------------|---|
| (Makridis et al., 2018) | To give insights on the anticipated impact of connectivity and/or automation in future transport systems. | MV AV CAV | Ring road of Antwerp, under three different traffic demands: 80% 100% and 120% of the estimated peak demand based on real counts | Aimsun | <ol style="list-style-type: none"> 1. The desired time gap of AVs and their inability to predict their neighboring vehicles' movement negatively affected the congestion and travel speeds 2. CAVs had small negative effects at low penetration rates and also when the traffic demand was low |

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|--|---|------------------------|---|---|--|
| (Ivanchev et al., 2017) | To investigate if dedicating a lane to AVs can have an impact on congestion | AV | Road network of the city of Singapore | Not known | <ol style="list-style-type: none"> 1. Roads leading to highways will be congested due to the fact that more AVs want to use the highways to enter to the dedicated lanes 2. A reduction of average travel time with increasing the penetration rate of AVs in the system was observed 3. Shorter headway times led to a decrease in travel time. 4. Implementing a dedicated lane before its saturation (AV penetration rate of 40-50%) will increase the travel time |
| (Talebpour et al., 2017) | To explore the potential effects of reserving one lane for autonomous vehicles on traffic flow dynamics and travel time reliability. | AV | <ol style="list-style-type: none"> 1. A two-lane hypothetical segment with an on-ramp 2. A four-lane highway segment in Chicago, Illinois | Not known | <ol style="list-style-type: none"> 1. Optional use of dedicated lanes could improve congestion and reduce the scatter in fundamental diagram 2. Forcing AVs to ride only in dedicated lanes significantly increased congestion. 3. Forcing AVs to use the dedicated lanes will cause shockwave formation due to the mandatory lane changes towards these lanes 4. Optional use of the dedicated lane by autonomous vehicles had positive effects in terms of travel time reliability |
| Van Arem, Van Driel, and Visser (2006) | To what extent can CACC contribute to a better traffic-flow performance? | CACC | Four-lane highway with a lane drop | MIXIC | <ol style="list-style-type: none"> 1. At high market penetration rates (>60%) of CACC, improvement in traffic stability and throughput was observed 2. In case of dedicating a lane to CACC vehicles, low CACC penetration rates (< 40%), led to a degradation of performance, demonstrated by lower speeds, higher speed variances, and more shockwaves. |
| Amoozadeh, Deng, Chuah, Zhang, and Ghosal (2015) | To develop a platoon management protocol for CACC vehicles with three basic maneuvers: merge, split, and lane-change and investigating the impacts on traffic stability | CACC | A long straight two-lane highway with the speed limit of 30 m/s, and unidirectional traffic flow. | VENTOS (VEhicular NeTwork Open Simulator) | <ol style="list-style-type: none"> 1. Simulation results showed that the protocol is able to maintain traffic flow stability at 100% penetration rate |

| Authors | Research goal | Type of vehicle/system | Type of road | Simulation tool | Impacts found |
|-------------------------------------|--|------------------------|---|-----------------|--|
| Arefizadeh and Talebpour (2018) | To design a constant headway policy based controller for automated vehicles capable of following specific speed profiles. | CACC | A straight line in a one-lane highway segment with infinite length | Not known | <ol style="list-style-type: none"> 1. The proposed platooning strategy was able to prevent shockwave formation and propagation 2. The proposed headway strategy in a fully automated system could enhance the travel time reliability |
| Mahmassani (2017) | To study the flow implications and traffic physics of Connected Vehicles (CVs) and AVs | AV CV | Freeways, arterials and urban junctions, as well as networks | Not known | <ol style="list-style-type: none"> 1. Analytical investigations showed that string stability can be improved by deploying CVs into the traffic 2. CVs impact on string stability is evident from low market penetration rates 3. When market penetration rate is high, AVs outperform CVs in improving stability 4. Simulation results revealed that oscillation and collision thresholds increase with decrease in platoon size and increase in market penetration rate |
| (Aria et al., 2016) | To investigate the effects of AV on driver's behavior and traffic performance | CAV | A segment of an autobahn which contains road sections such as weaving area, off-ramp, on-ramp and secondary urban roads all in one model. | Vissim | <ol style="list-style-type: none"> 1. 9% reduction of travel time during p.m. peak was achieved with 100% penetration rate of CAVs |
| Rios-torres and Malikopoulos (2017) | To explore the CAVs impact on travel time reduction in merging roadways | CAV | Single-lane merging on-ramp roadways | Not known | 100% CAV penetration rate allowed for a significant reduction in travel time (up to 60%) in moderate and high traffic congestion situations |
| Bailey (2016) | To investigate the impact of AV penetration rate on the average travel time experienced by vehicles in an isolated signalized intersection | AV | An isolated signalized intersection | Aimsun | As AV penetration rate increases, average travel time for vehicles in the network decreases |

3.3 Impact of CAV on Society

Automated and connected vehicles are expected to improve safety by warning drivers of dangerous conditions and/or taking the control of vehicles. Currently, there is no empirical data regarding the implication of Connected and Automated Vehicles (CAVs) on the number and severity of crashes since CAVs are not deployed widely yet on our road network. There is empirical evidence that collision warning and control assistance systems that augment the capabilities of human drivers reduce the rate

of occurrence of crashes, since these combine the vigilance of the drivers with the vigilance of the sensor systems. While numerous sources in the literature noted below predict that AVs will reduce accidents, it remains to be seen and to be tested whether automation systems without human supervision will be able to improve safety.

The following sub-sections synthesize impacts from key sources and identifies research gaps.

3.3.1 Safety Improvements Based on Vehicle Crash Reduction

Kockelman et al., (2016) quantified the crash-related gains of various vehicle automation and connectivity features and anticipated their near-term and long-range impacts on car crashes in Texas, in terms of economic cost and quality life years. Based on the most recently-available U.S. crash database (the 2013 National Automotive Sampling System (NASS) General Estimates System (GES)), the results show that advanced CAV technologies may reduce current U.S. crash costs by at least \$126 billion per year (not including pain and suffering damages, and other non-economic costs) and functional human-years lost by nearly 2 million (per year). These results rely on three different effectiveness scenarios (conservative (more cautious than human drivers), moderate, and aggressive effectiveness (shorter headways and harder acceleration)) with market penetration rate of 100% of all CV and AV technologies and the analysis was based on extremely optimistic assumptions about the capabilities of the automation systems rather than on any serious analysis of the likely performance of those systems. In terms of V2V and V2I warning systems that depend on the drivers to take action to avoid crashes, Najm, Koopmann, Smith, and Brewer (2010) based on pre-crash scenarios estimated that V2V systems, such as Forward Collision Warning (FCW), Blind Spot Warning (BSW), and Lane Change Warning (LCW), can serve as primary crash countermeasures, reducing U.S. light-duty vehicle-involved crashes by 76%. They further estimated that V2I warning systems, such as Curve Speed Warning (CSW), Red Light Violation Warning system (RLVW), and Stop Sign Violation Warning (SSVW), could address 25% of all light-duty-vehicle crashes in the U.S.

The impacts of CAV technology on crash reduction however is highly dependent on the type of vehicle and the safety estimation methodology. This was revealed by the outcome of the study by Yue, Abdel-Aty, and Wang (2018). These authors used a general crash avoidance effectiveness framework for major CAV technologies to make a comprehensive crash reduction estimation. Sensitivity analysis was conducted to estimate the crash avoidance effectiveness of 15 major CAV technologies that were tested in the recent 20 years. The results showed that the crash avoidance effectiveness of a CAV technology is significantly affected by the vehicle type and the safety estimation methodology. CAV can reduce light vehicles' crashes by at least 28.56% per year, and heavy trucks' crashes by at least 37.06%, under the conservative scenario. The rear-end crash warnings for light vehicles and the lane change crash warnings for heavy trucks have the most expected crash benefits.

Morando, Truong, and Vu (2017) investigated the safety impacts of AVs using a simulation-based surrogate safety measure approach in two case studies: signalized intersection and a roundabout while varying the penetration rates of AVs (0%, 25%, 50%, 75%, and 100%) in each case. The authors adapted two sets of AV parameters from Atkins (2016) and PTV (2017) in Vissim to reflect the behavior of AVs. Atkins (2016) was explicitly used to reflect more assertive behavior of AVs such as aggressive accelerations. The simulation time was set to 1 hour, excluding a warm-up time of 10 minutes. All scenarios were modelled with 10 simulation time steps and 20 runs with different seed numbers. The

Surrogate Safety Assessment Model - SSAM was used to extract the number of potential conflicts based on the surrogate safety measures (Time To Collision (TTC) measures with 1.5s and, and Post-Encroachment Time (PET) with 5s thresholds). SSAM was released by the Federal Highway Administration (FHWA), to help analyze potential conflicts between vehicles and the resulting crashes at four-way intersection, bottleneck-urban roadway, and on-ramp/off-ramp freeway. The results showed that the number of conflicts on signalized intersections decreased as the AV penetration rate increased. The reduction ranged between 21% and 47% for AV penetration rates of 50% or more compared to the base case (0% AV penetration rate). For the roundabout, the number of conflicts increases between the base case and 25% AV penetration rate but decreases between 25% and 100% AV penetration rates. At 100% AV penetration rate, the number of conflicts is 32% lower compared to the base case. In the case studies, AVs improve safety significantly with high penetration rates, even when they are expected to travel with shorter headways to improve road capacity. However, these SSAMs were derived based on human driver responses, so they may not be valid for evaluating the safety of automation systems that respond differently. However, these SSAMs were derived based on human driver responses, so they may not be valid for evaluating the safety of automation systems that respond differently. This emphasizes the need for research on critical SSAMs for AVs. The authors highlight that future research should apply more realistic models for connected AVs in Vissim as well as investigate additional surrogate safety measures.

Kockelman et al. (2016) also used microscopic simulation models in combination with the SSAM model. The VISSIM simulations and the subsequent SSAM analyses suggest that AVs may be safer on selected networks in comparison with human driven vehicles. It was observed that the number of crashes and their severity decreases as the concentration of AVs increases in the traffic. However, the authors also have some reservation from the results as the models incorporated in the simulation do not accurately represent the behavior of AVs. For example, legal and philosophical analysis of AV behavior and the choices in ethical dilemmas were questions which cannot be answered by engineering alone.

Although safety impacts of AVs on traffic become evident in higher market penetration rates, CAVs are shown with estimates in modeling to increase the safety even at very small penetration rates. This was demonstrated by Guérliau, Billot, El Faouzi, and Monteil (2018) which used a multi-agent-based simulation framework that integrates CAVs models in order to assess the impacts on traffic efficiency, safety and environmental sustainability. Several surrogate safety indicators were used, such as different TTC and PET measures. Different penetration rates of CAV (ranging from 0% to 40%) were simulated in mixed traffic flow (CAVs vs non-CAVs) on a 10 km stretch of a 3 lane-highway during 60 minutes. It was found that an increase in CAVs penetration rate harmonizes the traffic by smoothing the speeds distributions. Guérliau et al 2018 found that even a small percentage of CAVs (5% or 10%) will decrease the Time Exposed Time-To-Collision (TET), enabling a safer traffic.

Summary

Simulation studies have predicted that AVs and CAVs can increase safety and decrease the possibility and severity of accidents by eliminating human driving errors, smoothing the traffic and deterring shockwave formation and consequently stabilizing the traffic. These studies have been based on use of simulations that do not represent safety-critical traffic situations and using Surrogate Safety Assessment Models that were derived from human responses rather than automated driving system responses, so the findings need to be viewed with great caution. None of these analyses represents the new crashes that will be caused by failures of the automation systems. The literature lacks evidence-based research on AV safety

resulting from field test experiments since CAVs are not yet deployed widely on the road network, and the existing simulation studies are based on use of models that were designed to represent normal traffic flow, but not safety-critical situations. The dubious foundations of the available studies have included problems such as:

- *Assuming perfection of the automation systems, not accounting for their inevitable design and implementation faults that will lead them to cause new crashes;*
- *Not accounting for the new crashes that are likely to arise because of the imperfect interactions between the CAVs and human drivers and other road users based on the fact that CAV behaviors do not match human behaviors and the expectations of the other road users (but of course in the absence of real-world data on these interactions this cannot be quantified yet);*
- *Applying surrogate safety measures that were defined based on human driving performance capabilities and limitations to automated driving systems that will have different performance capabilities and limitations, leading to different safety problems and crash rates.*

3.3.2 Mode Choice, Vehicle Ownership and Shared Mobility

Because CAVs are not in widespread operation in urban areas, it is necessary to model shared mobility and how CAVs can fit into that concept. A recent study in Oslo Norway conducted between May 2018 and March 2019 by COWI and PTV on behalf of Ruter, the Oslo Region public transport company, examined mobility through traffic modeling (COWI-PTV 2019). The study team developed a traffic model for CAVs to investigate future scenarios for urban mobility in the Oslo region, and looked into a future where CAVs and MaaS-based car sharing schemes would replace private car ownership. The Oslo study was inspired by similar studies in other cities, especially Lisbon, Portugal (ITF-OECD 2015 titled *Urban Mobility System Upgrade: how shared self-driving cars could change city traffic*). Similar to the Lisbon study, the study team based its calculations for various scenarios on the current transportation demand. They simulated full implementation of CAVs in a shared fleet, with and without ridesharing, allowing them to assess isolated effects of different aspects of MaaS concepts.

The Oslo study used PTV's MaaS Modeller software. To match trip requests to vehicles from the shared fleet, the model used an algorithm that dispatches and routes the vehicles so that all travelers receive a ride, the overall fleet size is optimized, and the total distance travelled by the fleet is minimized. Significantly, the authors found in Oslo that shared transportation with a high level of service will not be sufficient to reach the traffic reduction targets in the Oslo region and will challenge road capacity. The miles traveled in the study scenarios decreased when private car users switched to shared vehicles. This also resulted in a significant drop of the number of vehicles needed to meet the traffic demand. The scenarios and assumptions in the study had limitations, but the authors of COWI-PTV 2019 believe their model can be a tool for further examining future transportation in Oslo, for example by looking at CAVs as feeding the existing public transit system.

The unavailability of CAVs also has meant it is not possible to do revealed preference experiments on travelers' responses for AVs, so only stated preference experiments have been possible. The validity of these is limited by the gap between the survey participants' mental images of the experience of using an AV and the actual reality of that experience.

A discrete choice experiment (DCE) was conducted using data from an online survey in order to investigate whether automated driving could change mode choices for commuting trips (Steck, Kolarova, Bahamonde-Birke, Trommer, & Lenz, 2018). The findings of this study showed that regular commuters prefer Private AVs (PAV) over shared ones. In the stated preference survey study by Yap, Correia, and van Arem (2016), the authors investigated travelers' preferences for using automated vehicles as last mile public transport of multimodal train trips. The outcome of the survey revealed that on average, first class train travelers chose AVs over other alternatives, while second class travelers chose a bus, tram, metro, or bicycle as the last mile transport mode. The results also show that in-vehicle time in AVs was experienced more negatively than in-vehicle time in manually driven cars. This indicates that travelers do not yet perceive the advantage of using the time inside the vehicle to perform other activities, and a low trust in AVs.

Nazari, Noruzoliaee, and Mohammadian (2018) addressed the question: "Is the future urban mobility a public utility and may AV private ownership no longer be necessary?" The authors used stated preference data to investigate public interest in considering AV as an owned asset versus three shared mobility services: AV rental, AV taxi without a backup driver, and AV taxi with a backup driver. The estimation results revealed that public interest in the four mobility options have a complementary relationship and, thus future urban mobility cannot be assumed as a public utility with no private AV ownership.

Regarding ride sharing, a stated choice survey was conducted to identify the characteristics of potential Shared Automated Vehicles (SAVs) users (Krueger, Rashidi, & Rose, 2016). Respondents were asked about their choices of switching to SAVs with or without Dynamic Ride-Sharing (DRS), meaning on-demand and real-time sharing of a vehicle with other passengers who travel from a similar origin to a similar destination. The results of the Mixed Logit Model revealed that service attributes like travel time, waiting time and fares may be significant determinants in SAV use and DRS acceptance. Besides, a strong relationship between an individual's modality style and the tendency to choose SAVs was found. Moreover, current car-sharing travelers tend to use SAV with DRS. In terms of travelers by car, those who drive would like to use SAV without DRS, while travelers as a passenger were relatively more likely to select SAV with DRS. Finally, public transport users were not willing to switch to any of the hypothetical options.

Apart from service attributes, other important factors which influence travelers' choice of trip mode were found based on a stated preference survey which was conducted to enquire about individuals' motivations to choose private automated vehicle, SAV or their own conventional cars in Israel and North America (Haboucha, Ishaq, & Shiftan, 2017). Five latent variables were found to be significant based on a factor analysis: technology interest, environmental concern, enjoy driving, public transit attitude, and pro-AV sentiments. Three factors among these five turned out to play a significant role in estimating the choice of the respondents. These are: enjoy driving, environmental concern, and pro-AV attitude. Interestingly, 25% of respondents were not willing to use SAVs even if it was completely free. In terms of accepting AVs, Israelis were more likely to accept AVs compared to North Americans. Moreover, commuters with longer commute distance were more inclined to accept AVs.

Winter, Cats, Martens, & van Arem (2017) investigated urban mode preferences in the event that Free-Floating Carsharing services (FFCS) and SAVs are fully accessible to all users. The results based on a

stated choice experiment on mode choice conducted among the Dutch urban population showed that for early adopters of mobility trends SAVs are more favorable compared to FFCS, while normal and late adopters rejected AVs and preferred FFCS.

3.3.3 Value of Travel Time

Impacts of CAV on value of travel time savings for commuting trips was investigated through a discrete choice experiment and analyzing the data using mixed logit (ML) model (Steck et al., 2018). Results confirmed the assumption that highly automated vehicles reduce the value of travel time savings for commuting trips. The authors further examined the possibility of utilization of the privately-owned AVs compared to shared AVs for different income classes and compared it with alternative modes of transportation. According to the results, highly automated driving reduces the value of travel time savings by 31% in comparison with driving manually. Comparing privately-owned AVs and shared AVs, people prefer riding privately-owned AVs. Regarding comparing shared AVs and driving manually, people perceived the travel time spent in shared AVs, 10% less negatively than driving manually.

1,782 Singaporean commuters participated in an online survey which aimed to compare commuters' attitude towards time use currently and in a potential future AV scenario (Bailey, Rosenfield, 2018). The survey results showed that currently (using manual vehicles) commuters are involved in leisure activities and not work activities. On the other hand, respondents were significantly more likely to do high-intensity activities like browsing their smart phone or sleeping if they were to commute using a highly automated mobility-on-demand service instead of an automobile. Although these are not considered as work activities necessarily, the satisfaction caused by this commute will still reduce the cost of travel for these commuters. This attitude could be different if the AV is designed exactly for doing office work as it can be concluded from the study by de Looft, Correia Homem de Almeida, van Cranenburgh, Snelder, and van Arem (2018). Through a stated preference survey from 252 respondents in the Netherlands, they found that the value of travel time is lower for an AV with office interior compared to conventional vehicles. The value of travel time for AV-leisure travelers is higher than a conventional vehicle. This may be explained by the fact that travelers are not willing to spend leisure time in a vehicle but do prefer working in an office-AV to cut working hours. However, the authors suggest considering these findings with a certain degree of uncertainty due to the unfamiliarity of the respondents with AVs.

Summary

It can be summarized that most of the research that has been done to study the impact of AVs on travel behavior is based on data from stated preference surveys analysed using discrete choice modeling methods.

The findings indicate that in general, AVs do not decrease vehicle ownership compared to regular vehicles. This is in line with the findings of the literature review of Rodier (2018) which suggests that AVs will reduce public transport and non-motorized mode shares and increase car mode shares.

Based on the findings of the mentioned studies, value of travel time may be reduced as an impact of AVs regarding the fact that travelers can be involved with other tasks than driving. However, this may not necessarily increase the productivity of the travelers during the trip, as some travelers are willing to continue watching the road when riding with an AV. The satisfaction of travelers caused by riding an AV would reduce the cost of travel time. Based on the above-mentioned studies it can be concluded that the

value of travel time is highest for manually driven vehicles, followed by shared-AVs, and lowest for privately-owned AVs.

3.3.4 Increased Fuel Efficiency and Related Emissions Reduction

Eilbert, Jackson, and Noel (2018) proposed a three-layered modeling framework to assess the impacts of CACC on energy and emissions. The three layers were: 1) a CAV driving behavior model with 2) a microscopic traffic simulation model to create vehicle trajectory data that can be evaluated in 3) a fleet-based modal emissions model. According to the results, CACC driving behavior based on an adjusted MIXIC car following model, was estimated to reduce fine particulate matter (PM_{2.5}) and carbon monoxide (CO) 25% and 20% respectively compared to the baseline which is human driving behavior with VISSIM's default Wiedemann 99 car following model. However, regarding fuel consumption, CACC driving behavior did not have any effects. Authors further investigated the fuel consumption and emission for CACC driving compared to another scenario where the Wiedemann oscillation parameters were set to zero. However, this scenario had negligible or no benefits over the baseline. This contradicts the results of the study by Rios-Torres & Malikopoulos (2017), which estimated CAVs will significantly reduce fuel consumption. They investigated CAV implications on fuel consumption via a microscopic simulation framework wherein the optimal control and Gipps car following model were used to simulate the behavior of CAVs and human-driven vehicles respectively.

Regarding CVs that provide advice to drivers but do not actively control vehicle motions, research has predicted that CVs equipped with a Speed Advisory System (SAS) can reduce fuel consumption (Wan, Vahidi, & Luckow, 2016). The SAS for pre-timed traffic signals used information from downstream signals to manage speeds and reduce idling at red lights. Results demonstrated a 30% reduction in individual vehicle fuel consumption comparing 100% and 0% SAS-equipped vehicles for the demand rate equal to 600 veh/h/l. More interestingly, as the penetration rate of the vehicles equipped by SAS increased, the fuel consumption by regular vehicles decreased as well. So, fuel economy was improved not only for the CV vehicle individually but also for the fleet in general, including MVs, through a speed harmonizing effect.

In terms of fuel consumption of AVs, Ivanchev et al., (2017) conducted a macroscopic simulation of the city of Singapore, examining the impact of a separate lane dedicated to AVs. Overall travel time decreased more than 20% which also meant overall fuel consumption decreased. The researchers used the Elemental fuel consumption model (W.H. Faris et al "Vehicle fuel consumption and emission modelling: an in-depth literature review" 2011) to determine the average fuel consumption of all traffic, of AVs, and of CVs and for various AV penetration rates. At 20% AV penetration rate, the fuel consumption for a 1-hour Singapore morning rush hour was approximately 0.8% lower than the base case, while at 100% AV penetration rate, it was 7.2% lower. The authors noted that the relative effect of greater AV penetration and the dedicated AV lane on fuel savings was less than the improvement in average travel time.

Apart from AVs and CAVs, several field tests have measured fuel saving enabled by truck platooning. As an example, Lu & Shladover (2014) conducted an experiment on coordinated automatic longitudinal control of a platoon of three Class 8 tractor-trailer trucks, using 5.9 GHz DSRC with 100ms update intervals for coordination. The experiment included constant-speed cruising conditions, acceleration and

deceleration profiles, up and down grades, and in platoon join and split maneuvers using the DSRC coordination. The desired gap between the trucks ranged between 4-10m to allow the evaluation of fuel savings as a result of aerodynamic drag. Fuel reductions of about 4-5% and 10-14% were measured at the 6m gap for the lead truck and the following truck respectively. Similarly, Al Alam, Gattami, & Johansson (2010) conducted an experiment in a Swedish highway with two identical trucks to measure the fuel reduction enabled by heavy duty vehicle platooning by ACC. The results showed a maximum fuel reduction of 4.7–7.7% depending on the time gap, at set speed equal to 70 km/h. Besides, a short relative distance allowed for a maximum fuel reduction due to both air drag reduction and suitable control.

McAuliffe et al (2018) reported on an extensive set of test track tests of the fuel consumption of a three truck platoon, comparing it with trucks driven individually and in two-truck platoons and as a long combination vehicle (LCV). This paper also made direct comparisons of its new test results with multiple previously reported sets of test data, showing strong consistency. These tests showed the variations in fuel consumption with respect to intra-platoon gaps between 4m and 87m at a speed of 65 mph, and also showed the differences in savings by the trucks in each of the three positions within the platoon. At the longest gaps, the last truck saves the most and the platoon leader does not save any energy. As the gaps become shorter, all the trucks save energy and at the shortest gaps, the largest savings are achieved by the middle truck. These results have been incorporated into the MOVES model to estimate energy savings in a traffic micro-simulation for truck platoons operating along a freeway corridor with a high volume of truck traffic for I-710 between the Port of Long Beach and downtown Los Angeles by Ramezani et. al. (2019).

Summary

It is expected that CAVs will reduce fuel consumption and emissions due to their smoother driving behavior, closer headway between vehicles, and also reducing congestion. Because of CAVs' access to preview information about the motions of multiple preceding vehicles, they are less likely to frequently accelerate or decelerate hard, which increases emissions. On the other hand, the enhanced comfort provided by CAVs could potentially increase the VMT and consequently fuel consumption and emissions (Rodier, 2018). It is also quite possible that more AVs will be electric vehicles which would decrease fuel use and emissions. In conclusion, there is no clear evidence to show what the net effect of CAVs will be on the fuel efficiency and emissions in the long term. This is concluded in a recent review of the literature by Rodier (2018) which suggest that CAVs may change the energy and GHG emissions. However, there is a lack of knowledge to determine if this change is positive.

3.4 Section 3 References

Amoozadeh, M., Deng, H., Chuah, C. N., Zhang, H. M., & Ghosal, D. (2015). Platoon management with cooperative adaptive cruise control enabled by VANET. *Vehicular Communications*, 2(2), 110–123. <https://doi.org/10.1016/j.vehcom.2015.03.004>

Arefizadeh, S., & Talebpour, A. (2018). A Platooning Strategy for Automated Vehicles in the Presence of Speed Limit Fluctuations. *Transportation Research Record*. <https://doi.org/10.1177/0361198118784176>

- Aria, E., Olstam, J., & Schwietering, C. (2016). Investigation of Automated Vehicle Effects on Driver's Behavior and Traffic Performance. *Transportation Research Procedia*, 15, 761–770. <https://doi.org/10.1016/j.trpro.2016.06.063>
- Atkins. (2016). Research on the Impacts of CAVs on Traffic Flow - Summary Report, (May). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/530091/impacts-of-connected-and-autonomous-vehicles-on-traffic-flow-summary-report.pdf
- Bailey, Rosenfield, and Z. (2018). Attitudes Toward Effective Time Use in Autonomous Mobility-on-Demand Services in Singapore, 1–8.
- Bailey, N. K. (2016). Simulation and Queueing Network Model Formulation of Mixed and Non-automated Traffic in Urban Settings. Retrieved from <https://dspace.mit.edu/bitstream/handle/1721.1/107069/971130623-MIT.pdf?sequence=1>
- COWI-PTV Group 2019 The Oslo Study – How Autonomous Cars May Change Transport in Cities Report to Ruter, the Oslo public transport company April 2019
- de Looft, E., Correia Homem de Almeida, G., van Cranenburgh, S., Snelder, M., & van Arem, B. (2018). Potential changes in value of travel time as a result of vehicle automation: a casestudy in the Netherlands. *TRB 97th Annual Meeting Compendium of Papers*, 31(15).
- Eilbert, A., L. Jackson, G. Noel, et al. (2018). A Framework for Evaluating Energy and Emissions Impacts of CCAV Traffic Microsimulations. *Transportation Research Board 92th Annual Meeting*, (5), 1–19. <https://doi.org/10.1111/bcp.12106>
- Guériau, M., Billot, R., El Faouzi, N.-E., & Monteil, J. (2018). Contribution to the Assessment Methodology for Connected and Automated Vehicles on Traffic. Retrieved from <https://trid.trb.org/view/1495033>
- Haboucha, C. J., Ishaq, R., & Shiftan, Y. (2017). User preferences regarding autonomous vehicles. *Transportation Research Part C: Emerging Technologies*, 78, 37–49. <https://doi.org/10.1016/j.trc.2017.01.010>
- ITF-OECD 2015 Urban Mobility System Upgrade: how shared self-driving cars could change city traffic International Transport Forum at the Organization for Economic Cooperation and Development 2015
- Ivanchev, J., Knoll, A., Zehe, D., Nair, S., & Eckhoff, D. (2017). Potentials and Implications of Dedicated Highway Lanes for Autonomous Vehicles, 1–12. Retrieved from <http://arxiv.org/abs/1709.07658>
- Kockelman, K., Avery, P., Bansal, P., Boyles, S. D., Bujanovic, P., Choudhary, T., ... Stewart, D. (2016). Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report Implications of Connected and Automated Vehicles on the Safety and Operations of Roadway Networks: A Final Report. *Fhwa/Tx-16/0-6849-1*, 7. <https://doi.org/FHWA/TX-16/0-6849-1>
- Krueger, R., Rashidi, T. H., & Rose, J. M. (2016). Preferences for shared autonomous vehicles. *Transportation Research Part C: Emerging Technologies*, 69, 343–355. <https://doi.org/10.1016/j.trc.2016.06.015>

- Liu, H., Kan, X. (David), Shladover, S. E., Lu, X.-Y., & Ferlis, R. A. (2018a). Quantifying Influences of Cooperative Adaptive Cruise Control (CACC) Vehicle String Operation Strategies on Mixed Traffic Flow. Retrieved from <https://trid.trb.org/view/1495866>
- Liu, H., Kan, X. (David), Shladover, S. E., Lu, X. Y., & Ferlis, R. E. (2018b). Impact of cooperative adaptive cruise control on multilane freeway merge capacity. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, 22(3), 263–275. <https://doi.org/10.1080/15472450.2018.1438275>
- Liu, H., Kan, X. (David), Shladover, S. E., Lu, X. Y., & Ferlis, R. E. (2018c). Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities. *Transportation Research Part C: Emerging Technologies*, 95(December 2017), 261–279. <https://doi.org/10.1016/j.trc.2018.07.027>
- Mahmassani, H. (2017). Autonomous Vehicles and Traffic Physics: Framing the Questions, (July 2016). <https://doi.org/10.13140/RG.2.2.35250.40647>
- Makridis, M., Mattas, K., Ciuffo, B., Raposo, M. A., Toledo, T., & Thiel, C. (2018). *Connected and Automated Vehicles on a freeway scenario. Effect on traffic congestion and network capacity*. Retrieved from https://ec.europa.eu/jrc/sites/jrcsh/files/connected-automated-vehicles-traffic-congestion-network-capacity_111621.pdf
- McAuliffe, B., Lammert, M., Lu, X.-Y., Shladover, S. et al.,(2018) “Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control,” SAE Technical Paper 2018-01-1181, doi:10.4271/2018-01-1181.
- Morando, M. M., Truong, L. T., & Vu, H. L. (2017). Investigating safety impacts of autonomous vehicles using traffic micro-simulation. *Australasian Transport Research Forum 2017 Proceedings*, (November), 1–6.
- Najm, W. G., Koopmann, J., Smith, J., & Brewer, J. (2010). Frequency of {Target} {Crashes} for {IntelliDrive} {Safety} {Systems}, (October). <https://doi.org/10.1371/journal.pone.0181675>
- Nazari, F., Noruzoliaee, M., & Mohammadian, A. (Kouros). (2018). Shared Mobility vs . Private Car Ownership: A Multivariate Analysis of Public Interest in Autonomous Vehicles. *97th Annual Meeting Transportation Research Board*, 04289(18), 1–7.
- PTV, 2017. Autonomous vehicle lateral space - example description. PTV AG, Karlsruhe.
- Rau, P., Yanagisawa, M., Najm, W.G., 2015. Target crash population of automated vehicles. 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Gothenburg , Sweden.
- Ramezani, H., Lu, X.-Y. and Shladover, S. (2019), Calibration of Motor Vehicle Emission Simulator (MOVES) to Incorporate Effect of Truck Platooning, Transportation Research Board Annual Meeting, Paper No. 19-05831.
- Rios-torres, J., & Malikopoulos, A. A. (2017). Impact of Connected and Automated Vehicles on Traffic Flow. *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*. <https://doi.org/10.1109/ITSC.2017.8317654>

- Rodier, C. (2018). Travel Effects and Associated Greenhouse Gas Emissions of Automated Vehicles A White Paper from the National Center for Sustainable Transportation About the National Center for Sustainable Transportation, (April). Retrieved from https://ncst.ucdavis.edu/wp-content/uploads/2015/10/NCST_Rodier_Automated-Vehicles-White-Paper_APRIL-2018.pdf
- Steck, F., Kolarova, V., Bahamonde-Birke, F., Trommer, S., & Lenz, B. (2018). How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting. *Transportation Research Record*. <https://doi.org/10.1177/0361198118757980>
- Talebpour, A., Mahmassani, H. S., & Elfar, A. (2017). Investigating the Effects of Reserved Lanes for Autonomous Vehicles on Congestion and Travel Time Reliability. *Transportation Research Record: Journal of the Transportation Research Board*, 2622, 1–12. <https://doi.org/10.3141/2622-01>
- Van Arem, B., Van Driel, C. J. G., & Visser, R. (2006). The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, 7(4), 429–436. <https://doi.org/10.1109/TITS.2006.884615>
- Wan, N., Vahidi, A., & Luckow, A. (2016). Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. *Transportation Research Part C: Emerging Technologies*, 69, 548–563. <https://doi.org/10.1016/J.TRC.2016.01.011>
- Yap, M. D., Correia, G., & van Arem, B. (2016). Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips. *Transportation Research Part A: Policy and Practice*, 94, 1–16. <https://doi.org/10.1016/j.tra.2016.09.003>
- Yue, L., Abdel-Aty, M., & Wang, L. (2018). Assessment of the Safety Benefits of Connected Vehicle Technologies. *Transportation Research Board 97th Annual Meeting*, (407).
- Zhao, Y. ; K. M. K. (2017). Anticipating the Regional Impacts of Connected and Automated Vehicle Travel in Austin, TX, 1–13.

4. TRAFFIC SIMULATION AS A TOOL FOR CAV ANALYSIS: STATE OF THE PRACTICE

4.1 Overview of CAV Analysis Tools

A range of CAV technologies exist or are emerging that serve a variety of purposes, whether it be to increase safety or to improve the efficiency and flow of traffic or transportation services. Some of these CAV technologies seek to correct or safeguard against human error, such as drifting into the opposite lane of traffic or failing to brake safely behind a leading vehicle. Traffic microsimulation simplifies complex human behaviors so that they can be tractably modeled, and in so doing driver behavior models are generally premised on the assumption that drivers observe strict lane-following discipline and keep a safe distance from leading vehicles.

That point was reinforced in the 2017 Final System Requirements for a CAV analysis/modeling/simulation framework for FHWA, (Mahmassani, Elfar, Shladover, Ma, and Huang 2017), which also noted that current tools assume that vehicles operate independently without close coordination or cooperation with other vehicles. The authors note that “as a result, current traffic analysis tools are not well suited for evaluating connected and automated vehicle technology applications due to their inability to incorporate vehicle connectivity as well as autonomy.” Their report defines system requirements for updated tools to evaluate the impacts of CAV technology on transportation systems at the strategic and operational levels.

In parallel with the FHWA requirements effort, there have been some research efforts to use and modify existing tools to attempt to analyze CAVs. For example, a Fehr and Peers’ Eliot Huang (2017) presentation and a related research paper by Stanek, Huang, Milam, and Wang 2017 described modifications to Vissim in two case studies on highway segments in California. They discuss adjustments made to the Wiedemann car following algorithms to more closely resemble CAV operation. The case studies were used to detail the varying levels of AV implementation that were analyzed, the parameter changes that were applied, and how changes affected operations.

Of the CAV technologies and strategies described earlier in this report, the following are identified as candidates for further study through microsimulation of freeway or arterial corridors. They lend themselves to a reasonable representation of driver behavior in traffic microsimulation models:

- Cooperative-Adaptive Cruise Control (CACC)
- Speed Harmonization
- Advanced Lane Detection
- Intelligent Traffic Signals
- Traffic Jam Assist (TJA)

The following strategies are less well-suited for corridor microsimulation. These may be better analyzed in a system-wide context in which demand (for routes or services) is more robustly treated than is

typical in microsimulation because they involve attempts to quantify supply (capacity) and to dynamically match it with demand:

- Dynamic Route Guidance
- Dynamic Transit Operations
- Dynamic Ridesharing

The impacts of the two following strategies specifically in regard to CAVs can be addressed through microsimulation when there is more consensus on how the technology will inform or instruct CAV behavior (e.g., Queue Warning systems, where it is unclear how the driver or CAV will translate warning information to action):

- Queue Warning
- Managed Lanes

A factor that confounds, and will continue to confound, practitioners and researchers seeking to model CAVs with greater clarity and confidence is that the behaviors of many of the technologies are or will be dictated by proprietary systems, whether on-board a vehicle, embedded in a traffic signal controller, or installed in a TMC. For example, the specific algorithms in ALMA systems are proprietary. However, as advanced lane detection becomes a reliable supporting technology, systems like ALMA are likely to see increasing interest among researchers wishing to evaluate lane management strategies in a microsimulation environment.

Similarly, CACC algorithms are also likely to be proprietary, but given their close relationship to ACC, the behaviors of which are reasonably well known, it is possible to make simplifying but reasonable assumptions about CACC to support microsimulation. Indeed, CACC is one of the most prevalent CAV strategy under study in the literature.

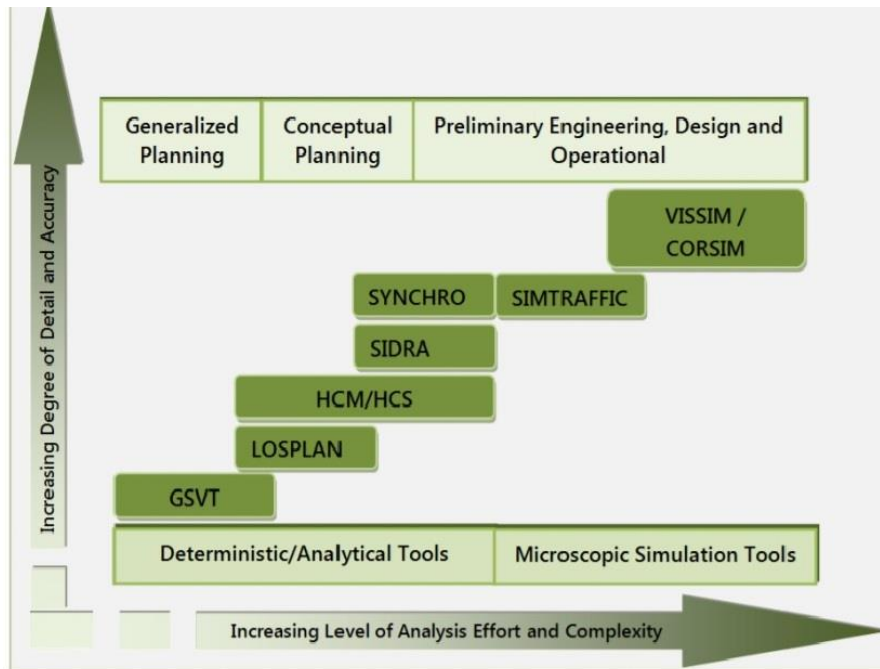
The remainder of Section 4 will focus on the use of travel demand model and traffic simulation models to analyze CAVs.

4.2 Incorporating CAV Characteristics and Impacts into Travel Modeling

Travel modeling uses a combination of travel demand and traffic simulation modeling. The authors of this report have observed in their research that the common practice in Ohio and the industry is to use a travel demand model (Bernardin, 2018) with the final outputs of origin-destination matrices by time of day, zone, and mode followed by a static traffic assignment process to determine equilibrium traffic flows on the roadway network. The results of the travel demand model process are then utilized in concert with observed demand data to help inform the demand characteristics to be applied in a traffic dynamics model (e.g. analytical/deterministic tools, traffic signal optimization tools, macroscopic simulation models, mesoscopic simulation models, microscopic simulation models). Figure 12 shows the range of traffic analysis models. The introduction of CAVs to the practice of forecasting and modeling poses added challenges to the process of demand and dynamics modeling as both types of models have

been built off observable patterns in movement. With CAVs comprising primarily future technologies, their impacts cannot yet be readily observed in action in the transportation system.

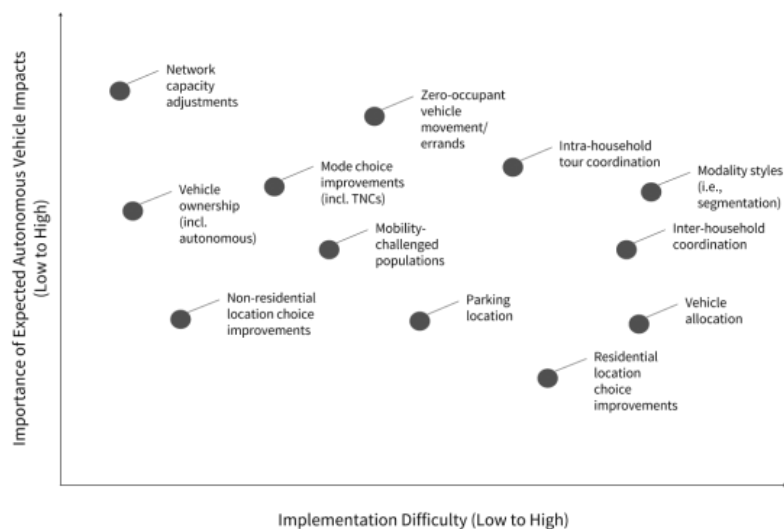
Figure 12: Traffic Analysis Tools



Source: *Traffic Analysis Handbook Florida Department of Transportation, March 2014*

While demand and dynamics models have not been developed to emulate CAV capabilities, methods for incorporating CAV characteristics into commercial software have been implemented to allow analysts to analyze the sensitivity of the transportation system to certain postulated impacts of CAVs based on assumed levels of penetration into the vehicle fleet. In the realm of travel demand models, a review of existing literature identified a variety of CAV impacts to standard modeling practice (see Figure 13).

Figure 13: TF Resource - Autonomous Vehicles: Modeling Frameworks



Source: *TFResource wiki http://tfresource.org/Autonomous_vehicles:_Modeling_frameworks*

4.2.1 Travel Demand Models

In assessing the impacts of CAVs on demand models, a distinction must be made between aggregate (trip-based) models and disaggregate (activity-based) models. Aggregate models are more limited in how they can internally model CAVs; most adjustments to three- or four-step trip-based models will be imposed as parameter adjustments. Examples of these adjustments would be to add a factor to existing trip tables for returning deadhead trips (CAVs are projected to sometimes travel with zero passengers between trips) or assuming impacts to volume-delay functions (including capacity) based on research from the dynamics side on CAV operations. The charette that led to the *tfresource* wiki page developed several lists of the kinds of adjustments that would be needed to represent the impact of AVs in traffic models. The charette created three separate tables covering activity-based models, trip-based models, and strategic models. The first two tables are shown side by side in Figure 8 below. Each table lists a series of model components or characteristics of traffic demand in a metropolitan area, and notes some of the adjustments (as in the two examples noted above) that would better represent AVs. The difference between the activity-based and trip-based models is in additional characteristics of activity patterns and travel demand in the trip-based model. The adjustments described in Figure 14 can be made in commercial travel demand modeling software or through their interface to external programming, but are not standard routines in the major platforms at this time. Still, the items in these tables provide an excellent starting point for advancing modeling tools to incorporate CAV.

Figure 14: Activity-Based (Left) and Trip-Based (Right) Travel Demand Model Improvements

| Model Component | Model Improvement | Model Component | Model Improvement |
|---|--|---|--|
| Vehicle Ownership and Availability | | Vehicle Ownership and Availability | |
| Vehicle Ownership | Add AV choice | Vehicle Ownership | Add AV choice |
| Vehicle Choice | Add vehicle choice model for AV and CV | Vehicle Choice | Add vehicle choice model for AV and CV |
| Location Choice and Land Use | | Location Choice and Land Use | |
| Urban Form | Adjust parking cost and supply | Urban Form | Adjust parking cost and supply |
| Urban Form | Residential Location | Urban Form | Residential Location |
| Urban Form | Firm Location | Urban Form | Firm Location |
| Destination Choice | Incorporate life cycle variables | Destination Choice | Segment by life cycle segment |
| Parking Choice | Integrated ABM/DTA | Parking Choice | Add zero-occupancy vehicle (deadhead) model |
| Coordinated Activity Patterns and Travel Demand | | Coordinated Activity Patterns and Travel Demand | |
| Daily Pattern Models | Inter-household coordination | Travel Optimization | Consider post-process adjustment for personal and household trip chaining |
| Deadhead Model (new) | Option to return AV home or off-site (deadheading) | Trip Generation | Feedback for induced demand |
| Mode Choice | | Mode Choice | |
| Transit Access | Modify Kiss-and-Ride to include TNC, CAV5 | Deadhead Model | Estimate extra service miles of for-hire shared CAV5s |
| Value of Travel Time | Reduce in-vehicle time coefficient for CAV5s | Deadhead Model | Estimate deadhead miles from personal CAV5 use |
| Additional Modes | Add Taxi/TNC/CAV5 nest in tour/trip mode choice | Mode Choice | |
| Mobility-challenged Groups | Add mode choice options for children, mobility impaired to use CAV5s | Transit Access | Add Kiss-and-Ride to include TNC, CAV5 |
| Network Supply and Route Choice | | Value of Travel Time | Reduce in-vehicle time coefficient for CAV5s |
| Trip Assignment | Separate class for private CAV5s and shared (for-hire) CAV5s | Additional Modes | Add Taxi/TNC/CAV5 nest in trip mode choice |
| Volume Delay | Adjust parameters for CAV5 | Mobility-challenged Groups | Add mode choice coefficients to include mobility limited population Groups |
| Route Choice | DTA/microsimulation | Network Supply and Route Choice | |
| | | Trip Assignment | Separate class for private CAV5s and shared (for-hire) CAV5s |
| | | Volume Delay | Adjust parameters for CAV5 |
| | | Route Choice | DTA/microsimulation |

Source: http://tfresource.org/Autonomous_vehicles:_Modeling_frameworks

Activity-based models are behaviorally more intuitive regarding complex travel movements that may arise from CAVs. With the ability to account for each household and individual traveler's schedule of activities, activity-based models are able to model the demographic impacts on CAV travel by accounting for the age of travelers, vehicle ownership, and the ability to engage in trips that may have otherwise been previously unavailable. Further, as schedules are built, CAVs can impact how much utility additional travel may yield, accounting for the lower burden of travel time and can generate shared vehicle trips with intermediate stops based on vehicle position.

Both activity-based models and trip-based models require modeler-imposed adjustments to the operations of the travel network assignment to replicate research-postulated impacts of CAVs to develop capacity and speed estimates for roadways carrying CAVs. Research and the transportation community at large are working toward integrating travel demand models with a dynamics model such as mesoscopic or microscopic microsimulation modeling, which could more realistically adapt to the presence of CAVs, with the Jacksonville, Florida representing a success in activity-based model and dynamic traffic assignment model integration (Stabler, Bradley, Morgan et al, 2018).

There have been some published findings on travel demand model innovations with respect to CAV enhancements. In the Coordinated Travel -Regional Activity Modeling Platform (CT-RAMP) platform, CAV impacts have been addressed in the levels of travel demand, vehicle routing (including empty trips), and network performance (Vovsha, Vyas, 2018). One key innovation in this platform is a new sub-model that supplements trip and vehicle allocation at the household level with shared CAVs to meet unsatisfied travel demand. This sub-model leads to fewer trips that are foregone or rescheduled and accounts for the cost of parking and vehicle repositioning and the associated impact on demand.

As noted in (Vovsha, Vyas, 2018), network performance adjustments can also be made to evaluate segment capacity and speeds, with the ability to compare factors such as ideal speed and capacity curves against the impacts projected by researchers. The platform has also been adjusted for easy user manipulation of what-if scenarios. Across a wide range of scenarios, impacts include:

- Limited impacts may include modest growth in trip rates, trip length, and VMT
- Moderate impacts may include mode shifts from local transit to rapid transit trips with CAVs providing first-mile and last-mile service
- Substantial impacts may include congestion reduction, substantial growth in trips due to increased modal options, and less joint travel

Exploratory modeling analysis was conducted for CAV influence in Jacksonville, Florida based on use of an integrated activity-based model and dynamic traffic assignment model (Bernardin, 2018).

Enhancements were made to account for CAVs in the activity scheduling and in the network modeling simulation. The activity scheduling was adjusted to allow a new vehicle ownership option for CAVs, a new mode of paid rideshare (could be CAV or human operated), and trip choices were adjusted based on a lower perceived cost of in-vehicle time. (See also the 2018 FHWA report by RSG that described in more detail the Jacksonville results – Stabler, Bradley, Morgan et al 2018.)

The model also adjusted for vehicle dynamics (discussed further below) including: acceleration/deceleration, car following headways, choice of travel speed, and gap acceptance in lane changing. The model was also adjusted so vehicle-controlled functions (which vary based on the user-defined vehicle capabilities) are deterministic, predictable, and homogenous. A large number of scenarios were run systematically adjusting for CAV adoption between private and shared ownership, the provision of reserved CAV capacity or lanes, and automation levels. Aside from the baseline model, all other scenarios represented high levels of mixed CAV and non-CAV traffic and resulted in several key findings of Bernardin (2018):

- Shared CAV trip distances are much shorter than non-CAV trip distances, but private CAV trip distances are longer.
 - Subsequently, scenarios with a high proportion of shared use vehicles compared to private vehicles lead to a VMT reduction.
- Vehicle-hours of delay fell both above and below baseline model levels, with the highest delays including high levels of private CAV use. The largest reductions in delay were roughly 15%, but the largest increase in delay was over 25%.

4.2.2 Traffic Simulation Modeling

PTV's Vissim and Caliper's TransModeler both provide flexibility in the representation of basic driver behaviors and vehicle types in their latest software versions that allow the user to build CAV operating characteristics into the vehicle fleet. As previously referenced in the Jacksonville synopsis, key traffic flow parameters impacted by CAV include:

- Acceleration/deceleration
- Car following headways
- Platoon size and formation
- Choice of travel speed
- Gap acceptance in lane changing
- Removal of stochastic processes on vehicle-controlled functions
- Fleet and vehicle type parameters that allow different adoption patterns and levels of autonomy

Beyond the driver behavior and fleet adjustments that are now streamlined in commercial microsimulation software, custom enhancements are still needed to better reflect V2V and V2I communications:

- Enhanced mobility applications such as platooning and adaptive speed control
- Safety applications such as dynamic conflict warning or automated braking to prevent collisions
- Real-time updates to demand and routing based on emerging mobility options
- Dynamic operations of the network and traffic control including reservation-based signal operations.

Prior to commercial mainstreaming of CAV functionality, researchers from University of California at Berkeley performed on-the-road testing of cooperative adaptive cruise control (CACC), which serves as a good surrogate for CAV operations on freeways due to vehicle speed control and vehicle gap control.

The research team used their field operations data to develop dynamics models reflecting the observed behaviors with a microsimulation tool and customizations to introduce logic control to switch between manual driving mode and vehicle control mode. The manual driving mode was calibrated to field conditions before running scenarios at various CACC penetration levels. The results show that for a congested freeway corridor an increase in platooning-capable vehicles to between 20% and 40% of the vehicle fleets leads to dramatic increases in travel speed and resultant decrease in delay. Freeway capacities in areas outside the influence of freeway ramps were estimated to reach 3,500 vehicles per lane, a 67% increase. (Liu, Kan, Shladover et al, 2017). The reference also contained a history of other studies of CACC in the literature.

Base Vissim operations were customized in Liu, Kan, Shladover et al (2017) to test CACC based on the field data. The customizations to Vissim included the following added functionality:

- Defining constant headways to maintain when operating in a platoon;
- Applying the cut-off criteria to determine whether vehicles should join a platoon;
- Identifying when splitting a platoon would occur; and,
- Resetting modified platoon behaviors to the vehicle's individual behavioral preferences when operating in isolation.

4.3 Overview of past Work on Model Use for States or Regional Agencies

Numerous evaluations have been completed for strategic-level decision making by states and MPOs in advancing awareness and preparation for CAVs, making the development of an exhaustive list of limited use. However, a short synopsis of several early applications of CAV modeling is provided below.

- *Capital Area MPO (Austin, TX) (Zmud, Sener, and Wagner)*: CAMPO utilized the application of a trip-based model to multiple scenarios where parameters were modified to replicate postulated CAV effects, such as a doubling of freeway capacity, a ten percent increase in arterial capacity, and mode shifts from transit to either single-occupant vehicles or high-occupancy vehicles. All scenarios estimated an increase in VMT between two percent and eight percent. However, the additional capacity on the system led to an estimated 50% decrease in the portion of VMT operating under congested conditions (VMT while traversing a segment at demand greater than or equal to 85% of segment capacity). For further information, see *Accounting for AV/CV in Long-Range Plans Using Current Travel Demand Models*, Kevin Hall (2017)
- *Puget Sound Regional Council (Seattle-area, WA) (Childress et. al.)*: PSRC developed an activity-based model application where roadway capacities, lower perceived cost of in-vehicle travel time, and significantly reduced parking costs were considered. The three factors were added to build upon one another, with the initial scenario considering only capacity adjustments and the final scenario considering all three factors. The results of the scenarios estimated a modest increase in the metro-wide VMT of 3 to 5 percent, but VHT for the metro was estimated to drop between 2 and 4 percent due to roadways less frequently operating at slower, congested speeds. For further information, see *Using an activity-based model to explore the potential*

impacts of automated vehicles Suzanne Childress, Brice Nichols, Billy Charlton, Stefan Coe (2015).

- Florida DOT*: Florida DOT developed a tool called TransFuture to look at emerging technologies and societal trends with CAV as a major factor. The tool is built on research of exogenous factors to apply to the regional travel demand models within the state and then uses probabilistic techniques to synthesize a range of potential impacts based on user specified factors, ranging from: CAV adoption, e-commerce, ride sharing, labor force impacts from automation, etc. The tool is a scenario planning decision support tool; due to its recent development, it has not been utilized in a published scenario planning exercise. Though the tool runs off data from regional travel demand models, its output is corridor-focused in nature. For further information, see *TransFuture - Innovate the Future of Transportation*, Zielinski, John; Roy, Santanu (2017).
- Iowa DOT*: In conjunction with statewide planning for rural Interstate 80, Iowa DOT developed a scenario analysis using microsimulation tools customized to model a mixed fleet of vehicles between CAV and human-operated vehicles on representative freeway facilities. The scenarios ranged from near-term aggressive CAV adoption (25% by 2025) to both conservative (20%) and aggressive (85%) projections for future year 2040. The customized microsimulation model was used to develop a potential curve of lane-capacity to CAV adoption, showing estimated capacities near 3,000 vehicles per lane at 85% adoption. The model results showed an estimated net increase in peak-hour speeds of up to 2% above existing conditions and also a net decrease in demand to capacity ratio of 35% under twice the traffic volume present in existing conditions. For further information, see *Interstate 80 Planning Study: Automated Corridors*. Iowa Department of Transportation (2017).

4.3.1 Vissim Customization

Vissim is a traffic dynamics model focused on the microscopic (individual vehicle, sub-1 second timescale) simulation of vehicles. Vissim has been used in several past cases to test the sensitivities of CAV technology and has seen recent added functionality for CAVs both through development of Vissim's own interface and through external programs (Stanek, Huang, Milam, and Wang 2017). In addition, there was some early research examining automated technologies using Vissim (Thanh-Son Dao, Christopher Michael Clark, Jan Paul Huissoon 2007 and 2008).

Table 7 describes common CAV behaviors that may impact future corridor operations based on past research (list compiled by PTV, reprint Fehr and Peers) where the highlighted entries can be modeled within Vissim's base programming and the unhighlighted entries can be modeled in Vissim then used in combination with external programs that interface with Vissim. Note that line 4 in the list (Keep constant speed with no or smaller oscillation at free flow) can now be modified within Vissim's base functionality as of the release of Vissim 11.

Table 7: Vissim CAV Use Cases

| | Connected and Autonomous Vehicle Behavior | Recommended Model Adjustment |
|----|---|--|
| 1 | Keep smaller standstill distances | W74: change W74ax parameter, W99: change CC0 parameter |
| 2 | Keep smaller distances at non-zero speed | W74: change W74ax, W74bxAdd, and W74bxMult parameters; W99: change CC0, CC1, and CC2 parameters |
| 3 | Accelerate faster and smoothly from standstill | W74: change acceleration functions, W99: change acceleration functions and CC8, CC9 parameters |
| 4 | Keep constant speed with no or smaller oscillation at free flow | COM Interface or External Driver Model/Driving Simulator Interface |
| 5 | Follow other vehicles with smaller oscillation distance oscillation | W74: reduce W74bxMult or set it to 0, W99: change CC2 parameter |
| 6 | Form platoons of vehicles | COM Interface or External Driver Model/Driving Simulator Interface |
| 7 | Following vehicles react on green signal at the same time as the first vehicle in the queue | COM Interface or External Driver Model/Driving Simulator Interface |
| 8 | Communicate with other AVs, i.e. broken down vehicle and others avoid it | COM Interface or External Driver Model/Driving Simulator Interface |
| 9 | Communicate with the infrastructure, i.e. vehicles adjusting speed profile to reach a green light at signals | COM Interface or External Driver Model/Driving Simulator Interface |
| 10 | Perform more co-operative lane change as lane changes could occur at a higher speed co-operatively | Switch to cooperative lane change, change maximum speed difference, and change maximum collision time |
| 11 | Smaller lateral distances to vehicles or objects in the same lane or on adjacent lanes | Same lane – change default behavior when overtaking on the same lane and define exceptions for vehicle classes |
| 12 | Exclusive AV lanes, with and without platoons | Define blocked vehicle classes for lanes, or define vehicle routes for vehicle classes, use COM for platooning |
| 13 | Drive as CAV on selected routes (or areas) and as conventional human controlled vehicles on other routes; i.e. Volvo DriveMe project | Use different link behavior types and driver behavior for vehicle classes; and/or (depending on complexity of CAV behavior) COM Interface |
| 14 | Divert vehicles already in the network onto new routes and destinations; i.e. come from a parking place or position in the network to pick up a rideshare app passenger on demand | COM Interface, Dynamic Assignment required (allows access to paths found by dynamic assignment, vehicles can be assigned a new path either when waiting in parking lot or already in the network, if path starts from vehicles current location) |

Source: PTV and Fehr Peers

The following will focus on three elements of Vissim that shape its suitability to CAV modeling: data and scenario structure, internal vehicle behavior, external network and vehicle adjustment.

Data and scenario structure: Vissim can adopt CAVs into the model process based on an open structure that allows users to custom-define vehicle types, vehicle attributes, and interactions of network elements with specific vehicle types. Vissim's flexibility allows development of vehicles that can be treated with either enhanced internal driver behavior models or interface with custom scripting. Further, Vissim's structure to tie vehicle demands and the attributes of network elements to a user

defined scenario allows the flexibility to evaluate a range of CAV operating characteristics. For example, a base Vissim model can be coded for only manual vehicles in the fleet, but then the same scenario can easily be replicated and the vehicle fleet adjusted to represent travel with a 50% manual vehicle fleet and 50% CAV fleet.

Built-in vehicle behavior: Vissim uses two car following behaviors known as Wiedemann 74 and Wiedemann 99 for typical auto behavior. Vissim leaves the selection of the values in the Wiedemann formula to be defined by the model user. One of the simplest adjustments to Vissim to test CAV behavior is through the use of the Wiedemann model to adjust the model to set smaller distances between vehicles (both in stopped conditions and while in motion), faster and smoother starts from a stop, and following other vehicles with negligible variation in following headway.

Table 8 shows a comparison of the driver behavior parameters that can be modified by the user within Vissim to describe CAV operations (Marando, Truong, Vu.; Stanek et. al. 2017). The table depicts default driver behavior for manually-operated vehicles, new defaults for CAV vehicles released with Vissim 11 (PTV Group), and parameters tested by researchers documented in this literature review. The values shown in Table 8 are included to illustrate the types of parameters that have been adjusted in Vissim models as the field of CAV modeling continues to evolve.

Note: the study team that prepared this document does not recommend adopting any of these values in the literature review at this time as the field continues to develop. For the purposes of testing, the study team suggests using parameter values used on recent CAV Vissim simulation completed by HDR, which are largely based on those included in Vissim 11. Parameter values suggested for testing are shown in Table 8 under the HDR heading.

Table 8: Vissim Parameter Ranges

| Car Following - Freeway (Wiedemann 99) | Fehr & Peers | Manual vehicle | AV Cautious | AV Normal | AV All-knowing | Atkins | PTV | HD |
|--|--------------|----------------|-------------|-----------|----------------|--------|------|------------|
| | | | | | | | | CAV Lea |
| cc0 - Standstill distance (m) | 1.24968 | 1.5 | 1.5 | 1.5 | 1 | 0.5 | 0.75 | |
| cc1 - Headway Time (s) | 0.25 | 0.9 | 1.5 | 0.9 | 0.6 | 0.5 | 0.45 | |
| cc2 - Following variation (m) | 9.84 | 4 | 0 | 0 | 0 | 0 | 2 | |
| cc3 - threshold for entering "following" | -12 | -8 | -10 | -8 | -6 | - | - | -8 |
| cc4 - negative "following" threshold | -0.35 | -0.35 | -0.1 | -0.1 | -0.1 | 0 | -0.1 | |
| cc5 - positive "following" threshold | 0.35 | 0.35 | 0.1 | 0.1 | 0.1 | 0 | 0.1 | |
| cc6 - speed dependency of oscillation | 0 | 11.4 | 0 | 0 | 0 | 0 | 0 | |
| cc7 - oscillation acceleration (m/s ²) | 0.249936 | 0.25 | 0.1 | 0.1 | 0.1 | 0.45 | 0.25 | |
| cc8 - standstill acceleration (m/s ²) | 3.499104 | 3.5 | 3 | 3.5 | 4 | 3.9 | 3.5 | |
| cc9 - acceleration at 80 km/h (m/s ²) | 1.499616 | 1.5 | 1.2 | 1.5 | 2 | - | - | 1.5 |
| Car Following - Arterial (Wiedemann 74) | | | | | | | | |
| Average standstill distance (m) | 1.499616 | 2 | | | | | | |
| Additive part of safety distance | 1.5 | 2 | | | | | | |
| Multiplicative part of safety distance | 2.25 | 3 | | | | | | |
| Car Following - Options | | | | | | | | |
| Use Implicit Stochastics | | Y | N | N | N | | | |

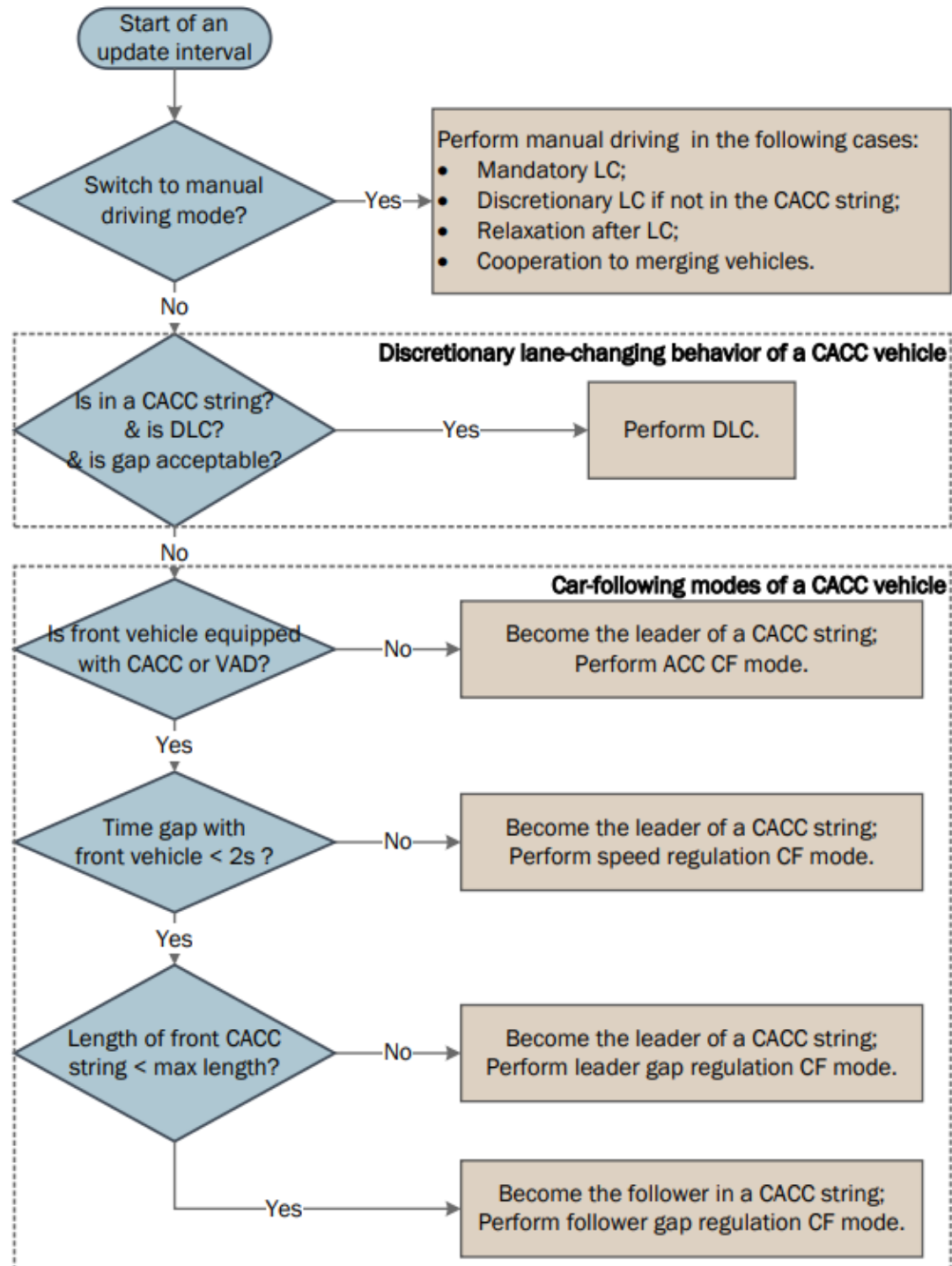
| | | | | | | | | | |
|-----------------------------------|--|---|---|---|---|--|--|--|--|
| Enforce Absolute Braking Distance | | N | Y | N | N | | | | |
|-----------------------------------|--|---|---|---|---|--|--|--|--|

Source: HDR

External vehicle behavior: Beyond parameters that can be user-adjusted in the Wiedemann model, Vissim allows more advanced CAV capabilities to be modeled through extensions to the program such as the External Driver Model and the Component Object Model (COM) Interface. The COM interface allows vehicle and network properties to be accessed and modified by an external program during simulation run time to execute more complicated movements and travel behaviors. With respect to CAV operations, some of the most significant additions that must be made externally include: formation of platoons of vehicles, infrastructure messages to vehicles, and vehicle messages to other approaching vehicles.

Figure 15 shows the logic to add platooning as a model add-in to Vissim. The diagram is specific to behavior of the vehicle, based on field and simulation test research by University of California Berkeley. Liu, Kan, Shladover et al 2017. The implementation of this logic in external programming utilized through Vissim's COM interface is not standard at this time and not documented in this report. A base set of programming for ODOT use of CAV platoon modeling will be developed in future phases of this project.

Figure 15: Added Platooning Logic



Source: "Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities" p 269
Liu, Kan, Shladover et al 2017

As shown in Table 9, Vissim has been used in a number of ways to test CAV as self-reported by the developer of Vissim, PTV. The central thread in each of these uses is the postulation of parameters that are logical to change and parameters that would remain the same. Once the set of parameters to change is identified, the authors typically assert the amount of change in the parameter based on judgment or similarity to technology with measured deployments.

Table 9: Example Use of Vissim to Test CAV

| Study | Application of CAV Parameters |
|--|--|
| DriveMe Volvo (Gothenburg, Sweden) ¹ | <ul style="list-style-type: none"> Used internal driving behavior parameter adjustments to evaluate impact of 100 pilot self-driving cars on public roads in typical conditions |
| Study on CAV Impact to Traffic Flow and Capacity (United Kingdom Department of Transport) ² | <ul style="list-style-type: none"> Used external model to apply CAV driving behavior adjustments |
| Impacts of CAVs (City of Costa Mesa, CA) ³ | <ul style="list-style-type: none"> Changed internal driving behavior parameters |
| Investigating safety impacts of autonomous vehicles using traffic micro-simulation, Monash University ⁴ | <ul style="list-style-type: none"> Reduced standstill distance by 50-67% Reduced time headway by 44-50% Reduced variation in following behavior Increased to no change in vehicle acceleration Increase to no change in look ahead distance |

Source: HDR Inc.?)

As studies have tested CAV behaviors and impacts in simulation tools, the simulation tools also continue to advance. PTV recently released Version 11. The release notes highlight new driver behavior for CAVs including: splitting the number of look ahead objects from the limit on number of look ahead vehicles, flexibility to enforce absolute braking distance, flexibility to remove the random elements of the car following model to allow for constant time headway following, and specification of car following by vehicle class to allow for varying safe following distances based on the presence or absence of a lead CAV.

4.3.2 TransModeler Customization

TransModeler is a traffic simulation software developed by Caliper Corporation. The software is capable of simulation at multiple resolutions – macroscopic, mesoscopic, and microscopic – but is principally used for microsimulation at sub-second time resolutions for planning, design, and engineering. As previously noted, TransModeler was recently used in a study for the Federal Highway Administration (FHWA) to analyze the impacts of CAVs in a model of Jacksonville, FL spanning the North Florida Transportation Planning Organization’s (NFTPO) six-county service area. The microsimulation-based dynamic traffic assignment (DTA) model interfaced with the NFTPO’s activity-based model (ABM), both

¹ PTV Vissim and Connected and Automated Vehicles April 2017 PTV Group presentation to San Francisco Institute of Traffic Engineers

http://www.sfbayite.org/wp-content/uploads/2017/04/1%20VISSIM_CAV_SFITE_April2017.pdf

² <https://www.gov.uk/government/publications/driverless-vehicles-impacts-on-traffic-flow>

³ Stanek, D., R. T. Milam, E. Huang, et al. 2017

⁴ http://atrf.info/papers/2017/files/ATRF2017_Abridged_Paper_50.pdf

of which accounted for CAV adoption, so that dynamic model runs between the ABM and DTA could be run in an integrated feedback loop.

All of the CAV capabilities in TransModeler can be modeled off the shelf without the need for any additions or external programming. Caliper has placed emphasis on ease-of-use in its development of CAV capabilities in TransModeler by requiring the user only to identify the automation level for a class of vehicle, leaving it to the software to make the appropriate adjustments associated with that level of automation. This removes the dangers associated with requiring users to make subjective, and potentially unqualified, adjustments to complex driver behavior and vehicle performance models, of which they may not have deep knowledge, to unknown net effect. Thus, the application of automated vehicles in TransModeler simply requires identifying an automation level with the appropriate vehicle classes and identifying permissions for certain automation levels with a set of lanes in the network. For academics, researchers, and expert practitioners with deep knowledge of driver behavior algorithms and vehicle dynamics, further customization is available either by modifying the parameters of an existing car following model or through use of the application programming interface (API).

In summary, there are three ways to model CAVs in TransModeler:

1. Apply TransModeler's off-the-shelf CAV capabilities:
 - SAE International-defined and USDOT-adopted levels of vehicle automation (Level 0 through Level 5) can be applied by vehicle class. See Table 10 for a summary on the specific effects by automation level.
 - Exclusive AV lanes can be designated and the permitted level of automation on those lanes can also be defined. This allows vehicles to operate as AV on certain roads and as a human-controlled vehicles on other roads.
 - Trip lists that explicitly identify AV trips, such as what is used in an ABM model, can be used as a source of demand.
 - Cooperative adaptive cruise control (CACC) operations can be applied by selecting a pre-existing Constant Time Gap (CTG) car following model. The car following model can be applied to certain vehicle groups/classes and/or only to certain links in the network. This allows the flexibility to apply CACC operations only to certain vehicle classes and/or certain parts of the network. Current research indicates headways should be between 0.5 and 1.1 seconds. Please see the section below entitled *Customization of TransModeler for Simulating Connected Vehicles* for more details.
2. Customize the driver behavior model parameters, including those of six car following models supported by TransModeler, to achieve the following effects:
 - Shorter following headways at non-zero speeds
 - Shorter standstill distances at a zero speed
 - Faster, more uniform, acceleration from standstill
 - Shorter reaction times to leading vehicles and to start of green at signalized intersections
 - More cooperative lane changing

- Increased tolerance for larger speed differentials between vehicles in adjacent lanes that are narrower or that have narrower lateral clearances
3. Utilize the API to apply deeper customization of CAV behavior. Please see the section below entitled *TransModeler Application Programming Interface Customizations for CAVs* for more details. In summary, the API permits achieving the following effects:
- Communication between vehicles (V2V) and between vehicles and infrastructure (V2I).
 - Vehicle platooning enabled by V2V communication.
 - Diversion or rerouting of vehicles to alternate routes or to intermediate or final destinations, whether to service a rideshare request or in response to routing information enabled by V2I communication.

It is worth noting that two of the six car following models supported in TransModeler are Vissim’s Wiedemann 74 and Wiedemann 99 models, enabling many of the Vissim customizations for CAVs in Vissim to be applied in TransModeler.

Customization of TransModeler for Simulating Automated Vehicles

To represent the capabilities of automated vehicles, TransModeler allows the user to choose from the six SAE International-defined and USDOT-adopted levels of vehicle automation (Level 0 through Level 5) – which include automation of acceleration, steering, and other aspects of driving – and apply that level of automation to a vehicle class (refer back to Figure 2 for the SAE level diagram). Table 10 summarizes the specific effects of each level of automation in the simulation environment

It should be noted, however, that the main differences between Automation Levels 3-5 is how much the driver must intervene:

- The driver must always be ready take control over the vehicle - Level 3, Conditional Automation
- The driver must be ready to take control of the vehicle only when notified - Level 4, High Automation
- The driver does not need to take control over the vehicle at all - Level 5, Full Automation

In a simulation environment, the line between driver and vehicle is not well defined. In much of the traffic simulation literature, in fact, the driver and vehicle are conflated, referred to as the “driver-vehicle entity,” or DVE. The same is true in TransModeler. No assumptions were made in TransModeler to represent how requests to intervene should be simulated. Hence, Levels 3 through Level 5 have no substantive differentiation in TransModeler at the time of this writing.

Table 10: TransModeler Automation Level Use Cases

| Automation Level | Driver Behaviors/Parameters Altered to Emulate Automation | Effects of Automation |
|------------------|---|-----------------------|
| 0 | None <i>Driving decisions subject to all elements of human perception, preference, error</i> | n/a |

| | | |
|----------------------|--|---|
| 1A (Acceleration) | Headway buffers <i>Reflect a safety factor human drivers apply in their perceptions of the headways with the vehicle in front of them and in combination with the headway represents the perceived headway. A larger headway buffer represents a more cautious driver desiring to follow at a greater headway.</i> | CAVs apply a zero buffer, trusting the sensors onboard the vehicle, which are not subject to errors of human perception or caution. |
| | Variance of acceleration <i>Randomizes acceleration rates applied by different drivers under the same conditions to account for human factors.</i> | This factor will be set to 0 so that a CAV will always apply the same acceleration rate under the same operating conditions. |
| | Modified GM car following model headway thresholds <i>These parameters demarcate the thresholds in following headways (in seconds) at which drivers apply an emergency braking rate, accelerate, or decelerate to follow a leader (car following), or, absent a leader, accelerate or decelerate to achieve a desired speed.</i> | Similar to the variance of acceleration, a CAV will always transition from one regime to another at the same headway thresholds, which are varied across the non-CAV driving population to account for human factors. |
| | Stopped gap distances <i>The distance between stopped vehicles</i> | CAVs will always stop behind the lead vehicle at 0 speed at the same bumper-to-bumper gap distance, which is otherwise randomized across the driving population to account for human factors. |
| 1B (Steering) | Random error term ϵ in lane changing gap acceptance model <i>The variance of the random error term associated with human perception and risk tolerance</i> | The decision to change lanes is still part of human decision-making, but gap acceptance and steering into the gap have no probabilistic error-term and hence are deterministic across vehicles with Level 1B automation. |
| | Sensitivity to lane connector connectivity bias <i>Represents anticipation /awareness of lane drops</i> | CAVs will exhibit no sensitivity to lane connector bias because it reflects driver (i.e., human) anticipation or awareness of factors such as lane drops, unless or until a proposed CAV technology supplies this information to the vehicle. |
| 2 | All of the behaviors/parameters altered for Level 1 (A and B) | CAVs with Automation Level 2 have aspects of both acceleration (1A) and steering (1B) automated and so assimilate all of the behaviors ascribed above to Level 1 automation. |
| 3 | All of the behaviors/parameters altered for Level 2 | Level 3 automation automates all of the aspects of driving that Level 2 does, but the vehicle assumes more complete control of the vehicle while still depending on an alert driver to take control when necessary. |
| | Desired speed <i>The desired travel speed, which depends on speed limit, geometric conditions, and an error term which represents variance in driver behaviors and preferences</i> | In addition to automating acceleration, the CAV also selects at which speed to travel in free flow conditions, assuming autonomy over that decision from the driver. |
| 4 | None that are automatic: Subject to user customization using the API; otherwise reserved for development in future versions of TransModeler | N/A |

| | | |
|---|---------------|-----|
| 5 | Same as above | N/A |
| 6 | Same as above | N/A |

Source: Caliper Corporation

Customization of TransModeler for Simulating Connected Vehicles

Cooperative adaptive cruise control (CACC) operations, where a vehicle follows the leading vehicle with very short headways that can be sustained because the direct communication allows for rapid responses to changes in the leading vehicle's speed or proximity, can be replicated by applying the built-in acceleration model identified in Wang and Ragamani (2004).

In CACC, vehicles use a feedback loop of measurement (of the position and speed of the vehicle in front) and acceleration (or deceleration) to maintain a safe and consistent following speed and distance or time headway. The customizations in TransModeler assume that vehicles operating in CACC will seek to maintain a desired following time headway. To achieve this, a constant time gap model (Wang and Rajamani, 2004) is among the car following models that can be used:

$$a_i = -\frac{1}{h}(dv + \lambda\delta_i)$$

where a_i is the acceleration to be applied by the subject vehicle i , h is the desired constant time gap, dv is the difference in speed between the subject vehicle and the vehicle in front of it ($v_i - v_{i-1}$), λ is a parameter, and δ_i is a deviation from the desired spacing given the desired headway and is calculated as:

$$\delta_i = \varepsilon_i + hv_i + L$$

where ε_i is the physical gap between the vehicles and L is the desired, or minimum, physical gap between the vehicles at zero speed ($v_i = 0$).

The constant time gap model can be found in numerous articles in the literature, such as the paper previously cited as a reasonable approximation of a cooperative adaptive cruise control system.

In TransModeler, the analyst can choose which classes or groups of vehicles operate with CACC and which target headways h are applied to each class. Target headways less than 0.5 seconds are probably not sustainable even with the assistance of CACC technologies, and headways greater than about 1.1 seconds probably approach those that some human drivers may apply and thus may not confer any benefits. A synthesis of the potential benefits of CACC compiled by FHWA identifies headways between 0.5 and 1.1 seconds as a range that has been explored in existing research (<https://www.fhwa.dot.gov/publications/research/safety/13045/003.cfm>). Current modeling should confine target headways to this range until future research indicates otherwise.

TransModeler Application Programming Interface Customizations for CAVs

In addition to the TransModeler CAV customizations described above, which are now standard features in TransModeler 5.0 requiring no external add-ins or any programming on the part of the analyst, TransModeler has an application programming interface (API) that allows deeper customization by the user. The API exposes aspects of driving behavior to programmers who wish to build upon or replace the

models in TransModeler for those representing CAV operation. Research relying on the TransModeler API for emulating the transmission of basic safety messages (BSMs) between CAVs and addressing CV cybersecurity concerns through microsimulation was featured at the 2019 Transportation Research Board Annual Meeting: *Collision-Inclusive Microsimulation Framework for Assessing Silence-based Pseudonym-Change Schemes* (W. Xin, et al.).

Testing and Validation of TransModeler Customizations

As part of the FHWA study, the impacts of the CAV model customizations were tested and validated by first running a small simulation model of approximately 2.5-miles of a 5-lane freeway with on and off ramps. The test study area was specifically chosen to include a range of complex merge, diverge, and weaving behaviors that are commonplace in the real world and that call upon all the aspects of driving that are subject to automation. In addition to ensuring the study area included complex driving behaviors, the vehicle fleet was set to have a representative mix of vehicle classes, including passenger cars, single-unit trucks, tractor-trailer trucks, and motorcycles. Sensors were placed on the mainline to measure the average flow per lane at several locations, including prior to vehicles arriving at the ramps and within weaving sections.

Numerous scenarios were run in which the simulated traffic volumes were gradually increased until capacity was reached in order to determine whether the CAV customizations had any impact on capacity. The following CAV technologies were evaluated:

- AV Level 1a (acceleration/deceleration task automated)
- AV Level 1b (lane-changing task automated)
- AV Level 2 (both acceleration/deceleration and lane-changing tasks automated)
- AV Level 3 (AV Level 2 + travel speeds coordinated)
- CACC (i.e., CV)

In the scenarios in which CACC was tested, a target following headway h of 1.0 second was assumed, which falls in the middle of the range of CACC headways considered to be plausible in the literature.

Modest or negligible increases in capacity (0-2%) were achieved when only acceleration was automated (1a), likely because traffic operations in heavy merge, diverge, and weaving areas stand to benefit the most from the automation of steering (1b). When steering was automated, lane changes that are motivated by human factors and are not necessary to follow one's path are minimized. This likely explains the more notable increases in capacity (1-8%) that were observed in the study at Levels 1b, 2, and 3. Further, the study concluded that CV technologies like CACC may have benefits that go beyond those of simple automation. The most significant improvements in capacity were observed when CACC was deployed, leading to increases in flow as high as 12%.

Table 11: Increases in Capacity by CAV Technology

| CAV Technology | Increase in Capacity |
|---------------------|----------------------|
| Automation Level 1a | 0-2% |
| Automation Level 1b | 2-7% |
| Automation Level 2 | 1-8% |
| Automation Level 3 | 1-9% |

| | |
|------|-------|
| CACC | 4-12% |
|------|-------|

It was also concluded that the benefits of CAVs increase as demand increases and congestion worsens. In Table 11, the lower end of the range in capacity increases occur when demand and congestion are low.

In summary, the testing and validation of the CAV capabilities in TransModeler suggest that the benefits that CAV technologies afford in terms of increasing capacity may be modest or negligible with basic automation of acceleration tasks (i.e., Levels 1a). Rather, the most significant improvements in capacity are likely to be achieved when steering is automated or when another aspect of driving, one that brings about shorter following headways (i.e., CACC), is enabled through CV technologies.

4.4 Section 4 References

- Bernardin, Vince. "Why One Size Doesn't Fit All: Activity-Based vs. Trip-Based Models and Everything in Between." Resource Systems Group, 2015.
- Vovsha, P. and G. Vyas. "Incorporating AVs in Ohio C3 CT-RAMP2 Model." WSP, 2018.
- Zmud, Johanna and Ipek Sener, Jason Wagner. Consumer Acceptance and Travel Behavior Impacts of Automated Vehicles, Texas A&M Transportation Institute, Transportation Policy Research Center, 2015.
- Childress, S., B. Nichols, B. Charlton, S. Coe. "Using an Activity-Based Model to Explore Possible Impacts of Automated Vehicles." Submitted for presentation at the 2015 TRB Annual Conference, 2015.
- "TransFuture: Innovate the Future of Transportation." Florida Department of Transportation. 2017.
- Interstate 80 Planning Study: Automated Corridors. Iowa Department of Transportation, 2017.
- Evanston, A. "List of Scenarios for Connected & Autonomous Vehicles." PTV Group, 2016.
- Marando, M. M., L. T. Truong, and H. L. Vu. "Investigating Safety Impacts of Autonomous Vehicles Using Traffic Micro-Simulation)." Monash Institute of Transport Studies, 2017.
- Stanek, D., R. T. Milam, E. Huang, et. al. "Measuring Autonomous Vehicle Impacts on Congested Networks Using Simulation. Fehr & Peers, 2018.
- "PTV Vissim 11 Release Highlights." PTG Group, 2018.
- Cisco, B. "PTV Vissim & Connected Autonomous Vehicles." PTV Group, 2017.
- "Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow." United Kingdom Department of Transport, 2016.
- Stabler, B., M. Bradley, D. Morgan, H. Slavin, and K. Haque. "Volume 2: Model Impacts of Connected and Automouse/Automated Vehicles (CAVs) and Ride-Hailing with Activity-Based Model (ABM) and Dynamic Traffic Assignment (DTA) – An Experiment." FHWA, 2018.
- J. Wang and R. Rajamani (2004) "Should Adaptive Cruise-Control Systems be Designed to Maintain a Constant Time Gap Between Vehicles?" IEEE Transactions on Vehicular Technology, Vol. 53, No. 5, pp. 1480-1490.

5. ADDRESSING RISK AND UNCERTAINTY IN CAV MODELING

Travel demand forecasters are no strangers to uncertainty. Predictions about the demand for travel on our transportation systems via private and public transportation modes in metropolitan areas hinge on shifts in economic health, land use development and regulation, public attitudes toward travel, and other variables that are intrinsically uncertain. CAVs, however, introduce deep uncertainty, to borrow a term from the literature, that has the potential to be disruptive and transformational. CAVs, if or when they come to pass, may fundamentally alter the way the public perceives and experiences travel, with ripple effects on how traffic flows and how land uses are developed in response to changes in traveler behavior. In this section, we examine the ways in which this uncertainty might be addressed when modeling a future with CAVs and make recommendations for managing the uncertainty and risks a future with CAVs carries.

5.1 Recent Examples Treating CAV Uncertainty

Techniques for managing CAV uncertainty in transportation planning have precedent in the literature. The Federal Highway Administration (FHWA) and state departments of transportation (DOT), like the Florida DOT (FDOT), have taken the lead in encouraging a more explicit and systematic accounting for uncertainty in planning for CAVs. FHWA sponsored a study demonstrating the use of Exploratory Modeling and Analysis (EMA) to model the impacts of CAVs and ride-hailing with an Activity-Based Model (ABM) and Dynamic Traffic Assignment (DTA) (Stabler, Bradley, Morgan, Slavin, & Haque, 2018). FDOT also sponsored the development of TransFuture, a scenario planning tool for exploring the possible futures with CAVs (Zielinski & Roy, 2017). These approaches provide useful insights and helpful resources for readers wishing to learn more about recent relevant experiences in the research.

These techniques – EMA and scenario planning – and others are discussed in additional detail in the sections that follow. Three approaches are considered in the order of decreasing historical precedence but increasing relevance to deep uncertainty, a relatively new concept, in transportation planning.

5.2 Visioning and Strategic Planning

Though they are not one and the same, visioning and strategic modeling are grouped together in this discussion because strategic planning often begins with visioning. In its simplest form, strategic planning begins with a (desirable) vision for the future, setting goals, outlining an approach, and designing a course of action to achieve that vision. In the urban and transportation planning context, visioning is the act of involving the public and other stakeholders in crafting a collectively agreed vision for the future. While visioning has existed as a concept in the literature for decades, there is little evidence that in practice the modeling of a desired future is effective in helping to bring about that vision as an outcome, particularly as (uncertain) environmental, technological, and societal forces impose themselves on the future (Minowitz, 2013).

A process – a strategic plan – must complement the vision so that the goals, approach, and course of action evolve in anticipation of and in response to those emergent forces. There is a breadth of strategic planning models in the literature, but it is hard to make the case for their application in the context of CAV technology and the deep uncertainty it entails. Strategic planning is suitable in the context of metropolitan planning, where the MPO wields considerable influence over outcomes through the levers of funding, prioritization, and zoning. On the contrary, in the CAV context, the Ohio DOT is one of many actors playing a part in shaping the future with CAVs. What that future will look like will be decided in some part by other actors, including but not limited to auto, sensing, and communications manufacturers, standard-setting professional organizations like SAE International, regulatory bodies like the National Highway Traffic Safety Administration (NHTSA), and the public that ultimately will or will not accept or embrace a technology. These are the sources of deep uncertainty.

That being said, there may well be merit to choosing an approach to this uncertainty based on visioning and strategic planning if through the Drive Ohio initiative, ODOT is able to leverage the cooperation and coordination of the aforementioned stakeholders toward achieving a desired vision for the future. Additionally, if by proving through credible microsimulation modeling that one or more CAV concepts, strategies, or technologies can deliver compelling benefits (e.g. reduced delay), then it may be possible to incentivize the investment and research that will realize those concepts, strategies, or technologies.

Whether strategic planning is the selected approach, there are practices from strategic planning that should be a part of any approach to CAV uncertainty. These include:

- Collecting data: when data become available from published CAV studies or research, assimilate that data into existing models to improve their validity
- Staying current: update assumptions as new information about CAV operations emerges
- Forecast based on trends: observe trends in collected data and the direction of change in updated assumptions to refine future assumptions
- Model frequently: as assumptions and models improve, run model(s) of the future, adjust approach and action plans accordingly to those outcomes that appear more likely

If stakeholders are continually involved and invested in the vision and in the strategic plan through this process, ODOT will be as well-positioned as it can be to manage and reduce uncertainty and to make better-informed decisions.

5.3 Scenario Planning

Scenario planning is probably the most prevalent approach to planning under uncertainty and so is the most easily adopted and adapted in the CAV context. Scenario planning involves making assumptions about those variables whose values are uncertain and modeling a variety of future conditions to better understand what outcomes are possible. Hence, in contrast with visioning and strategic planning, scenario planning more explicitly acknowledges the sources of uncertainty outside the planning organization's control and prepares the organization for a multitude of possible outcomes. This approach is particularly attractive in the CAV context because, in the presence of deep uncertainty,

scenario planning recognizes that the future cannot be known, and so preparation for one of multiple possible futures is prudent. By modeling a range of plausible futures and considering their outcomes and the implications and sensitivities of various assumptions, an organization is more likely to be prepared for the future that does emerge.

Constructing a manageable scenario planning approach hinges on making informed judgments about which variables are critical – i.e. that have the most influence on the outcomes – and what set of assumptions about those variables are reasonable and plausible. Better assumptions will be made through effective involvement from stakeholders most knowledgeable about the source of the uncertainty, for instance manufacturers of CAV technology.

Scenario planning originated as an approach to business strategic planning but has more than a decade of precedent in transportation planning. These precedents are summarized concisely in Zegras, Sussman, & Conklin (2004), which also addresses the use of probability in organizing or ranking the likelihood of various futures. While there is a natural desire to do so, scenario planning does not require that probability be quantified, which in all likelihood is very difficult to do with any degree of confidence at the present stage of CAV evolution, because the exact nature and operational specifics of CAVs are not known.

This has not stopped FDOT from taking a probabilistic approach to scenario planning, as mentioned above, nor does it preclude taking on quantifying probabilities in variables of uncertain value at a later stage, in keeping with the strategic planning practices of collecting data and staying current. A notable application of scenario planning was by ICF for FHWA as described earlier in section 2.3 and in the Twaddell 2018 presentation. That presentation includes useful discussion of what goes into creating scenarios including examples of *external forces* (e.g. technologies or the environment); *levers* including trade policy, tax incentives, government mandates, consumer preferences, social-economic factors (e.g. population, workforce trends, market forces); and *desired outcomes or goals* such as equitable access, reduced congestion or environmental sustainability.

Other state DOTs have taken a scenario planning approach to CAVs. The Iowa DOT used scenario planning in a study of the impacts of AVs and advanced technologies on I-80 – specifically smart truck parking along the interstate – and varying levels of AV adoption in different forecast years to evaluate different possible futures (Iowa DOT, 2017). Millennial traveler behavior and the aging population were also part of the assumptions in the scenario construction. Through scenario planning for AVs, the Iowa DOT arrived at a set of recommendations for infrastructure improvements on the corridor.

5.4 Exploratory Modeling and Analysis

EMA has seen increasing interest across a multitude of disciplines over the past decade as an alternative to scenario planning where deep uncertainty is present in the system under study. One of the primary challenges in scenario planning is the difficulty in deciding a manageable number of scenarios that captures the full breadth of uncertainty. According to the Society for Decision Making under Deep Uncertainty (DMDU), deep uncertainty exists where there is no clear consensus among stakeholders about:

- the structure of the model that relates inputs and assumptions to outcomes,
- the probability distributions of the system variables about which the parties are uncertain, or
- which system behaviors are most important (DMDU Society, 2018).

This is an apt description of the current stage of evolution of CAVs, where there is no clear agreement which CAV concepts, strategies, or technologies will be realized; how quickly or whether they will be adopted; or how they will operate in the field if or when they are adopted. Indeed, the literature research summarized in this report confirms that the future with CAVs amounts to little more than speculation as to the benefits, with the consensus surrounding only the inevitability of CAV technology in some form or fashion.

EMA seeks to structure the approach to scenario planning in a systematic way that uses sensitivity analysis to explore patterns in model results to reduce the range and number of asserted model input values and scenarios (Banks, 1993). Whereas scenario planning can produce a picture of a relatively small number of possible futures, it does not necessarily illuminate the relationship between the different assumptions and possible futures. EMA seeks to uncover the patterns or relationships in the system so as to provide more guidance to decision-makers about how their decisions might shape the future.

There is recent precedence of EMA in planning, specifically in relation to CAV uncertainty. The FHWA study described above used an integrated dynamic traffic assignment (DTA) model and activity-based model (ABM) to explore the relationships between AV adoption, traveler behavior, and the operational benefits of AVs and served as a demonstration of a framework for using EMA in regional transportation planning (Stabler, Bradley, Morgan, Slavin, & Haque, 2018).

5.5 Section 5 References

- Banks, S. (1993, May-June). Exploratory Modeling for Policy Analysis. *Operations Research*, 41(3), 435-449.
- DMDU Society. (2018). *About Us*. Retrieved from DMDU Society: <http://www.deepuncertainty.org/about-us/>
- Iowa DOT. (2017). *Interstate 80 Planning Study (PEL)*. Office of Location and Environment, Automated Corridors. Iowa DOT.
- Minowitz, A. (2013). *Visioning In Urban Planning- A Critical Review and Synthesis*. A Thesis Presented in Partial Fulfillment of the Requirements for the Degree Master of Urban and Environmental Planning, Arizona State University.
- Stabler, B., Bradley, M., Morgan, D., Slavin, H., & Haque, K. (2018). *Volume 2: Model Impacts of Connected and Autonomous/Automated Vehicles (CAVs) and Ride-Hailing with an Activity-Based Model (ABM) and Dynamic Traffic Assignment (DTA) - An Experiment*. Washington, DC: Federal Highway Administration.
- Zegras, C., Sussman, J., & Conklin, C. (2004, March). Scenario Planning for Strategic Regional Transportation Planning. *Journal of Urban Planning and Development*, 130(1), 2-13.
- Zielinski, J., & Roy, S. (2017). *TransFuture – Innovate the Future of Transportation*. HDR.

6. RECOMMENDATIONS

This section includes recommendations for enhancing traffic simulation methods and practices that will support ODOT in its analysis and planning for CAVs. The recommendations include changes to simulation models that ODOT and its consulting partners use to analyze the impacts of CAVs. General recommendations relating to CAV modeling practice were developed by the CDM Smith team, and recommendations relating more specifically to traffic simulation software enhancements were prepared by Caliper Corporation.

CDM Smith Recommendations (organized by report section)

Section 2 – CAV Penetration Rates

- To address the uncertainty of CAVs implementation rates, set up the simulations so that the market penetration level is an adjustable parameter and then vary that parameter to do sensitivity studies.
- Researchers should use caution in estimating dates when AV technologies will be implemented. Many studies found in the literature search were judged to be overly-optimistic. This is especially true regarding mobility as a service and the probability of major reductions in private vehicle ownership. Continuing research is needed to accurately predict the most disruptive potential impacts of CAVs.

- The study team recommends that ODOT consider the use of the eight scenarios in the table below in creating regional traffic demand model inputs and simulating the uncertainty of CAV operations at various penetration rates.

Table 12: Candidate Scenarios and Penetration Rates

| Scenario | Target Year | Penetration Rate | SAE Level 3 Rate | SAE Level 4-5 Rate |
|----------------------------|-------------|------------------|------------------|--------------------|
| Pilots proliferate | 2025 | 5% | 4% | 1% |
| Private AVs | 2030 | 10% | 6% | 4% |
| Shared and private AVs | 2035 | 20% | 10% | 10% |
| More AVs, some Level 5 | 2040 | 50% | 25% | 25% |
| More MAAS and more Level 5 | 2045 | 80% | 16% | 64% |
| More Level 5 | 2045 | 100% | 10% | 90% |
| No more Manual Vehicles | 2050 | 100% | 5% | 95% |
| Widespread MAAS | 2050 | 100% | 0% | 100% |

Source: CDM Smith

Section 3 – Effects of CAV Technologies

- CAV technology implementations haven't been sufficient to rely on field tests or initial operational implementation to assess impacts. Traffic demand modeling should be used to study CAV impacts on existing traffic until those impacts can be measured in field tests or initial operational implementation.
- Researchers should carefully review the various reports in the literature to understand the assumptions that were used in attempting to quantify the impacts of CAVs. Some assumptions were found to be overly-optimistic. Hopefully, new research and modeling can improve the assumptions and result in improved estimates of CAV impacts.

Section 4 – Traffic Simulation

- The study team recommends that ODOT embrace the proposed modifications to Vissim and TransModeler included in this report and that they carefully review and take advantage of experience gained in Iowa, Florida, and other states in analyzing the applicable Ohio corridors. It is important to not duplicate effort and for the modeling community to collectively move forward with model improvements.
- Industry and government should promote completion of the PTV-identified modifications that would allow Vissim to model the impacts of CAVs. In addition, there should be comparisons with the PTV changes and those identified by the *tfresource* wiki, and additional model improvements made as appropriate, while involving stakeholders in the analyses.
- Since the *tfresource* wiki-like website (http://tfresource.org/Autonomous_vehicles:_Modeling_frameworks) explores many of the same modeling issues for CAVs that ODOT wants to apply to its several corridor projects, ODOT should work with the modeling subcommittee that oversees the wiki to provide continuing

updates and use that information along with the literature search spreadsheet created in this project to keep the wiki up-to-date and relevant to AV modeling advancements.

- The study team recommends that ODOT utilize the work done by WSP on the 3C model CAV adaptation and carefully input and analyze the Section 2 Scenario rates. The travel demand modeling output will be crucial in making subsequent traffic simulation runs and analysis.

Section 5 –Addressing Risk and Uncertainty

- As with penetration rates, there is need to consider the uncertainties of AV technology capabilities by modeling various scenarios of technology implementation. A number of scenario planning efforts related to AVs have been included in the literature search results in this project and should be consulted for applicability to individual corridor projects that ODOT may undertake. Full advantage should be taken of past studies and the scenario assumptions they used.
- As field tests are completed in ODOT corridor projects, or when ODOT concludes there have been significant CAV advances nationally, the study team recommends that this report be updated to include CAV improvements, simulation model changes, or results of other studies and analyses underway. New reports and papers could be added to the spreadsheet provided in Appendix B.

Caliper Corporation Recommendations (Section 4)

In making recommendations regarding proposed enhancements to Vissim and TransModeler above and beyond their current capabilities summarized in section 4 of this report, several factors were taken into consideration, including:

- Emphasis was given to technologies and strategies whose methods, algorithms, or specific logic are well enough described to be considered implementation-ready.
- Conversely, de-emphasis was given to proprietary technologies or strategies such as Advanced Lane Management Assist (ALMA) whose methods or algorithms are interesting but undisclosed.
- Technologies or strategies were favored whose benefits were supported by field tests.
- Special consideration was given to technologies or strategies that may support ODOT's various ongoing CAV-related initiatives, such as variable speed limits on the I-90 Lake Effect Corridor and in the I-670 SmartLane projects.
- Due to the sheer volume of literature on some of the more extensively-covered technologies or strategies, namely cooperative adaptive cruise control and vehicle platooning, more recent studies were favored.
- Research conducted with the support or direct involvement of industry partners (e.g., auto manufacturers) or public agencies with outsized influence in shaping the future of CAVs (e.g., FHWA) was also favored.

Given these considerations, we make the following recommendations for modifications to Vissim and TransModeler:

- Modify the implementation of CACC to reflect more recent research
- Implement platooning controls to manage/regulate CACC operation, particularly where merging and weaving are important
- Implement a speed harmonization strategy that leverages CAV, V2I, and variable speed limit signs

Based on our literature review, CACC remains the most promising CAV technology for reducing congestion and improving level of service on our surface transportation systems. CACC continues to receive the lion's share of attention in the research community. However, there is a gap between what simulators can currently model (see section 4 of this report) and what various research studies and field tests suggest will be possible.

First and foremost, we recommend modifications to Vissim and TransModeler that will close this gap. Several of the research papers that were reviewed have enough detail to represent a blueprint for implementing the CACC logic in a simulation environment. Some of the research even points to CACC strategies that will address problems inherent in most of the CACC studies we reviewed, that of achieving gaps for merging vehicles in a traffic stream in which vehicles follow one another very closely (i.e., in merging areas predominantly found at entrance ramps to freeway facilities). We propose to identify one or more CACC studies supported by field studies in the implementation phase of this project and to proceed with the requisite software modifications after having received the concurrence of ODOT.

Second, we recommend improving the representation of platoon management so that the models that simulate CACC more accurately reflect the system of rules that are likely to be in place to govern when and where vehicles may join a CACC platoon and how many members a CACC platoon will permit. The implementations currently available in existing microsimulation software do not abide by any of the systems that are likely to come to fruition or are obsoleted by more recent research.

Third, we recommend modifications to Vissim and TransModeler that will enable the analysis of the benefits of CAV-enabled speed harmonization strategies. We recommend making such modifications in a way that also enables microsimulation of strategies that rely on variable speed limit signs (VSLS). This will allow ODOT to use microsimulation as it continues to explore VSLS designs in parallel in the I-90 Lake Effect Corridor, I-670 SmartLane, and other projects. Moreover, speed harmonization appears to be gaining momentum with agencies around the U.S. and the world as a means to smooth the flow of traffic, reduce incidents, and, consequently, improve reliability.

It bears mentioning that V2I systems that improve the efficiency of, or negate entirely the need for, traffic signals at signalized intersections remains an important topic in the research, but the research does not present a consensus as to where the future is headed with regard to CAV-enabled traffic signal system improvements. We recommend that ODOT closely monitor developments in this area going

forward, but modifications to microsimulation software at this early stage are likely to be both expensive and to be outmoded as consensus around the direction of such strategies grows.

APPENDIX A: OVERVIEW OF THE CURRENT STATE OF CONNECTED AND AUTOMATED VEHICLES (CAV) (THE BIG PICTURE OF CAVS)

1.0 Introduction

Driverless cars have been of interest to futurists and technologists for many decades. Figure A-1 dates 1957 and has been used as cover photos in at least two recent documents about connected and automated vehicles (CAV). The concept was that passengers in the automated vehicles could spend their travel doing other activities. The 1957 ad said *“One day your car may speed along an electric super-highway, its speed and steering automatically controlled by electronic devices embedded in the road. Highways will be made safe—by electricity! No traffic jams...no collisions...no driver fatigue.”* While fully-automated vehicles that would allow such activities are probably a long way off, there has been recent research to examine value of time and other impacts of automated vehicles.

Figure A-1 Advertisement from 1957 for “America’s Independent Electric Light and Power Companies”



Source: Vince Bernardin presentation, RSG 2018 as well as RAND 2016. (art by H. Miller)

Every day new articles and reports about CAVs appear in the popular and trade press. With 21st century advances in computer hardware, communications systems, and innovative software development, there has been keen interest in applying those technologies to automating the driving function.

This document provides a brief overview of the state of CAV development and implementation as of mid-2018. It also indicates some of the key reports and documents which help explain and advance CAVs. Cooperative research, analysis, testing, and limited deployments have helped advance CAVs, even as the public maintains skepticism about full automation. Highly-publicized accidents in some of the

demonstrations have fueled the skepticism while causing the developers, researchers at universities, and governments at all levels to focus their efforts on moving forward with CAV implementation while assuring safety and mitigating potential negative impacts of CAVs.

There is a wealth of literature about connected and automated vehicles. The Federal government as well as universities and consulting firms have sponsored interesting analyses and projections of the anticipated further development and implementation of CAV. Our team has compiled a large body of literature, with new reports and news articles appearing every day. Table A-1 contains some of the key overviews of CAVs that can provide readers with additional information on the status and progress toward automated vehicles.

Table A-1 Connected and Automated Vehicle Reports

| Report Title | Authors/sponsors | Date |
|--|---|------|
| <i>Updating Regional Transportation Planning and Modeling Tools to Address Impacts of Connected and Automated Vehicles, Volume 2: Guidance</i> | Zmud, Williams, Outwater, Bradley, Kalra, and Row for TRB's NCHRP Report 20-102(09) 25319.pdf | 2018 |
| <i>Connected and Automated Vehicle Concept Dimensions and Examples</i> | Shladover and Greenblatt Ucal Berkley for USDOE | 2018 |
| <i>The Future of Autonomous Vehicles: Lessons from the Literature on Technology Adoption</i> | UCal Berkley for Caltrans | 2018 |
| <i>From Connected to Autonomous: A Vision for the Future of Automotive Travel</i> | DMI | 2018 |
| <i>Autonomous Vehicle Implementation Predictions</i> | Todd Litman Victoria Transport Policy Institute | 2018 |
| <i>An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs</i> | Kockelman et al Univ of Texas Austin | 2017 |
| <i>Preparing for Automated Vehicles: Traffic Safety Issues for States</i> | Governors Highway Safety Association | 2018 |
| <i>Workforce and the Self-Driving Future: Realizing Productivity Gains and Spurring Economic Growth</i> | Securing America's Energy Future | 2018 |
| <i>Taming the Automated Vehicle: A Primer for Cities</i> | Bloomberg Philanthropies/Ashen Institute | 2017 |
| <i>Beyond Speculation: Automated Vehicles and Public Policy</i> | Eno Foundation | 2017 |
| <i>Automotive revolution – perspective towards 2030</i> | McKinsey and Co. | 2016 |

TRB Zmud et al 2018 included a chapter on uncertainties associated with CAVs that will affect the ability to predict when CAVs will be widely deployed. The uncertainties they listed include:

- The cost of the technology will certainly drive the rates of adoption.
- Whether the technology is used in privately held vehicles or through private corporations supplying fleet services will drive the rate of market penetration.
- On-road testing of CAVs continues, but actual usage safety statistics and experience will drive public attitudes about the technology.

- Comfort and convenience, in addition to cost, will drive consumer preferences regarding AVs.
- Roadway and parking infrastructure will need to be adapted to CAVs.
- Government policy and traffic laws, including tests of liability in the court system, will undoubtedly drive market penetration scenarios.
- The technology will certainly advance and change, and features will be added or subtracted on the basis of cost effectiveness in the market.

The TRB report emphasized the uncertainty about CAV development. Their review of the literature, which was corroborated by the study team for this current report, found high uncertainty in published deployment scenarios. They defined three “eras” during which varying but increasing rates of CAV penetration will occur:

1. CAVs are developed and tested.
2. Consumers begin to adopt CAVs.
3. CAVs become the primary means of transport.

They went on to note that the industry does not have enough information to provide exact timing and details for the start and end of these eras. They state on page 12 that “There will be a long period of time (perhaps three to four decades or more) with a mix of human-driven vehicles and CAVs on the roadways. While acknowledging that “this is not a consensus view,” the authors include a number of expectations and general forecasts of what will occur within each era. See page 12 in the TRB report.

2.0 SAE Levels of Automation

Some years ago, the Society of Automotive Engineers (SAE) instituted a series of levels of automation that were embraced by the industry and researchers. The National Highway Traffic Safety Administration (NHTSA) subsequently adopted the same levels. Figure A-2 provides the Society of Automotive Engineers and Federally-accepted definitions of the five levels of automation and the definition along with some additional information about the respective roles of the human driver and the automated technologies. This 2018 version of the SAE levels took the SAE task force that developed the definitions at least six months to reach agreement on the precise wording in this new chart to minimize the likelihood of misunderstandings.

Figure A-2: Automated Vehicle system and Levels of Automation



SAE J3016™ LEVELS OF DRIVING AUTOMATION

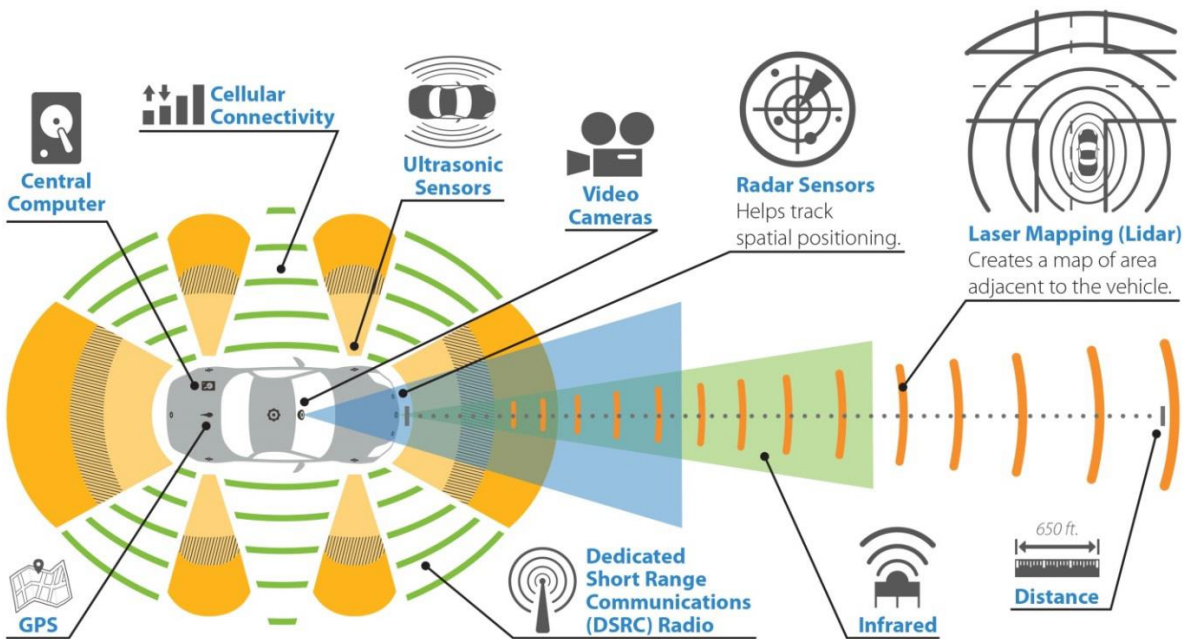


Source: <https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles>

3.0 Connected and Automated Vehicle Technologies

Figure A-3 shows some of the hardware and communications technologies that are used in CAV. The higher levels of automation involve those technologies that transfer responsibilities from the human driver to the AV system. The cameras and radar and lidar technologies provide situational awareness for the vehicle that is used in the on-board computer applications for driving situations (e.g. lane change warning, collision warning, cooperative adaptive cruise control) that drive the vehicle safely in its interactions and encounters with other vehicles, pedestrians, or objectives on or near the roadway. The set of technologies along the bottom of the diagram are connected vehicle applications and involve both vehicle to vehicle (V2V) communications and vehicle to infrastructure (V2I) communications including road conditions, weather, traffic alerts, location information the automated systems need, Basic Safety- Messages and related.

Figure A-3 CAV Technologies



Source: Iowa DOT I-80 Planning Study 2017

Industry experts understand that the technical challenges of automating driving under the full range of roadway, traffic and environmental conditions (SAE Level 5) is far beyond the current state of the art and will remain so for the foreseeable future. Even after the initial highly automated driving applications become available for public use, their use is likely to grow gradually. The vehicles will be expensive for the foreseeable future because of the complexity of the needed sensor and software systems, and not all of the components will be available. There will be both direct and indirect impacts of CAV deployment, and not all these impacts will be positive. Experience with other technological developments in the past, for example personal computers or cell phones, has shown that there are often indirect and unintended consequences from rapid changes, and the planning community needs procedures and methods to address both potentially positive and potentially negative outcomes.

While pilot testing is important to prove CAV technologies and introduce the public to CAV capabilities, the testing is not sufficient for states and MPOs to plan for widespread CAV implementation. Planning requires traffic, economic, and demographic data and models of trips by various modes based on assumptions about the future. According to Zmud et al 2018, the basic tenet of CAV planning and modeling is uncertainty of implementation of this new and evolving technology. As time passes, the relevancy of data becomes less. Therefore, predictive modeling is more valid for the shorter term, while exploratory modeling is useful for long-term planning. In any case, current models built around current modes and vehicles with drivers cannot adequately analyze CAVs. Therefore, updates to modeling and forecasting tools will be necessary to more appropriately account for the expected impacts of automated vehicles (AVs) and connected vehicles (CVs). (TRB Zmud et al 2018).

According to information provided by the organizers of the 8th annual Autonomous Vehicles Summit 2019 in their *Accelerating the Deployment of Level 5 Automation*, there are four key technical challenges that must be overcome in order to achieve Level 3 to 5 automation.

- Big Data - Improving Data Collection and Processing for Better Vehicles
- Optimizing Artificial Intelligence and Machine Learning for Safer and Better Performance
- Scaling – Transferring Autonomous Hardware and Software from Testing to Production
- Mobility as a Service – Growing Public Sector Integration and Regulation

“Through the use of big data technologies, automotive OEMs and other stakeholders are beginning to make use of vehicle-generated data assets in a number of innovative ways ranging from predictive vehicle maintenance and UBI (Usage-Based Insurance) to real-time mapping, personalized concierge, autonomous driving and beyond.”

4.0 Impacts of Automated Vehicles

Table A-2 shows some of the projected impacts of CAVs as found in the literature –For each impact in the table, a general timeframe for realizing the impact is shown along with whether the impact is positive or negative. The importance of the impact is indicated along with an example or two of that helps illustrate the impact. Finally, several sources from the literature are shown

Table A-2 Impacts of CAVs

| Impact | Timeframe | pos or neg - | importance | examples | sources |
|-------------------------------------|------------------|--|----------------------------------|---|--|
| Safety including vehicle crashes | Mid-to-long term | pos although conventional vs AV conflicts could be neg | Very important | Faster reaction time than humans | <ul style="list-style-type: none"> • AV 3.0. 2018 • RAND 2018 • Morando et al 2017 • Kockelman 2016 |
| Congestion | Long term | neg until high penetration. pos thereafter | important | Closer headway and more predictable movements | <ul style="list-style-type: none"> • Makridis et al 2018 • Zhao 2017 |
| Value of time | Long term | pos | Nice to have | Work or leisure while on trip | <ul style="list-style-type: none"> • Kockelman 2017 in surveys and simulations |
| Mobility | Long term | Pos for equity to underserved populations. | Important, but will increase VMT | Disabled and older non-drivers | <ul style="list-style-type: none"> • Bloomberg/Aspen 2017 • TRB EC236 AV Forum 2018 |
| Cost of Transportation and mobility | Mid-to-long term | Likely neg, but pos with less car ownership | Not a key factor | AVs will be more expensive | <ul style="list-style-type: none"> • AAA study of AV costs • Litman 2018 |
| Workers | Mid-to-long term | Neg in transportation industry | Planning concern for govts | Job shifts from automation | <ul style="list-style-type: none"> • Workforce report by SAFE 2018 |
| Fuel efficiency | Mid-to-long term | Pos if trend to electric vehicles. Neg w VMT increase | Not much of a factor w/o EVs | Some improved fuel economy from platooning | <ul style="list-style-type: none"> • NEFL truck platooning tests. • Rodier 2018 • Simulations of strings of AVs |

Source: CDM Smith

Researchers have tried to investigate and quantify these impacts through field tests and demonstrations and through modeling and analysis. Most of the impacts have never really been demonstrated because they involve actual operation in existing traffic on existing roadways, but that it is a key part of modeling and simulation work that has been documented by a number of researchers. Particularly notable are the projected impacts on congestion and related roadway capacity, on urban mobility, and on workers.

The projected impacts on workers and companies as noted in the SAFE Workforce study 2018 is for slight job loss with high penetration of CAVs in the 2040s. Similar points are made in Sam Schwartz's 2018 article "Autonomous Vehicles are Coming and There's no Roadmap (yet)". It discussed effects on labor, both positive and negative as some transportation jobs are eliminated while others are created (e.g. AV fleet managers or maintenance crews). Both reports note that policies are needed so that economic benefits of AVs are shared with those whose jobs are negatively affected. Past technology disruptions such as computers, ATMs, and cell phones (and even supermarkets described in the Schwartz article) illustrate that while technological change leads to large social benefits in the long run, some benefits can be long-delayed, and the change can result in significant uncompensated costs to those displaced and their communities. The UCAL Berkeley 2018 report for Caltrans is a good illustration of that point.

5.0 Pilots, Deployments, Tests

CAVs are developing rapidly, and according to TRB Zmud et al 2018, manufacturers and shared fleet operators are involved in at least 17 shared automated vehicle (SAV) pilots in eight states in current deployment. Most of these states have taken steps to adjust their regulatory and policy structure to accommodate the pilots. The Federal government has issued guidance, most recently as AV 3.0, to help facilitate CAV development while maintaining public safety. Because of the central role the automobile plays in transportation in the U.S., a very gradual rollout of automated driving features and an even more gradual expansion of the market penetration of these features among the vehicles on the road should be expected.

As noted in the National League of Cities' *Autonomous Vehicle Pilots Across America*, on the federal side, NHTSA and the U.S. DOT led the bulk of the federal response to emerging AV technology between 2013 and 2017. The agencies' approach embraces a permissive environment marked by regulatory restraint and heavy trust in AV developers. City governments also report learning more about the public's willingness to accept an AV presence and, in turn, utilizing the AVs to educate the public.

Tests and deployment related to freight and passenger vehicles have followed different, but complementary, paths with a concentration on the freight side in truck platooning. This has advanced and taken advantage of research in cooperative adaptive cruise control (CACC) and relates to Level 2 and 3 automation in trucking. Table A-3 shows some of the key truck platooning tests in North America and Europe. Most of the testing has been done in controlled or limited distance or duration situations, with an exception being some of the European Truck Challenge tests that occurred in operational situations in mixed traffic on existing major highways. In 2019, U.S. DOT initiated a truck platooning program with the objective of a 1-year-plus demonstration in actual operation with a host fleet. Three

separate teams are defining operational concepts and extensive data collection and performance measurements. One or more may be selected to perform the operational demonstration in 2020.

Table A-3 Truck Platooning Tests

| Test | Timeframe | # of trucks | Location | Technology |
|---------------------------------|---------------|-------------|--|---|
| NACFE and Peloton tests | 2013 and 2014 | 2 | highways in Utah, Nevada, and Michigan | Peloton |
| NREL, TxDOT, TTI | 2014 | 2 | Uvalde, Texas Continental Tire test track2 | Peloton on Peterbilt trucks |
| USDOT, ATRI, Auburn | 2014-15 | 2 | Test tracks in AL and OH | Peloton on Peterbilt trucks |
| TNO Europe Platooning Challenge | 2015-16 | 2 and 3 | Highways in Scandinavian countries across country boundaries | Various OEMs including Scania and Bosch technology |
| FHWA Caltrans, and PATH | March 2017 | 3 | I-710 Freeway in Southern Calif. | PATH technology on Volvo trucks |
| NREL, PATH, Transport Canada | 2017 | 2 and 3 | Blainville Quebec test track | PATH technology on Volvo trucks |
| EMSEMBLE | 2016-2019 | 3 to 7 | Europe across country boundaries | Various OEMs with emphasis on platoons of multi-brands of trucks and technology |
| FedEx and Volvo | 2018 | 3 | North Carolina highway 540 | Volvo V2V and CACC technology |

Source: CDM Smith

With few exceptions, tests and deployments of CAVs have been in even more controlled and limited situations. Nevertheless, there are tests in the U.S. and a number of countries throughout Europe, Japan, Singapore, China, and the US. The TRB Zmud et al 2018 report indicates that as of February 2018, there were 17 active pilots of shared AVs on public roads in the United States in eight states—Arizona, California, Florida, Massachusetts, Michigan, Pennsylvania, Texas, and Washington—by companies such as Waymo, Uber, EasyMile, Ford, Navya, GM Cruise, and Drive.ai (Stocker and Shaheen 2017). Some of the pilots are in limited traffic areas, such as on industrial parks or closed communities, while others are on public roads. Virtually all are Level 4 automation and have a human present in case needed. Table A-4 lists some of the US tests and deployments that have been conducted in recent years.

Table A-4 Selected U.S. AV Testing

| location | Dates | Participants | equipment | Results | references |
|---------------|---------|-------------------|--|--|----------------------------------|
| Phoenix | 2016-8 | Waymo and Phoenix | Waymo vehicle, then Chryslers and Volvos | Successful mixed operation until fatal pedestrian accident | Numerous trade press articles |
| Pittsburgh | 2016 | Uber | Volvos | App-based ride share successful | Trade press |
| Boston | 2017 | City and Nutonomy | Nutonomy shuttle | App-based ride share | World Economic Forum report 2017 |
| San Francisco | | Waymo and Uber | Waymo vehicle, than Volvos | | |
| Austin | | | | | |
| Detroit | 2015-17 | U of Mich | | | |
| Las Vegas | 2016-17 | | | | |
| Arlington TX | 2017 | City | 12 pax shuttle | Successful fixed route 1 year pilot | |

Source: CDM Smith

AV development in the U.S. started in the tech sector with companies such as Waymo and Nutonomy building their own vehicles. More recently auto makers began working with tech companies (e.g. Waymo and Volvo and with Fiat Chrysler) to make current brands automated. Table A-5 is taken from Bloomberg/Aspen Institute's 2017 *Taming the Automated Vehicle* and shows some of the global locations where AV testing has been conducted.

Table A-5 – Selected National Government AV Pilots

| Country | Project | Agency Involved | Description | Types of Vehicles |
|------------------|-------------------------------------|---|---|---|
| Australia 2014 | CITI Trial | New South Wales Road Safety Program, National ICT Australia | CV Evaluation | Tractor trailers with DSRC |
| Finland 2015 | CityMobil2 | EU, Finland Ministry of Transport | Impact on cities of AVs, remove legal barriers | EasyMile shared electric 12 pax shuttles |
| France 2014 | CityMobil2 | EU, French Ministry of Transport | Impact on cities of AVs, remove legal barriers | Robosoft Robucity shared electric 12 pax shuttles |
| Germany 2016 | A9 Autoban Digitization | Ministry for Transport | Preparation for AVs | AVs |
| Japan 2016 | Dynamic Map Planning | Japan Ministry of Economy, Trade and Industry | Dynamic map for AV navigation, AV fleet for 2020 Olympics | Japanese makers AVs |
| Netherlands 2016 | European Truck Platooning Challenge | Dutch Ministry of Infrastructure, European Directors of Roads | Long haul truck platooning to Port of Rotterdam | Tractor trailers |
| Singapore 2016 | Delphi Automotive | Singapore Land Transport | 6 fixed-route vehicles | Audi Q6 hybrid SUV |
| Singapore 2016 | NuTonomy | Singapore Land Transport | AV taxi service with fixed origins and destinations | Mitsubishi iMEV |
| Sweden 2017 | DriveMe | Swedish Transport, City of Gothenburg | Fixed route AV testing | Volvo XC90 hybrid SUV |
| UK 2015 | GATEway | UK, Transport Research Library | AV shuttle vehicles and valet parking | Oxbotica and modified Toyota Prius |
| UK 2016 | UK Autodrive | Innovate UK | On road testing of AVs | Range Rover, Ford, Teta Motors, RDM Group pods |
| USA 2015 | MCity | MichDOT, USDOT | AV test site incldg 16 pax shuttles | ARMA NAV'YA shuttles |
| USA 2015 | Nissan/NASA | NASA | AVs and zero emissions vehicles | Nissan Leaf |

Source: Bloomberg Aspen 2017 and Royal Dutch Touring Club

Through industry and government cooperation, the projected impacts and outcomes of tests are well documented including lessons learned. The tests have been important in advancing the technology and in increasing the public awareness of CAVs and their potential benefits. Future tests should be based on previous results, successes, and failures.

6.0 Regulatory and policy issues related to CAV Testing and Implementation

Federal policy involving AVs. In September 2018, the USDOT issued what it called *Preparing for the Future of Transportation – Automated Vehicles 3.0*. In announcing 6 principles, USDOT stressed that the latest guidance builds on its safety-oriented AV 2.0 2017 guideline. The six principles are:

- Prioritizing Safety for operators, pedestrians, and other transportation users
- Remaining Technology Neutral to promote competition and innovation
- Modernizing Regulations that unnecessarily impede development of AVs, emphasizing voluntary, consensus-based technical standards
- Encouraging a consistent regulatory and operational environment that allow AVs to operate seamlessly across the US
- Preparing proactively for automation by providing guidance, best practices, and automation pilots
- Protecting and enhancing freedoms enjoyed by all Americans, including the ability of consumers to make mobility choices they need, including private AVs

AV 3.0 urges states and local governments to remove unnecessary and incompatible regulations to support AV deployment and interoperability. USDOT plans to update or revamp NHTSA safety regulations to allow innovative level 4 or 5 technologies such as no steering wheels, pedals, or mirrors. The Department also plans to update the 2009 Uniform Manual of Traffic Control Devices (UMTCD) to take AV capabilities into account.

In 2017, the U.S. House of Representatives passed legislation that promotes and clarifies roles in the future of AVs. That legislation was never taken up by the Senate, in part because of concerns by some Senators about the potential extent of changes to NHTSA safety regulations and the concern of diluting safety regulations that apply to AVs. Following the November 2018 elections, the Senate again considered the legislation, but could not reach agreement enough to bring it to a vote. Some consumer organizations worry about safety standards. Some of the trade press is concerned that the divided government that will be in place in January 2019 may mean a delay in anything concrete emerging from Congress.

Schwartz 2018 noted that a major economic advantage of AVs may be the side effect of reductions in traffic crashes and related health care costs, with the possibility of adverse impacts on the insurance industry.

State Regulation of AVs. As noted in the AV 3.0 principle comments above, consistent regulations are needed across the states. Most immediately, legislation changes are needed to facilitate testing and pilot operations. Several states already have such legislation and regulations. The League of Cities as

well as the National Conference of State Legislatures maintain websites and have reports that maintain information about what states are doing to prepare for AVs.

Twenty-nine states and Washington DC have enacted legislation related to AVs: —Alabama, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maine, Michigan, Mississippi, Nebraska, New York, Nevada, North Carolina, North Dakota, Oregon, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Virginia, Vermont, Washington and Wisconsin.

Governors in Arizona, Delaware, Hawaii, Idaho, Maine, Massachusetts, Minnesota, Ohio, Washington and Wisconsin have issued executive orders related to autonomous vehicles.

(National Conference of State Legislatures website accessed 10/22/18)

State and local regulations are needed for testing and implementation. The states in which pilots or early deployments are underway (Arizona, California, Nevada) already have addressed the need. Bloomberg/Aspen Institute's 2017 document discusses the needs for the economic costs and benefits to local communities, government revenue losses and tax and fee policies with example cities and regions included.

7.0 CAV Implementation Uncertainty and the Importance of Safety.

Expectations for the higher levels of automation among the general public and politicians have been raised to unrealistically high levels by media accounts that amplify the overheated marketing rhetoric of some industry spokespeople. Reality is much more likely to be represented by a very gradual rollout of automated driving features and an even more gradual expansion of the market penetration of these features among the vehicles on the road.

An impetus for higher levels of automation is found in annual accident statistics, with more than 40,000 fatalities in 2016 of which more than 90% were found to be caused by human error (USDOT AV 3.0 2018). Automated vehicle safety is a prerequisite for the public to trust in AVs and to their widespread deployment. As the U.S. Secretary of Transportation has observed, public and consumer perceptions of safety will drive growth of this technology. See also Flaade-Blancar et al 2018 of Rand Corporation which examined how safety can be measured in a technology- and company-neutral way, and included recommendations about information sharing within industry and the publicizing of advancements and test results in development and demonstration phases of AV proliferation.

There have been some surveys done to understand how the public views the growth of CAVs and to help determine how public opinion would affect AV penetration rate. One problem with such surveys is that because there aren't actual AVs in operation, researchers only have survey participants' mental images of the experience of using an AV rather than the actual reality of that experience.

The acceptance of CAVs by the public has been negatively affected by several high-profile accidents, notably the pedestrian fatality in Phoenix involving an Uber automated car with a back-up driver (in other words, a Level 4 vehicle). Thus, more recent surveys have shown 55% of respondents as not trusting fully automated (Level 5 cars). As will be discussed in more detail in section 9, AV companies

have responded with incremental technology improvements and with low risk, controlled area AV pilots. (Joann Muller 2018). A Semiconductor Engineering article (Fogarty and Sperling 2018) discussed AV testing and safety and noted that 40% of connected vehicle drivers in a survey would not trust a car to automatically respond to traffic with automatic brakes or other driver assists. Kockelman 2016 reinforced this point by noting that the public is more comfortable with connected vehicle applications than the AV applications of Level 4 or 5. Bloomberg Philanthropies/ Aspen Institute's Taming the AV Spread 2017 contains a useful discussion of consumer attitude, including a Europe survey of comfort level with AVs, and also some discussion of the "sharing attitude" of millennials which could influence future private vehicle purchasing trends. In any case, the key to winning over the public is careful testing oriented toward public safety. Fogarty and Sperling 2018 noted the complexities of doing AV testing.

8.0 CAV Infrastructure and Agency Needs and Readiness.

In October 2018, the League of Cities issued a guideline to cities related to AV testing (Autonomous Vehicle Pilots Across America). According to the League, the municipal action guide is meant to give cities the ability to better understand and approach impending rollout of AVs in cities. The guide notes that cities and other levels of government are working together with the private sector to begin to integrate self-driving cars onto the roadways. TRB held some planning meetings and a forum to address research needs related to agency needs (TRB ec236, Forum on Preparing for Automated Vehicles and Shared Mobility 2018). The 10 highest priority AV research needs that affect public agencies defined by participants are:

1. Models for data sharing
2. Safety scenarios during the transition to highly automated vehicles
3. State and local policies to ensure safety prior to deployment
4. Infrastructure needs for AVs and shared mobility
5. Social impacts of AV deployment and shared mobility
6. Inclusion and equity needs for AVs and shared mobility
7. Impacts of higher-level AVs and shared mobility on traveler behavior and freight movement
8. Impacts of shared mobility on transit and vice versa
9. Implications for transportation planning and planning models
10. Impacts of AVs and shared mobility on land use and vice versa

State and federal governments have played and will continue to play a significant role in the development and deployment of AVs. As discussed earlier in section 6.0, the Federal government develops and manages nationwide safety standards for vehicles. Many current regulations and laws are under deliberation. These could greatly impact the future speed and safety of AV rollouts, although as described in AV 3.0, the Federal government is trying to facilitate deployment which addressing safety issues. The Federal effort is also aimed at harmonizing policies to the extent possible to avoid regulatory problems if AVs travel from one state to another.

State and local government have traditionally managed and regulated licensing and fees, local traffic rules, and provided and maintained roadway infrastructure. State preemption has emerged as a prominent theme for state legislation, particularly in 2018. Georgia, Illinois, Texas, Tennessee and Nevada have laws that directly forbid local governments from prohibiting AV piloting. Most cities have

found that a gradual introduction of AVs helps to ease public concerns and sets the conditions for an overall positive implementation, so they have established policies for conducting pilots.

The League of Cities guide book contains summary descriptions of pilot programs underway in Arlington, TX; Boston, MA; Portland, OR; Pittsburgh, PA; San Jose, CA, and Chandler, AZ

One area that is crucial to the long-term deployment of AVs is infrastructure. Although there are differences between CVs and AVs, it is clear from the literature that Level 4 and 5 AVs must also be connected vehicles if they are to achieve the safety and mobility benefits that are possible. This means implementing *and maintaining* such infrastructure components as lane markings and signage, V2I communications of situational data for CAVs, and V2V communications among the AVs and CVs operating together. USDOT has played an important role in connected vehicle testing and has piloted various CV technologies in several high-profile locations including Columbus, OH; New York City, Tampa, FL, and I-80 in Wyoming.

Some researchers and some local governments have given consideration of dedicated lanes as CAVs evolve. Some of the scenarios considered in Lui and Shladover 2017 as well as Stabler, Bradley, Morgan, Slavin, & Haque 2018 looked at the effects of mixed traffic of CAVs and manually operated vehicles and impacts of confining the CAVs to a single lane of highway. Implementation of such lane restrictions would need to be handled and enforced by local agencies. All of this means that there will need to be continued involvement of state and local agencies in development of such dedicated infrastructure. Because Level 4 and 5 vehicles rely on their sensors to detect road signs and lane markings, continued and future maintenance of those will be crucial – and the responsibility will fall to the local agencies.

While there is no consensus in the literature that person ownership of CAVs is going away, studies including the Bloomberg/Aspen report mentioned earlier, postulate significant impacts on mobility in cities as a result of significant rise in the number of shared AVs owned and operated by TNCs. They also discuss the proposition that if there are fewer private vehicles, there would be fewer parking requirements and long-range land use could change. Obviously such speculation is just that and cannot be accurately predicted until CAVs start to become the majority of vehicles on the road. Still, the requirement and opportunity to deal with potential urban growth changes would fall to local and regional planning agencies.

9.0 The Private Sector

Virtually all of the development of automated technologies has taken place in the private sector. Early adaption of automation sensors and software took place in Silicon Valley by start-ups or automation units within some of the technology firms (Waymo and Nutonomy are two examples). However, the automotive industry has made significant investments in recent years and, in some cases, has purchased CAV start-ups. Various automation technologies, discussed earlier in the report, have moved forward under the major auto makers (Volvo and Ford for example) as well OEMs or Tier 1 suppliers to the auto industry (Bosch for example). There are now important partnerships testing CAVs, including Volvo and Bosch, Fiat-Chrysler and Waymo. General Motors has an AV subsidiary which it acquired; Ford has AVs under development and has a long-term strategy for AV implementation. The Transportation

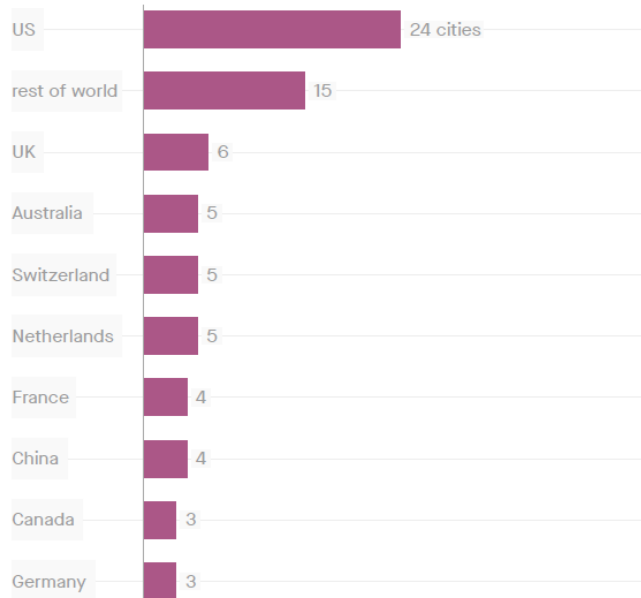
Networking Companies Uber and Lyft have been major players in shared-use AV development and pilot testing. While there has been some Federal support of AV pilot testing, most has been done by the private sector partnering with local governments and universities.

The U.S. is a global leader in AV innovation, home to 163 AV-related companies (Joann Muller, Dec 2018). But a flourishing market requires rigorous and consistent safety testing of all new technology, and NHTSA New Car Assessment Program (NCAP) updates will play a crucial role.

Figure A-4 provides a high-level overview of where AV testing is underway.

Figure A-4 International Automated Vehicle Pilots 2018

Number of cities with autonomous vehicle pilots by country



△ T L △ S Data: Silicon Valley Mobility, Bloomberg Philanthropies, Aspen Institute, various data source

Source: Michal Coren All the places self-driving cars are being tested around the world Dec 10, 2018

The auto makers are in the best position to assure that safety requirements are met because of their long record of meeting NHTSA regulations. Some private sector firms have advocated waiving safety regulations, although Congress and consumer groups are not inclined to back off safety. Another aspect of AV safety that is being investigated and pursued almost completely by the private sector is cybersecurity (Parkinson, Ward et al 2017 Ohio State University for IEEE). As private companies continue to development sensors, communications, and software applications, they realize that failures could erode public confidence in the technology, so they are committing resources to protecting against such threats. Many start-ups and smaller companies are supporting the auto and computer industries in security testing and protocols.

According to Joann Muller, writing in Axios, there were fewer cars and more tech on display at early December 2018 preview of the Los Angeles auto show, which she viewed as a sign that automakers are shifting their strategy to shared but personalized autonomous transportation. Her view is that the auto industry is moving away from gasoline, steering wheels and personal ownership as cities get more crowded and polluted and people look to avoid the hassles of owning a car.

As noted earlier, there is no consensus about vehicle ownership declining substantially for many decades. But, it is clear that the conventional auto manufacturers and their Tier 1 suppliers see a future to CAVs and are investing private funds and their corporate energy in facilitating the safe development and implementation of CAVs, with more and more automation as the years go by.

APPENDIX B. LITERATURE SEARCH ANNOTATED CAV REFERENCE LIST



MASTER_ODOT
Database_11-08-2015