Task 4: Incorporating Automated Vehicles into Scenario Planning Models

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Final Report – December 23, 2020
FHWA-JPO-22-926

U.S. Department of Transportation

Produced by
U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology
Federal Highway Administration
Intelligent Transportation Systems Joint Program Office

Notice

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-JPO-22-926		

4. Title and Subtitle	5. Report Date
Incorporating Automated Vehicles into Scenario Planning Models	December 23, 2020
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
9. Performing Organization Name and Address ICF International, Inc. 9300 Lee Highway Fairfax, VA 22031	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Highway Administration 1200 New Jersey Avenue SE Washington, DC 20590	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The objective of this project was to inventory the state of the practice for integrating AVs into the modeling process and to develop metrics, models and prototype tools for quantitative evaluation of AV scenario planning impacts. The outcome of the project is a usable framework and prototype planning model to establish the viability and access to these models for state and regional planning agencies. The protype tools (proof of concept) will lead to deployable models to support scenario planning conducted by States and MPOs. In addition to supporting direct consideration of AV impacts under a wide range of plausible assumptions, this task order will also lead to further research on future shared mobility, mobility on demand, and on-demand goods delivery that are expected to be affected by or to influence the deployment of AV technology.

This report has an Introduction, a Project Overview, three chapters, and appendices. The three chapters correspond to the tasks of the Task Order (Chapter 1 is Task 1, etc.). The chapters/tasks are based on each of the final Task Order task reports. The first chapter is a literature review of existing resources related to planning models for AVs and other emerging technologies. The second chapter specifies a set of AV models intended for use in scenario planning and is based on the literature review findings. The third chapter provides a prioritized list of parameters and models to implement as prototypes. It also specifies the process of developing the prototype models including documentation of inputs, outputs, implemented functions, ranked potential next steps, and a sample of code.

17. Keywords	18. Distribution Statement
Automated vehicles, modeling, vehicle miles traveled, roadway capacity, V2X, scenario planning	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
(		48	

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

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Introduction

There is significant uncertainty around how and when autonomous vehicle (AV) technology will affect the day-to-day experience of travelers in the United States. How deployments play out could have significant impacts (positive or negative) on transportation cost and availability, with implications for economic vitality and quality of life in communities. Opinions about how AVs will affect everything from travel behavior to system performance have evolved over time, with very optimistic initial predictions of impacts competing with sometimes with skyrocketing apocalyptic forecasts of environmental and congestion externalities.

Forecasting travel behavior and impacts in this context has become very complicated, especially when coupled with other trends and factors, like system performance outcomes, environmental impacts, and economic and distributional effects. Vehicle miles traveled (VMT) per capita has been steadily declining since before the Great Recession while transit ridership was increasing. Reasons included lasting changes in employment and the economy, demographic trends, and the growing role of technology as a substitute for travel and mobility. More recently, mobility as a service (MaaS) through Transportation Network Companies (TNCs) like Uber and Lyft have made personal travel easier. Shopping online with same day deliveries and for-hire services for tasks like grocery shopping makes access to goods and services much easier without the need to own a vehicle. These developments have contributed to offsetting impacts, yielding increased VMT and reduced transit ridership for these activities in recent years. With the future more uncertain than ever, forecasting experts differ widely in their estimates of 2040 US VMT per capita, enough to either underprepare us or overwhelm our communities and infrastructure.

Travel forecasters are developing ways to both learn from the shifting travel dynamics and to understand and forecast the significance of trends that began to emerge over the last ten years. We are using newly available Big Data from GPS and cellular devices and more sophisticated and interactive models to improve the accuracy and responsiveness of our forecasts. An equally important realization is that we can better inform decisions on transportation investment needs if we are clear about the level of confidence and variability in our forecasts, the reasons for those uncertainties, and the extent that those reasons can be influenced.

Moreover, today we are dealing with a world that has become dramatically more dynamic and unpredictable, which emphasizes the importance of exploring alternative futures, and addressing situations with “deep uncertainty.” The advent of AVs in particular will require a greater ability to evaluate future scenarios quickly and respond to a wide range of uncertainty in potential future parameters. Similar to major shifts in transportation in the past such as the adoption of the car over the horse and buggy, the range of potential future scenarios to be evaluated has grown complex, with many interdependencies. For example, auto operating cost per trip depends on if the AV is owned or shared and how many people are in the vehicle, so the more people who take a shared vehicle the lower the potential cost. The more stops a shared AV makes for other passengers the longer the travel time. This is a complex, iterative process that current models do not include since they were developed before the adoption of TNCs, much less AVs.

The extreme uncertainty associated with AVs – including when, where and how they will be deployed; the effects of AV technology on vehicle ownership; and the wide array of other potential impacts including effects on vehicle travel demand – emphasizes the importance of exploratory scenario planning in order to make the most informed transportation investment decisions. Scenario planning that considers alternate futures allows agencies to consider risks associated with different possible futures. Scenario planning also permits agencies to support prioritization of investments and policies to mitigate the potential negative effects of risk. Yet challenges remain for agencies to explore such scenarios, particularly using traditional travel forecasting models.

FHWA and its planning partners have been applying scenario planning methods to try to understand, and possibly prepare for, the range of possible future impacts. This includes exploring AV scenario planning approaches through an initial framework study. This study brought together stakeholders and experts from around the country to develop possible deployment scenarios that FHWA and partners could explore. More recently, an unpublished FHWA study on the Impacts and Costs of Connected and Automated Vehicles was completed. This research developed an inventory of variables affecting costs and an exploratory tool for examining and updating the different scenarios' forecasts.

Project Overview: Better Models for Better Informed Decisions

Just as models before the 1970s neglected to address the significant shift in household dynamics with women entering the workforce, current travel forecasting models often lack the ability to evaluate a wide range of potential changes that AVs may bring. State Departments of Transportation (DOTs) and metropolitan planning organizations (MPOs) are looking for ways to consider the impacts of AVs in their long-range planning. These agencies face many challenges in identifying the range of scenarios to be evaluated, estimating performance metrics, and applying or adapting tools for this purpose.

The recent development of "strategic models" in transportation planning helps to support analysis of performance outcomes under a wide range of demographic, social, policy, and investment assumptions. These models may serve as a foundation for scenario planning for AVs to help address the wide array changes associated with their deployment. For instance, the VisionEval suite of models, has been used by several metropolitan planning organizations (MPOs), including the Atlanta Regional Commission (ARC) and Delaware Valley Regional Planning Commission (DVRPC), to explore alternative futures. The VisionEval suite was developed from the initial GreenSTEP platform by the Oregon DOT. VisionEval, is under active development. It is designed to allow new model features to be added to extend capabilities for addressing emerging technologies and other issues

The objective of this project was to inventory the state of the practice for integrating AVs into the modeling process and to develop metrics, models and prototype tools for quantitative evaluation of AV scenario planning impacts. The outcome of the project is a usable framework and prototype planning model to establish the viability and access to these models for state and regional planning agencies. The protype tools (proof of concept) will lead to deployable models to support scenario planning conducted by States and MPOs. In addition to supporting direct consideration of AV impacts under a wide range of plausible assumptions, this task order will also lead to further research on future shared mobility, mobility on demand, and on-demand goods delivery that are expected to be affected by or to influence the deployment of AV technology.

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A proof of concept to test different scenarios with automated vehicles is presented in Appendix A. It is in the format of a flow chart. The flowchart is an exploratory tool that provides a user with a variety of inputs to be examined in a future scenario incorporating AVs. It offers directions on the process of planning for a future alternative that considers a variety of AV implications. Appendix B has the Prototype Models and Documentation. It focuses on the details for the Roadway Capacity Pseudocode, including the R script. Appendix C contains a link to the AV and Model Literature Review Tracking spreadsheet, in which each source is listed as rows with the columns representing each of the topic areas. The values identified for each source describe the key takeaways for each document and topic, so that the spreadsheet can be sorted and filtered.

Chapter 1. (Task 1): Review of Resources and Practice

The ICF and Fehr & Peers team conducted a literature review that explored existing resources addressing the state of research and practice related to planning models for AVs and other emerging technologies. These included published and unpublished documents from past FHWA projects, DOT and MPO project reports, academic research, and software model documentation or development reports. Our goal was to ascertain the state of thinking in the profession for capturing the system dynamics for building a more structured approach – what pieces of literature will be part of our modeling strategy, and how will these pieces serve to create final metrics for the tool. This chapter serves as the groundwork for, and linkage to, Chapter 2 on Model Specification.

Findings from the literature review were organized around the following topic areas:

1. Data
2. Scenarios
3. Model Functionality.

Topic 1: Data

The data topic includes both inputs to models and performance metrics for validating or comparing models to observed data. With AVs being mostly experimental, data primarily focuses on the demographics of travelers and their current options at the planning level. Researchers and transportation agencies have drawn from a variety of data sources to conduct scenario planning and modeling exercises that involve AVs. This section summarizes the data that can be used to model issues and impacts associated with transit, demographics, commuting, congestion, technology, policies, and emissions.

Transit

Transit availability and ridership data is available from the National Transit Database.[1] Since AV adoption rates are currently low, there is no data to relate the availability of transit and access to AVs to changes in ridership. However, there is, some data from studies about changes in availability of TNCs (including wait time and cost)[2] relative to transit availability, and associated changes in transit ridership; this could be considered as a proxy data source for AV scenarios.

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[1] National Transit Database (2017 Service, Operating Expenses, Revenue Vehicle Inventory) FTA

Demographics

Demographic data is available from numerous sources to determine existing characteristics of household and individuals, transportation options, and costs of living and travel. Regional agencies, DOTs, and state economic development departments typically serve as sources to forecast this data.

AV-related research and modeling activities draw upon several types of demographics. Oregon's greenhouse gas (GHG) modeling exercise with the VisionEval tool[2] considered urban form characteristics (e.g., density and diversity or mix of land uses), public transportation, non-motorized transportation, car sharing, and parking management. The household Survey was used in another Oregon scenario planning model using the GreenSTEP tool for Statewide Transportation Strategy (STS).[3] Household income and Public Use Microdata Samples (PUMS) were used for mitigation strategies and policy evaluation using the EEPRAT tool.[4] Census Tract level data is used for equity emphasis areas in the Washington Council of Governments (MWCOG) model to investigate the equity impact of AVs in the DC area.[5]

Commuting

Commuting data produced by household and employee surveys includes mode, distance, cost, time, and travel patterns (i.e., linked trips). Although commute trips are not typically the highest proportion of network travel, work travel dominates much of the daily trip making decision process. Understanding work-related travel activity patterns can help researchers formulate models with expanded AV options. Commute data can also serve to validate models in development. Table 1 provides an example of mode choice coefficients for a regional travel demand model.[6]

Table 1. Examples of Commute Mode Choice Coefficients

Model	IVTT	OVTT	Walk Time	First Wait Time	Transfer Time	Cost
A	-0.021	n/a	-0.054	-0.098[9]	-0.098	-0.31
B	-0.030	-0.075	n/a	n/a	n/a	-0.43
C	-0.036	-0.053	n/a	n/a	n/a	-0.77
D	-0.019	n/a	-0.058	-0.081	-0.04	-0.72
E	-0.025	-0.05	n/a	n/a	n/a	-0.25
F	-0.044	-0.088	n/a	n/a	n/a	-0.67
G	-0.028	-0.065	n/a	n/a	n/a	-0.55

[2] Oregon greenhouse gas modeling and analysis tools, Bettinardi Alex, Weidner Tara, ODOT, 2018

[3] Use of the GreenSTEP Model for Scenario Planning in Oregon, Gregor Brian, ODOT, 2012

[4] Energy and Emissions Reduction Policy Analysis Tool, Houk Jeff, FHWA Resource Center, 2012

[5] Examining the Equity Impacts of Autonomous Vehicles – A Travel Demand Model Approach, Cohn, J., Ezike, R., Martin, J., Donkor, K., Ridgway, M., Balding, M., 2019

[6] Benefits Estimation Model for Automated Vehicle Operations Phase 2 Final Report. Scott Smith, Jonathan Koopmann, Hannah Rakoff, Sean Peirce, George Noel, Andrew Eilbert, and Mikio Yanagisawa, U.S. Department of Transportation Intelligent Transportation Systems (ITS) Joint Program Office (JPO), and Volpe National Transportation Systems Center. 2018.

Model	IVTT	OVTT	Walk Time	First Wait Time	Transfer Time	Cost
H	-0.033	n/a	-0.093	-0.038	-0.038	-0.21
I	-0.025	-0.05	n/a	n/a	n/a	-0.5[10]

Congestion

Agencies and researchers have used a variety of data sources to examine congestion issues. Critical indicators that are informed by data sources include recurring and non-recurring congestion, as well as travel reliability. The National Transit Database contains data on transit Right-of-Way.[7] Public road mileage, lane miles, and VMT are available from the FHWA Federal Highway Statistics database.[8] The National Household Travel Survey (NHTS) provides statistics on vehicle ownership by household type, daily travel, and vehicle age. The Urban Mobility Report provides speed and average daily traffic (ADT) per lane. Both sources were implemented in EERPAT tool to analyze energy and emissions reduction policies.[4] Daily average trips, daily total trips, average trips by time of day, and trip distances are included in the New York City guidebook on the taxi industry.[21] Additionally, parking is another source of congestion. Analysis cited by Donald Shoup indicated up to 30% of urban congestion may be caused by drivers circling for, and pulling into/out of, on-street parking spaces.[9]

Technology

A key technology indicator for AV modeling is the level of adoption or penetration of new technologies in the marketplace, which affects the mix of vehicle types in travel fleets. Since the deployment of AVs onto public roadways is still very limited, there is little opportunity for studies and data sources on this topic. It will be important to monitor this topic and to update data and forecasts over the coming years to reflect changing conditions, especially since changes may occur in quantum leaps rather than gradually. The development and adoption rate of new technologies across a wide variety of sectors may be much faster in the 21st century's Internet of Things (IoT) environment than it was in previous eras.

Policies

While there is little information on the quantifiable impacts of AV-related policies, planners and researchers are concerned with the policy implications associated with commonly anticipated outcomes of AV deployment such as mode share, VMT, and emissions. Modeling functionality may also need to be updated as new policies are implemented at the federal, state, or local level.

In the meantime, it may be useful to consider lessons learned from studies of policy impacts on existing travel patterns. For example, exploring the real and potential impacts of parking policies on urban congestion can provide examples of congestion reduction as well as revenue generation enabled by

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[7] National Transit Database 2017 Service, Operating Expenses, Revenue Vehicle Inventory, Federal Transit Administration (FTA). 2017-2019.

[8] Federal Highway Statistics, Federal Highway Administration (FHWA). 2016

[9] The High Cost of Free Parking, Donald Shoup. 2011.

policies that equalize fees for on-street and garage spaces, or to establish “parking benefit districts” in urban neighborhoods for daytime usage by downtown employees.[7]

Emissions

Other than data about the energy sources used by AVs, emissions are represented by system performance metrics such as congestion. VisionEval enables visioning and testing of GHG policy scenarios by matching policies with micro-simulated reactions among individual households, primarily using relationships found in the National Household Transportation Survey (NHTS).[10] Estimated fuel economy based on Motor Vehicle Emissions Simulator (MOVES) is used to generate EERPAT mitigation strategies and policy evaluation analysis.[11]

Topic 2: Scenarios

There have been few published studies which significantly evaluate AVs. Most studies have a horizon year of 2035 and a couple have gone to 2050. Performance metrics have generally been the same as traditional analyses conducted without AV considerations such as VMT, mode share, emissions, etc. With expanded model capabilities and policies, new performance metrics should be evaluated.

The six scenarios created for the CAV Scenario Planning Guide drafted by ICF for FHWA[12] represented different combinations of three basic “building blocks:” Technology Assumptions, Driving Forces, and Drivers and Levers. Each of these building blocks is described in more detail below.

Scenario Technology Assumptions

These topics relate to both input parameters and the formulation of model functions and equations. With the low implementation of current AVs, the range of concepts lead to a need for flexibility of inputs and modular models while data is collected, or new forecasts are created.

Mobile Technology Advancement

Six levels of driving automation are defined as follows: no automation, driver assistance, partial, conditional, high, and full. In the first three levels, a human monitors the driving environment, and in the second three levels an automated system monitors the driving environment. Only the conditional high and full automation levels eliminate the requirement for a human driver to be available to take over control of

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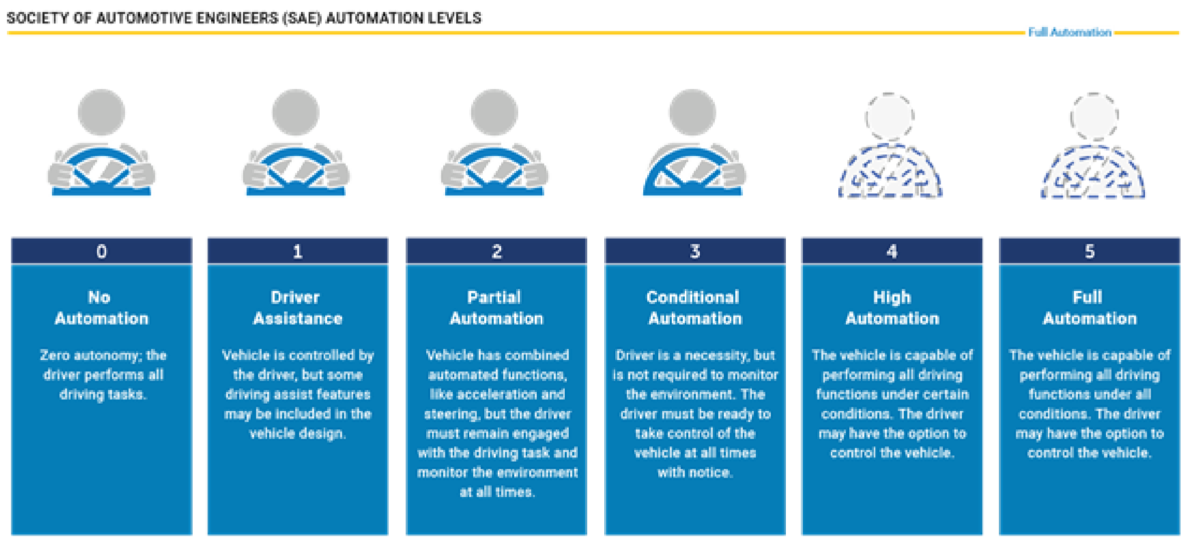
[10] Oregon greenhouse gas modeling and analysis tools, Bettinardi Alex, Weidner Tara, ODOT, 2018

[11] Energy and Emissions Reduction Policy Analysis Tool, Houk Jeff, FHWA Resource Center. 2012

[12] Scenario Planning for Connected and Automated Vehicles, Deepak Gopalakrishna, Hannah Twaddell, Tim Storer, Radha Neelakantan, Richard Mudge, ICF. 2018

the vehicle if necessary.[13] Different percentages of AV and Connected Automated Vehicle (CAV) advancement were tested in explanatory scenario planning for Atlanta.[14]



(Source: NHTSA)

Figure 1. Six Levels of Vehicle Automation

International Standards V2X

Vehicle communication is referred to as Vehicle to Vehicle (V2V) or Vehicle to Infrastructure (V2I). V21 can refer to a traffic signal controller, and Vehicle to any other entity (V2X) with entities being such things as a building. Vehicle communication assumptions are acknowledged as a key uncertainty and not addressed in detail in scenario planning.

Cybersecurity & Safety

Cybersecurity and the fear of hacking are acknowledged as key uncertainties associated with AV deployment but have not been fully addressed in detail due to lack of available research.

Other Technology Assumptions

There are several assumptions based on uncertainties of regulations and transforming technologies. An example is Dedicated Short Range Communication (DSRC) versus Fifth-generation wireless technology (5G). CV/AV technology implementation in traditional vehicles is possible but can be hindered by delayed

[13] SAE J3016TM Levels of driving automation, SAE, 2018, 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

[14] Atlanta Exploratory Scenario Planning 2050, Kim Kyung-Hwa, Atlanta Regional Commission, 2018

issuance of federal DSRC rulemaking. Such delay may cause DSRC to become obsolete if 5G becomes widely available in the foreseen future.

Scenario Driving Forces (Key Uncertainties)

In exploratory scenario planning, driving forces are underlying conditions that that have a great deal of influence on the scenario outcome, but may evolve in very different ways that are difficult to predict. The three key driving forces influencing the six CAV scenarios discussed in this section involve different levels of automation among vehicles on the roadways; different degrees of connectivity among vehicles and the surrounding environment; and different levels of cooperation among governing entities and transportation service providers.

Automation

Any modeling for CV/AV needs to state the level of automation based on the SAE International definition. SAE develops standards related to CAVs. Automation technology in vehicles can be considered in three levels of low, medium, and high in modeling as described below:[1]

- Low: SAE Level 2 capability is widely available and implemented on virtually all new vehicles accounting for 30% to 40% in the general fleet.
- Medium: SAE Level 2 is common in the general fleet, and Level 3 and Level 4 are present but only in small numbers.
- High: SAE Level 4 automation is common on new vehicles and is rapidly becoming common in the general fleet due to high turnover rates. Lower levels of automation are also common on many older vehicles.

SAE Level 5 operation in all environments is not anticipated to be widely available by the 2035 horizon year.[15] A mix of traffic between human driven vehicles, and different percentages of CV, AV, and CAV is a common assumption in the modeling process. In any of the above setups, key uncertainties involve liability, insurance, legislation, cybersecurity, and consumer preferences.[1]

Connectivity

Connectivity includes the ability of a vehicle to communicate with other nearby entities including Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and Vehicle to any other entities (V2X). Connectivity determines support applications such as safety warnings to drivers, distress messages to authorities, harmonizing and monitoring vehicle travel speeds, and real-time routing. The AV market penetration rate and percent error in sensors can affect the efficiency of applications. Other key uncertainties involve the issuance of any federal rulemakings, cybersecurity and hacking, evolving standards and uncertainties about V2I integration, and customer preference for connectivity.[1]

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[15] Development of an Analysis/Modeling/Simulation (AMS) Framework for V2I and Connected/Automated Vehicle Environment

The connectivity rating scale can be defined in three levels to account for AV market penetration and uncertainties as described below:[1]

- Low: All vehicles have some ability to receive information either through the vehicle itself or through smartphones, but little data are transmitted out from vehicles. Fewer than half of vehicles have direct V2V communication, and those that do only have it for safety purposes.
- Medium: Transmissions of both basic safety information and trip planning information is still uncommon in the general vehicle fleet but is common in new vehicles and is more robust in certain applications and subsets of vehicles.
- High: Infrastructure catches up with market-driven vehicle applications such as intersection signals, stop signs, and other road infrastructure and city components that are connected to vehicles to give them information on their surroundings. Infrastructure advancement is becoming common in most locations. Further, all new vehicles have capabilities to receive and transmit data on immediate movement as well as aggregate information on trip plans where applicable. Multimodal information is widely available for both passengers and freight shippers.

Cooperation

Cooperative systems integrate connected, automated, and alternative fuel/ electric vehicle systems. In an ideal world, cooperative vehicle systems are safer and “right-sized”. This system results in less fuel consumption, fewer emissions, and less parking space. The cooperation rating scale can be defined in three levels:[1]

- Low: Some amount of data is shared among entities to facilitate limited cooperative functionality such as transit connection protection, multimodal trip aggregators, and integrated fare payments.
- Medium: Many companies and public agencies are sharing data and actively working to adjust their operational strategies and policies to account for the actions of other companies and modes. Public transit systems coordinate with other modes to time arrivals and departures with customer schedules. Freight operators engage in broad multimodal arrangements to maximize efficiency, and truck platoons are common for long-haul movements.
- High: Policies, business models, and infrastructure change to accommodate a new mobility paradigm with seamless integration between entities and modes. Payments are integrated across many modes through a variety of service packages, and fares are adjusted in real-time on trip-by-trip levels to optimize system efficiency. Mobility-as-a-Service (MaaS) packages are available and commonly used. Transit stations and other infrastructure are in various stages of being redesigned to facilitate intermodal trips (e.g., drop-off/pick-up areas instead of parking lots, new payment infrastructure). Further, many people/vehicles now submit data on planned travel to allow for immediate traffic forecasting and dissemination of optimal routes and mode choices.

One application of connectivity is access to transit using CAVs and Shared Automated Vehicles (SAVs) along routes with different ridership value and fares.[5,9]

Scenario Drivers and Levers

Key drivers and levers include technological developments, consumer preferences, socio-economic factors, and government actions.

Technological Developments

Many types of technological developments are drivers of change in AV deployment. The advancement of 5G and/or DSRC and rapid sensorization with low-cost sensors can accelerate the connectivity of applications. Growth in mobile platforms and smartphone applications can improve connectivity to a non-auto mode of traveling, ETA, or connectivity of human-driven vehicles to other entities. The development and adaptation of cybersecurity standards are critical to safety assurance. Big data analytics, growth in machine learning and artificial intelligence are key elements to the quality of CV/AV operational data and mapping requirements. Vehicles may change shape, weight, design, and function depending on their levels of automation and fuel types. Purchase and usage of EVs can be advanced through lower prices, better battery storage and faster charging infrastructure and lower costs. Entirely new physical modes of transportation such as hyperloops, flying cars, drones, can be possible as a result of industrial automation and manufacturing advancement. Changes in Traffic Management Center (TMC)-related technologies such as decision support, field infrastructure, and signage readable by vehicles are other elements that contribute to the application of AVs.[1]

The most recent technological developments studied in research are routing routines to model dynamic ridesharing (Uber Pool), coordinated multi modal mobility services (MAAS; automated tour planning), and network flow coordination (real time speed governing and predicted arrival rates).[10] Sensor technology includes distance measurements error on the effect of overall traffic performance and sensor range reduction's effect on max speed of AVs being investigated.[11]

Consumer Preferences

Consumer preferences include vehicle ownership, acceptance of new technology, security, and convenience, eco-consciousness, cycling and walking preferences, and adoption rate of shared ride/ car services.[1,9] An Oregon study showed that a statewide transportation strategy (STS) to reduce GHG emissions can lead to a 25% increase in walking trips and urban living growth can reach up to 31%.[6] A study on AV and equity in the DC area showed that AVs can shift trips from transit to auto without significant transit investments, and further improve overall performance with regional investments for heavy rail, bus rapid transit routes, and express bus routes.[5]

Socio-Economic Factors

Socio-economic factors include demographics, urbanization, and new business models for mobility as a service (MaaS) such as TNCs. Demographics will be an important driver in that many millennials have grown up with a mindset more open to sharing rather than owning cars, while the increasingly large number of aging Baby Boomers will demand more mobility options and could be served by AV choices. Characteristics and behaviors that could have a strong influence on GHG include income levels, vehicle ownership, reduced demand, and EV and technology acceptance.[3,16] Low-income people may be more deeply affected by gas price increase and automation of jobs.[3] Factors associated with urbanization such

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[16] TransFuture: Innovate the Future of Transportation, "John Zielinski, FDOT District Five Santanu Roy, HDR, 2017

as non-driving urban population growth, housing prices, employment levels/workforce trends, and immigration levels can contribute to new traveling patterns different from the current form.[1,9]

Cost will be a major driver in the adoption of CVs/AVs. Market forces include fuel and materials prices, international leapfrogging, and car manufacturing/vehicle prices. Depending on the cost of technology, ancillary operating costs like insurance, and sharing models could shape the future of AVs toward either a small fleet of luxury owner-occupied vehicles, or a mass market of shared-use vehicles. The public and private ownership of both vehicles and connectivity networks can be the most uncertain socio-economic factor. Port traffic and freight's role on the economy in addition to traveler safety and mobility could be a good entry point for automation.[6]

Government Actions

Government actions include technology mandates or bans, Federal tax incentives, International/national climate policies, VMT/congestion pricing, and strategic investments in transit and roadway infrastructure and operations.[1,9] On one hand, the pricing of fuel, VMT, parking, and car/ride sharing can affect congestion. On the other hand, congestion and incident management can influence vehicle fuel economy. Government actions can also influence vehicle operation and maintenance, eco-driving, emissions, and market preferences for EVs.[4] The Metropolitan Washington Council of Government modeling indicated that policies incentivizing or mandating higher vehicle occupancy and transit AV could lead to a fare decrease.[5]

Drivers and Levers Associated with Alternative Scenarios

The authors of the CAV Guidebook assembled different combinations of these basic "building blocks" in order to craft six distinct scenarios, each of which represents a different potential trajectory of CAV development and impacts. For the literature review, the authors examined the drivers and levers associated with these scenarios and looked for similar drivers and levers developed by other authors and agencies. See Table 2 below.

Table 2. "Building Blocks" of Six Distinct Scenarios

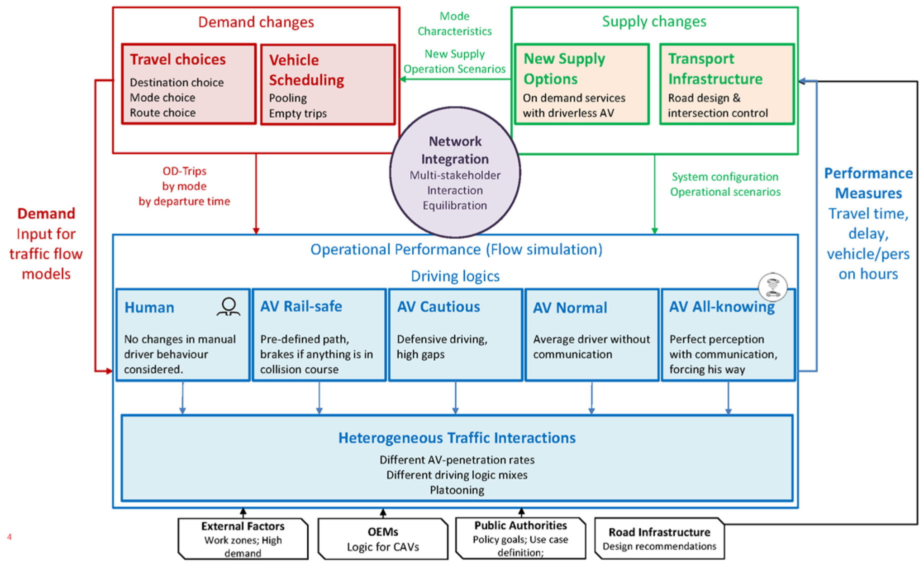
Scenario	Driving Forces
Baseline: Minimum plausible change; nothing beyond currently available technology and investments already in motion.	• Connectivity: Low. 40% V2V/V2I/V2X capability • Automation: Low. Level 2 AV market share 30%-40%; Level 3+ not commercially available • Cooperation: Low
Ultimate Traveler Assist: CV technology progresses rapidly, but AV stagnates.	• Connectivity: High. 85% of all vehicles have V2X capability • Automation: Low. Level 2 AV market share 30%-40%. Level 3+ not commercially available • Cooperation: Medium
Managed Automated Lanes: Certain lanes become integrated with CV and AV and managed for consistent speeds.	• Connectivity: High overall, high on Managed AV lanes. 75% of all vehicles have V2X capabilitiy • Automation: Medium overall; High on Managed AV lanes. Level 4 widely adopted among shared mobility and freight fleet owners. 50%-60% of vehicles have some form of automation. Level 2 AV market share 30%-40%; Level 3 20%; Level 4 commercially available but rare

Scenario	Driving Forces
High level Avs become common but need special lanes.	• Cooperation: Low overall; High on Managed AV lanes
Niche Service Growth: Innovation proliferates, but only in special purpose or "niche" applications.	• Connectivity: Low overall, High in Niches. 40% of vehicles have V2X capability • Automation: Low overall, High in Niches. 30%-40% Level 2. Level 3-4 commercially available, but not functional in unmapped, unequipped, or unpredictable conditions • Cooperation: Low overall, High in Niches
Competing Fleets: TNC-like services proliferate rapidly: freight automation grows but none of these services operate cooperatively.	• Connectivity: High. 75% of all vehicles have capability • Automation: Medium. Level 4 AV widely adopted by shared mobility fleet owners, not as high among personal vehicle owners. 70% of vehicles have some form of automation; 30%-40% Level 2; negligible % Level 3; 30% Level 4 Avs, highest among fleets • Cooperation: Low
Integrated Automated Mobility: On-demand shared services proliferate and integrate with other modes via cooperative data sharing, policies, and infrastructure.	• Connectivity: High. 75% of all vehicles have V2X capability • Automation: High. 70% of vehicles have some form of automation. 30%-40% Level 2; negligible % Level 3. 30% Level 4. • Cooperation: High

Topic 3: Model Functionality

Modeling may account for various aspects of AVs such as adoption rate, AV market penetration rate, size of vehicle and or passengers, and ownership versus shared fleet. Many types of driving behaviors facilitated by AV technology can be considered in modeling, such as car-following, platooning, and aggressive versus moderate driver patterns. Measures of effectiveness related to AV deployment can include emissions, VMT, and roadway capacity. Other aspects of AVs to investigate are safety concerns and opportunities, AVs in public transit, and AVs in freight and other commercial vehicles. To consider each element, different models can imply different methodology using variety of mathematic models, equations, logics, and algorithms. Figure 2 provides a high-level summary of key inputs and outputs to consider when modeling impacts of CV/AV technologies. The framework was developed and tested by CoEXist, a European project (May 2017 – April 2020) which aims at preparing the transition phase during which automated and conventional vehicles will co-exist on cities' roads.[17]

[17] CoEXist – Highway Capacity Implications for the Coexistence of Conventional and Automated Vehicles in Europe, Jochen Lohmiller, PTV Group, presented at TRB2020.



(Source: ICF)

Figure 2. Model Functionality Framework

Software, models, and academic research or microsimulation provided insight into the potential need to change or expand the capability of models. While the specifics differ based on the assumptions, a general framework for evaluating AVs would benefit from evaluating the following model functions, which are discussed in more detail within this section:

- Auto ownership
- AV Adoption
- AV Market Penetration Rate
- AV Usage
- Car-Following
- Commercial Vehicles
- Drive Mode
- Driving Behavior
- Emissions
- Parking
- Passenger Size
- Priority
- Roadway Capacity
- Shared / Ownership
- Transit

- Truck Platooning
- Vehicle Size
- VMT
- Other Policies

Auto Ownership

Automobile operating costs traditionally bear a strong correlation to a road user's choice to own and operate a personal vehicle rather than to share rides with others. Increases in the price of gas or alternative fuels, due to private market forces and/or tax hikes, along with other operating costs such as insurance, purchase price, and maintenance, may lead to a rise in the use of shared mobility services.[18] Fleets of shared AVs would "cruise" streets day and night, carrying passengers and/or cargo, or traveling empty to a pickup location. This would generate a rise in VMT, reduce the need for personal parking spaces in city centers, and incentivize the use of cheap, efficient fuels such as electricity.

AV Adoption

The rate of AV adoption by the traveling public is affected by the availability and accessibility of AVs, and by the level of trust with emerging technologies among individual roadway users. Scenario assessments in previous studies indicate policies to reduce AV costs may incentivize higher rates of electric AV adoption.[17] AV adoption rates may differ by vehicle type and market. One study discussed the earliest adopters of highly automated trucks (Levels 4+) would be fleet owners who could utilize truck platooning lanes.[19]

AV Market Penetration Rate

The AV market penetration rate refers to the percentage of AVs among all vehicles on a network. Any scenario for the future can be tested with different AV market shares, but lower levels of automation and penetration rates of AVs are generally thought to be more realistic than a sudden turnover of the entire vehicle fleet. Penetration rates may be different for AVs and CVs, with CV use rising more quickly than AV use.[10] The literature studied indicated AV/CV Market penetration of 10% for 2035 and 50% for 2060.[20]

AV Usage

Usage of AVs compared to other modes, including human driven vehicles can occur in different percentage ranges. In research conducted on the effect of AV on equity and auto availability for households with zero traditional vehicles, the parameters were adjusted to assume all households would have access to at least one AV.[5]

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[18] VisionEval wiki VERPAT, https://github.com/VisionEval/VisionEval/wiki/VERPAT-Inputs-and-Parameters#inputs

[19] Automation in the long haul: Challenges and opportunities of autonomous heavy-duty trucking in the United States,2018, Peter Slowik and Ben Sharpe

[20] TransFuture: Innovate the Future of Transportation, 2017, "John Zielinski, FDOT District Five Santanu Roy, HDR"

Car-Following

Car-following, measured in the distance between traveling vehicles, influences roadway capacity and safety. CV and AV technologies that enable consistently close car-following patterns (i.e., harmonized travel speeds) create the opportunity for the use of more vehicles per lane with fewer rear-end crashes. Advanced traveler assist CV technologies generate the highest levels of connectivity including harmonized travel speeds.[1] Longitudinal car-following is influenced by adaptive cruise control (ACC), and cooperative ACC (CACC). Truck platooning is made possible by CACC for CAVs. Previous research associates a drop-in roadway capacity with high ACC usage, and an increase in capacity with high CACC usage.[21,22] Ongoing research for the *Highway Capacity Manual* is investigating planning-level capacity adjustment rates along roadway segments given the presence of AVs and CAVs.[23] Table 3 illustrates the anticipated influence of AV market penetration rates (MPR) on 2-lane and 3-lane highway capacities.[24]

Table 3. Effects of Effects of AV Market Penetration Rates on Highway Capacity

2-Lane	Base Capacity (pc/h/ln)			3-Lane	Base Capacity (pc/h/ln)		
MPR (%)	2,400	2,100	1,800	MPR (%)	2,400	2,100	1,800
0	1.00	1.00	1.00	0	1.00	1.00	1.00
20	1.02	1.03	1.14	20	1.01	1.01	1.15
40	1.07	1.10	1.27	40	1.07	1.10	1.26
60	1.13	1.26	1.43	60	1.12	1.23	1.37
80	1.22	1.37	1.63	80	1.21	1.36	1.56
100	1.34	1.52	1.82	100	1.36	1.54	1.82

Commercial Vehicles

Quantifiable indicators associated with commercial vehicles include the sizes and types of vehicles, as well as the reservation of curb space (quantity and timing) to enable parking while loading and unloading cargo or passengers.

[21] Highway Capacity for mixed traffic with CAVs, 2020, Xia-Yun Lu, University of California, Berkeley, presented at TRB2020

[22] Benefits Estimation Model for Automated Vehicle Operations Phase 2 Final Report,2018, Scott Smith, Jonathan Koopmann, Hannah Rakoff, Sean Peirce, George Noel, Andrew Eilbert, and Mikio Yanagisawa, U.S. Department of Transportation Intelligent Transportation Systems (ITS) Joint Program Office (JPO), and Volpe National Transportation Systems Center.

[23] Planning-Level Adjustments for Connected and Automated Vehicles in the Highway Capacity Manual, 6th Edition, Bastian Schroeder, Kittelson, presented at TRB2020

[24] Source: https://www.kittelson.com/ideas/how-connected-automated-vehicles-may-change-freeway-capacities/

Drive Mode

The differentiation of drive modes in AV modeling relates to an AV's ability to cruise without human occupants, typically while heading to or from a pickup/drop-off location. According to research, zero-occupancy AV trips increase by 25% of inverse trips for given origin-destination pairs.[5]

Driving Behavior

Driving behavior refers to the ability of CV/AV vehicle operators to accomplish non-driving activities or use their time differently than they could while driving a traditional vehicle. Vehicle operations may also depend on drive mode.

Emission

In current times, GHG emissions caused by transportation are considered a major contributor to climate change. Vehicles burning fossil fuels account for about 14% of global annual emissions of non-CO2 gases and 25% of CO2 gases; auto trips account for 76% of these transportation-related emissions, while the remaining 24% is generated by air traffic, shipping, and rail combined.[25] AVs, regardless of their fuel source, are expected to operate far more efficiently than human-driven vehicles due to their smoother, more consistent travel pattern.

Table 4 illustrates components of the VisionEval model parameter input associated with fuel consumption, specifically the proportions of VMT generated by different vehicle types powered by different fuel types (diesel, compressed natural gas, and traditional gasoline). Other parameters that affect emissions documented in the VisionEval tool include fuel consumption, costs, taxes, and emission rates, along with elasticities for the 4D metrics of urban form (Table 5) that are associated with shares and numbers of vehicle trips, transit trips, and walking trips.[12]

Table 4. Fuel Types Associated with Vehicle Types in VisionEval

VehType	PropDiesel	PropCng	PropGas
Auto	0.007	0	0.993
LtTruck	0.04	0	0.96
Bus	0.995	0.005	0
Truck	0.945	0.005	0.05

Table 5. Elasticities in VisionEval Associating Urban Form Variables to VMT and Modal Trips

Parameters	VMT	VehicleTrips	Transit Trips	Walking
Density	-0.04	-0.043	0.07	0.07

[25] http://www.multiguide.com/index.php/177.html

Parameters	VMT	VehicleTrips	Transit Trips	Walking
Diversity	-0.09	-0.051	0.12	0.15
Design	-0.12	-0.031	0.23	0.39
Regional Accessibility	-0.2	-0.036	0	0
Distance to Transit	-0.05	0	0.29	0.15

Parking

Currently dense urban areas face parking challenges such as perceived and actual lack of availability to customers and employers, costs to develop and operate parking structures, opportunity costs associated with utilizing valuable downtown real estate for surface parking lots, and congestion due to drivers circulating city streets in search of on-street spaces. One of the promising features of AV deployment is the reduced demand for parking due to a rise in the use of shuttles and shared mobility on demand (MOD) vehicles. Other challenges, however, would continue to exist or would increase with widespread AV deployment, primarily associated with curbside management for passenger pickup/ drop-off and cargo loading/unloading. The effect of parking-related cost and supply as well as policies can be investigated in VisionEval.[12]

Scenarios should consider the impacts of AV shuttles and shared rides in urban core areas as well as around airports, train stations, and main transit hubs. The New York City Taxi and Limousine Commission has investigated curb management at NYC Airport and areas with high volumes of pickups and drop-offs.[26]

Passenger Size

Passenger size refers to the number of passengers in a vehicle. For example, a 2019 study showed that current public transit seat utilization is less than 50% in Sacramento, CA.[27] Research from the California Air Control Board showed in 2018, 39% of TNC trips were in deadhead status (circulating without any passengers), accounting for 1.6 billion miles of travel with a single driver.[28] In an AV, the passenger size value is zero during deadhead periods when an AV is traveling empty from one location to another for a pickup, recharge, or other purpose. Depending on the efficiency of the fleet dispatching system, the deadhead time among AVs in future scenarios may not be this high, but some proportion of AV travel is likely to be in a zero-passenger state.

[26] NYC TLC Factbook 2018, NYC Taxi & Limousine Commission

[27] Our Roads Are Getting More Crowded, But Are Our Vehicles? Presentation by Ron Milam, Fehr and Peers. TRB 2020 Annual Meeting.

[28] The California Clean Miles Standard Regulation and the Role of Pooled Rides, Jennifer Gress, California Air Resources Board (CARB), presented at TRB 2020

Roadway Capacity

Roadway Capacity is calculated based on the supply of lane miles and the efficiency of travel, which is affected by parameters such as vehicle size, car following, driver behavior, and population growth. CV and AV deployment can impact several of these variables, as discussed in other sections of this report. Scenario planning may assume that the amount of freeway and/or arterial lane mile capacity in some regions may grow faster than its population or vice versa; assumptions can be modified in model parameters in VisionEval.[12]

Shared/Ownership

Differences in the proportions of shared versus personally owned AVs can affect numerous outputs and outcomes, including VMT, fuel consumption, and equitable access to transportation. Proportions are affected by users' ability and preferences regarding choices to pay per trip, travel alone or with groups, and to own a vehicle. Experts have predicted that the deployment of AVs and shared mobility options could lead to a decline in vehicle ownership and SOV usage; the rate of change could be influenced in either direction by influences policies, regulations, crash litigation, and insurance costs. One study estimated that vehicle ownership could be reduced by 43% and travel per vehicle could increase by 75% if each AV served several residents of a household.[29] Previous research considered several aspects of AV ownership including routing routines to model dynamic ridesharing[9], and comparisons of different scenarios for shared AVs and robust, coordinated AV transit.[5]

Transit

Transit and rail operations and costs can be affected by AVs and regional policies. Transit revenue miles in a region can change given different levels of AV deployment, which can be modeled for the future scenarios in Transport Supply in VisionEval.[12]

Vehicle Size

Vehicle fleet characteristics can affect emissions and fuel consumption rates, including the proportions of autos and light trucks, the age distribution of vehicles, and vehicle sizes.[2,4] To improve efficiency, AVs may be smaller and shaped differently than vehicles driven by humans. EVs may also be smaller and lighter than gas-powered vehicles.[1] Vehicle size assumptions are also related to assumptions about the proportion of shared versus personally owned vehicles, as well as passenger size and seat utilization. Previous research showed that 50% of single-occupancy vehicle trips can be shifted to shared trips by assuming at least two passengers per vehicle.[5]

VMT/Auto Operating Surcharge

For decades, transportation planners have based decisions about roadway investment needs on broad Level of Service (LOS) ratings calculated by travel demand models. LOS incorporates VMT with other variables such as physical roadway capacity and travel speeds. As cities and dense urban areas come to grips with the reality of roadways that continually score poorly in LOS ratings due to operating at

[29] (Sivak & Schoettle, 2015) in Page 8 of Scenario Planning for Connected and Automated Vehicles

congested levels for long periods of time, planners are looking more carefully at VMT trends independent of LOS ratings. Policymakers are focusing more strategies on reducing VMT to effectively increase roadway capacity without physically expanding the infrastructure, and to reduce GHG emissions from gas powered vehicles. An Auto Operating Surcharge Per VMT is a cost in cents per mile that could be levied on auto users through the form of a VMT charge. Cities such as Washington, DC and New York are currently considering or implanting congestion pricing solutions such as VMT-based surcharges. This value can be edited in VisionEval model parameters.[12]

Policy Variables Associated with AV Deployment

Safety: Road safety impacts can be expressed by factoring VMT in terms of per-mile numbers of fatalities, injuries, and property damage rates. The current fatality rate nationwide is 1.14 per 100 million miles traveled; the injury rate is 51.53. One of the promising features of AVs is the potential for significant reductions in crashes, which can be represented by editing the fatality and injury rates in the model accident component of VisionEval.[12]

Travel Demand Management/Non-auto modes: VisionEval parameters can be adjusted based on the availability of, and participation in, regional travel demand management (TDM) program such as ridesharing, vanpool, and bike/walk programs, transit passes, and telecommuting or alternative work schedule programs.[12] AVs have the potential to boost the effectiveness and attractiveness of these programs by, for example, augmenting mobility choices in areas that are poorly served by transit, and/or for people that cannot drive or do not have access to personally owned vehicles.

Intelligent Transportation Systems/Infrastructure Connectivity: Intelligent Transportation System (ITS) treatments can improve traffic safety and efficiency, as well as traveler mobility. Advancement of technology can enable ITS applications on more miles of roads, which can enable more widespread deployment of CVs and AVs. VisionEval accounts for percent road miles with ITS treatment.[12]

Non-motorized Travel: Another area influenced by policy is the availability, safety, and mode share of non-motorized travel options, including pedestrian trips and trips on bicycles, e-bicycles, e-scooters, and other lightweight vehicles that can travel at speeds up to about 20 mph. A Deloitte study on user preferences predicts that bicycling technology improvements could double the number of bicycle commute trips in some U.S. cities between 2019 and 2022.[30] Increased bicycle usage can support policy goals to reduce congestion and GHG emissions, and to improve public health due to better air quality and increased rates of physical activity. Policy considerations associated with CV/AV deployment and usage of nonmotorized options center around the sharing of roadway space, in terms of safe interactions between non-motorized travelers and CVs/AVs, and the increased demand for curbside pickup/drop-off space that could impact bicycle lane usage and pedestrian crossing patterns.

AV and Model Literature Review Tracking Spreadsheet

In support of the summaries by topic described in the previous sections, a summary for each document is listed in the accompanying spreadsheet (Appendix C contains a link). Each source is listed as rows with

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[30] Technology, Media, and Telecommunications Predictions, 2020, Deloitte Insights, https://www2.deloitte.com/content/dam/insights/us/articles/722835_tmt-predictions-2020/DI_TMT-Prediction-2020.pdf

the columns representing each of the topic areas. The values identified for each source describe the key takeaways for each document and topic, so that the spreadsheet can be sorted and filtered. Details can thus be quickly seen by topic and the user can find the associated reference document number if they would like to read the full document themselves. The electronic version of the spreadsheet is included and can be updated based on future research and provides a basic structure and place holder for various topics. The summary spreadsheet lists each document with a reference number that corresponds to a PDF copy, which is stored in a local folder for easy access and review.

In addition to the summary of each resource by topic, other worksheets in the spreadsheet organize the various topics into the amount of influence on various factors. These have been developed by public agencies as a starting point for considering for future scenarios.

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Chapter 2. (Task 2): Model Specifications for Estimating Metrics on AV Effects

This chapter identifies a set of autonomous vehicles (AV) models intended for use in scenario planning. Using these models in scenario planning can help authorities investigate the broad range of uncertainties, benefits, and challenges of this transformational technology along with economic, lifestyle, and technological changes in the future. AVs would affect different aspects of land use and transportation systems that, at present, cannot be reliably quantified. This chapter describes models that support scenario planning and enable agencies to prepare for possible outcomes of AV deployment. It also documents model specifications.

Because of the complex interconnection of concepts involved in these model specifications, the chapter is built in the form of a chain of flowcharts. The main model specifications diagram contains contextual input groups whose values define a scenario. Each scenario is formed based on three primary AV technology characteristics: automation, connectivity, and cooperation. A scenario may be established for the global system or for a particular subarea. Authorities, planners, and researchers can select their scenarios and identify all required contexts through the flowchart.

Initial prototype models, such as road capacity, have been described with comprehensive details in tabular format accessible through the interactive flowchart structure. This documentation is not intended to be used as a tool or calculator to define any output for a scenario. Rather, it illustrates the structure of the models being developed to explore AV effects and helps analysts identify key decisions required to define scenarios for which that effect might be evaluated. An example scenario flowchart and the required transition steps to build a modeling tool are described for building a future prototype.

A proof of concept (not a calculator) is presented to help planners, decision makers, and jurisdictions define scenarios given different AV technology adoption and market penetration rates. The chapter also specifies model structures for three prototypes that can be implemented as a step toward refining these specifications, and eventually building tools for scenario evaluation.

Required model specifications are noted for a future scenario planning process. At this time, an order of magnitude for presumed changes in the transportation system is uncertain. Also, the direction or number of combinations of modeling factors is in doubt. This chapter intends to present a comprehensive view of a variety of transportation considerations and their effects on each other as well as AV technology. The prototype models allow the most important assumptions regarding rates and degrees of impact to be specified explicitly and explored through alternative scenarios.

There are three main sections of this chapter: a Model Specifications Flowchart description; a Model Specification Example description; and the requirements for Model Specification Transition to a Prototype Model.

Model Specifications – Flowchart

The Model Specifications Flowchart presents a proof of concept to test different scenarios with automated vehicles. The framework includes comprehensive contextual inputs and setup for scenarios in a conceptual system of decisions. It offers directions on the process of planning for future alternatives that consider a variety of AV implications.

Each scenario can be defined by its level of connectivity, automation, and cooperation in system-wide and specific subareas. The test scenario inputs fall into four main contextual groups: technological, regulatory, social, and network supply-demand.

The flowchart is not intended to be a calculator. It is a tool containing comprehensive descriptions of different elements to consider in order to find answers given different AV technology adoption and market penetration rates. Depending on what question you wish to address in scenario testing you may need to consider several inputs or modify the data from current values. Enough detail has been provided that it would be feasible to add additional items to the implementation if desired.

The model specifications flowchart in Appendix A presents the connected pieces of several fundamental concepts such as Road Capacity, Vehicle Occupancy, and VMT, as well as their relationships to different levels of AV Market Penetration Rate (MPR) and AV Ownership that are explained in detailed tabular format.

The flowcharts in this document are interactive. The organization of the flowcharts allows for connections to other parts, such as a back button to the previous flowchart, and/or to the main flowchart (home button). Drilling down through the flowchart elements eventually arrives at a detailed table of relationships.

Model Specifications – Flowchart Example

An example of how to use the Model Specification Flowchart was created to identify the required inputs, changes, and uncertainties in the outputs. The model specifications flowchart example in Appendix A illustrates the chain of logic based on a simplified version of the main flowchart. A sketch-level analysis of the impacts has a two-fold setup: first, AV MPR and AV ownership rates; second, considerations where an increase or decrease of each AV factor can increase or decrease a transportation concept such as vehicle occupancy and road capacity. An increase or decrease of variables refers to the influence of a subarea in combination with AV MPR or AV ownership. The interaction of different variables and their collective impact, combined with policy and regulation, is not argued/addressed in this document.

An example of these considerations is the operational environment, which has several sub-areas. One case of such impact is where AV MPR increase can lead to an increase in VMT in urban streets (a sub-area under operational environment). The reason is that more trips and longer trips will take place with an increase in AV MPR — consequently, VMT increases. The suggested direction of change for each variable is in isolation and based on the literature review and our understanding.

The main structure of this section is flowcharts. Each flowchart presents the connected pieces of a concept such as Road Capacity, Vehicle Occupancy, and VMT. Their relationships to AV Market Penetration and AV Ownership under different circumstances are explained in detailed tabular format. A few notes and caveats regarding the presumptions and logic applied to this example are discussed below.

An example scenario might imagine allowing on-demand services to automate most of the travel without drivers, reducing costs, and vastly increasing their market share. There is a strong public sector role to support system optimization. Dynamic pricing and other mechanisms emerge to coordinate travel across modes. Seventy percent of vehicles have some form of automation (Levels 2-4), and 75% have V2X capability. Vehicle ownership declines heavily in cities and suburbs. Transportation Network Companies (TNCs) costs plummet while market share rises; in urban and suburban areas, up to 85% of VMT is completed by CAVs owned by private TNCs. Electric Vehicle (EV) market share sharply increases, particularly in terms of VMT; all TNC rides are electric. The models described here would allow a quantitative estimate of VMT shifts based on these presumed inputs.

A few notes and caveats regarding the presumptions and logic applied to this example are listed below:

- The example scenario is only one of many possible alternative scenarios. Technological driving forces described here are based on the definition of this scenario.
- Under the uncertainties, while auto ownership of AVs is assumed to drop by 15%, the modeling approach should predict accessibility to AVs, as a vehicle may be in use for some other tasks. So even if it is privately owned, it may not be available for an immediate pickup.
- In the socioeconomic and travel flowchart, one of the items is telework. While we are not sure how many employers and employees will be keen on teleworking in the future, we need to consider that part of teleworking can be performed in an AV ride. However, depending on the size and type of AV, only certain types of employment can benefit from telework in AVs.
- In this scenario, one of the assumptions is that AVs are EVs that can lead to reduced emissions and state gas tax income. However, it is not clear if long trips, such as inter-city, are possible via EVs.
- Vehicle characteristics such as size and dynamics can play an important role in vehicle occupancy and road capacity. AVs can offer small size vehicles for only two passengers. Such a small car can be eight feet long and take up less space on the road than a regular 14-foot car. It can also offer a shuttle and van pool to accommodate eight to 16 passengers.
- AVs offer the promise of improved vehicle dynamics. Cooperative adaptive cruise control (CACC) can enhance car-following and reduce headway safely between CAVs, which can increase road capacity. Moreover, AVs' smooth braking and shorter reaction time to surrounding vehicles can improve road safety.
- Some of the appealing features of AVs are enabled in-car activity and trip making for non-drivers. Zero Occupant Vehicles (ZOVs) can increase VMT but reduce parking demand. ZOVs makes food and goods delivery possible. Delivery services currently account for up to 17% of daily trips in urban areas. It is also a side effect of mobility assistance for people with disabilities, which can increase access to those currently needing an escort to travel alone.
- Other in-car activities are working, sleeping, and eating, which can increase the value of time spent in traffic.
- AVs have the potential to affect land use patterns in different ways. The availability of affordable, convenient TNCs and (Mobility-on-Demand) MOD services in cities and suburbs can influence shifts in travel modes from SOV to transit and shared ride services; the associated decrease in private vehicle ownership could reduce the amount of land required for parking in urban and suburban areas, which can encourage compact development of new housing, employment, and commercial/ civic/ recreational space. Conversely, an increase in personally owned AVs could incentivize sprawl in suburban and rural areas by making long-distance commutes more tolerable and even productive. The ability to conduct in-car activities in AVs – such as working, sleeping, and eating – can increase

the value of time spent in traffic and make it more attractive for urban dwellers to buy larger homes and lots in suburbs and rural areas.

To navigate the flowchart, a user can select one of three buttons located at the bottom right of each page. The home icon takes you back to the first flow chart, the back arrow takes you to the previous flowchart, and the information icon takes you to the information page. Items that are linked in another flow chart are accessible by clicking on round diagonal corner rectangular boxes.

A proof of concept to test different scenarios with automated vehicles is presented in Appendix A. The framework includes comprehensive contextual inputs and setup for scenarios. It offers directions on the process of planning for a future alternative that considers a variety of AV implications. The flowchart is an exploratory tool that provides a user with a variety of inputs to be examined in a future scenario incorporating AVs.

The model specifications flowchart starts with four contextual input categories shown in the green box on the left. Each input group helps users consider different aspects of the context needed to plan a scenario. For example, under regulatory input, an MPO could test a new policy that only allows for shared AVs, and another policy only allows for AVs in the form of EV. The measure of effectiveness (MOEs) to compare the policies could be Vehicle Miles Traveled (VMT) and Emissions.

Each scenario is defined by its level of connectivity, automation, and cooperation in system-wide and specific subareas. The test scenario inputs fall into four main contextual groups: technological, regulatory, social, and network supply-demand. Each flowchart presents the connected pieces of a concept. Fundamental concepts such as Road Capacity, Vehicle Occupancy, and VMT, as well as their relationships to AV Market Penetration and AV Ownership under different circumstances, are explained in detailed tabular format. More information about the tables context is in the Description Pages Information.

The first row of the table describes a metric that is evaluated in the table, with green cells indicating an increase and orange cells indicating a decrease in its magnitude under different circumstances. The table has three main columns. The first column is considerations that identify nine areas in scenario planning, including infrastructure (operational environment and roadway conditions), land use types, user preference (economic impact and willingness to share), etc. The second column defines subareas for each consideration, e.g., urban, suburban, and rural are subareas of land use consideration. The third column introduces the AV presumptions. This column splits into two; higher AV MPR and higher AV ownership, which create a condition to evaluate the direction of change for Road Capacity (a concept). Under each presumption, the table splits to two more columns to show the roadway capacity's change and a description to explain why it increases or decreases.

The second part of the description page recommends model formulation that can be implemented in a scenario in the form of model, equation, or a defined range. In the road capacity example, a suggested range based on new NCHRP research for HCM is recommended. The last piece directs us to more information about upstream and downstream concepts. Upstream concepts affect the roadway capacity, and downstream concepts are influenced by roadway capacity in a scenario planning model. For example, roadway capacity changes due to AVs can change congestion, parking demand, VMT, and emission.

Planners can define scenarios to test the future of AVs. As previously noted, this application is not intended to be a calculator. It is a tool containing comprehensive descriptions of different elements to consider in order to find answers given different AV technology adoption and market penetration rates. Depending on what question you wish to address in scenario testing you may need to consider several inputs, modify the data from current values, or add items that have not been implemented before. The modifications can occur in input entry, methods, and functions; those modifications can alter the intermediate inputs of other steps in a model.

To navigate Appendix A, you can use one of three buttons located at the bottom right of each page. The home icon takes you back to the first flow chart, the back arrow takes you to the previous flowchart, and the information icon takes you to the information page. Items that are linked in another flow chart are accessible by clicking on rounded corner rectangular boxes. A glossary of terms is on the next page.

Each rounded corner rectangle takes a user to another flowchart with more details about that variable. For example, land use expands to economic, lifestyle, and regulatory factors. The land use flowchart can help a user to account for lifestyle changes that lead to the densification of urban areas or migration of people to suburbs. These lifestyle trends could be encouraged with higher AV MPR and AV ownership.

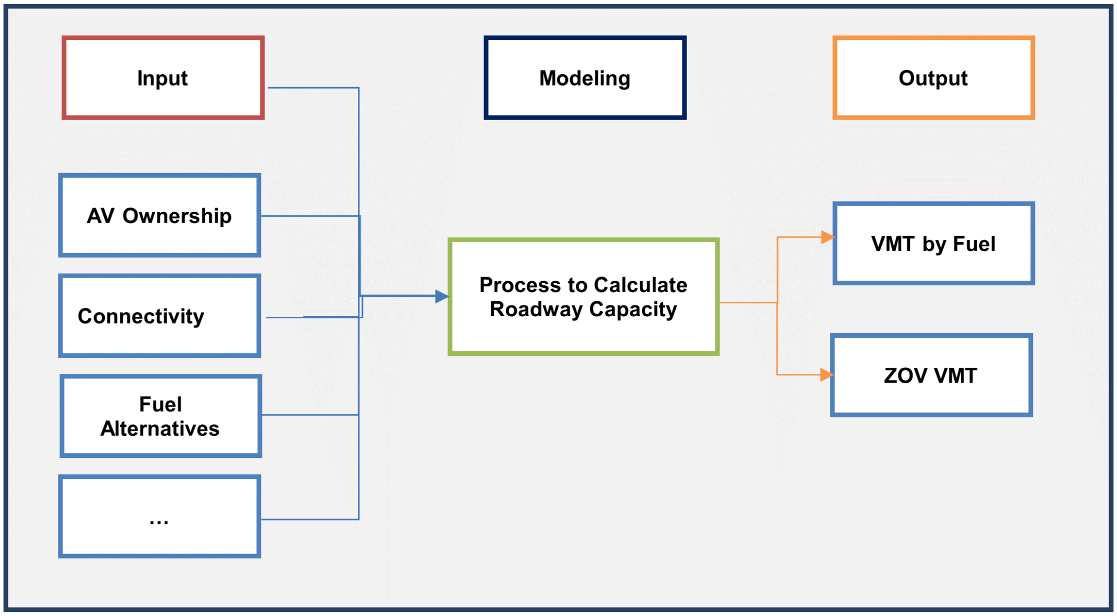
Model Specifications – Transition to a Prototype (Task 3)

The flowchart contains a wide variety of variables, processes, and performance indicators. This section provides a short list of parameters and models to implement in a prototype in Chapter 3.

To transition from the list to a prototype a pseudo-code first had to be generated. Then, with a similar approach to the VisionEval tool, a framework was proposed including modules, inputs, and output reports in RStudio.

Roadway Capacity Prototype

At the outset of Chapter 3, the focus will be on three concepts. One of them is roadway capacity (vehicles per hour per lane). Upstream factors that affect roadway capacity are based upon user-defined input. The upstream elements feed into a mathematical formulation to calculate roadway capacity. The downstream elements are Vehicle Miles Traveled (VMT) and Zero Occupant Vehicle (ZOV) VMT. This concept is illustrated in Figure 3.



(Source: ICF)

Figure 3. Schematic Prototype Process – Roadway Capacity

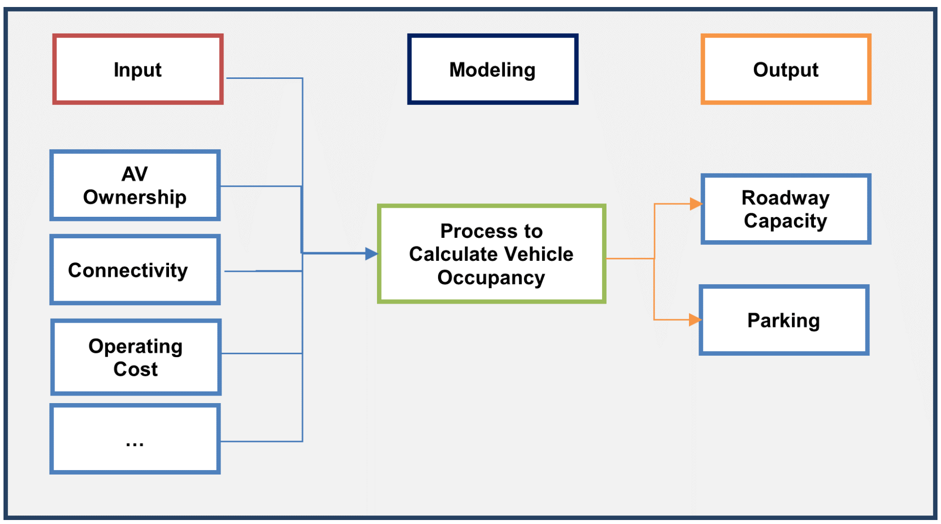
- Automation: User defines percent of the fleet in each AV level to calculate the maximum percentage of vehicles able to operate with or without a licensed human driver.
  - Level 0 = AA %
  - Level 1 = BB %
  - Level 2 = CC %
  - Level 3 = DD %
  - Level 4 = EE %
  - Level 5 = FF %
- **AV Ownership**: User defines percent of owned or shared per each level of AV. It can determine types of shared trips with strangers and non-family members.
  - Level 0 = aa % shared
  - Level 1 = bb % shared
  - Level 2 = cc % shared
  - Level 3 = dd % shared
  - Level 4 = ee % shared
  - Level 5 = ff % shared
- **Zero Occupant Vehicles (ZOV)**: User defines percent of AVs that operate as ZOV to determine the AV fleet without a licensed human driver that performs activities such as food delivery or passenger pickup.
  - ZOV = gg % of the level 4 or 5 AVs

- **Connectivity**: User defines percent of roadway facilities with technology to allow for connected autonomous vehicles (CAVs) applications.
  - Facility type = GG % CAV
  - Level of AV = HH % CAV
- **Cooperation**: User defines the percent of collaboration between organizations in a region. It determines the efficiency and ease of traveling between modes.
  - Auto-Transit: II%
  - Transit-TNCs: JJ%
  - Micromobility-Transit: KK %
- **Employment- Telework**: User defines percent of telework and in-vehicle telework.
  - Telework: LL% for each type of work
  - In-AV Telework: MM% for each type of work
- **Fuel Alternatives**: User defines percent of fleet utilization per fuel type. It defines emissions and VMT by fuel type.
  - Gas: NN%
  - Electric: OO%
  - Hydrogen: PP%
  - Fuel X: QQ%
- **In-AV activity:** User defines the percentage of model-defined in-vehicle activities. It influences passengers' willingness to share rides and/or take long trips.
  - Work: RR% passengers work
  - Sleep: SS% passengers sleep
  - Recreation: TT% passengers attend recreation activities
  - Other: UU% of other activities
- **Trips per Land Use**: User defines population and employment to generate trips using VisionEval Modules. The output is total trips per mode per purpose, which will be used in VMT calculation.
- **Mobility Service**: User defines percent of people using mobility service platforms to schedule a trip and pay for it. It affects trip generation and VMT.
  - Auto: VV%
  - AV: WW%
  - Transit: XX%
  - Micromobility: YY%
- **Vehicle Driving Dynamics**: User defines headway value in terms of time (second) per vehicle type and level of AV. It affects the speed limit and roadway capacity.
- **Vehicle Occupancy**: User defines average vehicle occupancy (number of people per vehicle) by vehicle type and AV level.

- **Vehicle Size**: User defines AV size in terms of both length and passenger car equivalent (PCE) factor. It affects roadway capacity and seat utilization.
- **Roadway Capacity**: A prototype contains the equations and inputs for roadway capacity per facility type. The capacity calculation adjusts the baseline capacity for AV MPR, headway, vehicle size, connectivity, and policies that prohibit or encourage AVs by facility type.
- ***Vehicle Miles of Travel (VMT)***: A prototype contains the equations to calculate VMT, VMT for ZOVs, and VMT by fuel type.
    - VMT
    - ZOV VMT
    - VMT by Fuel

Vehicle Occupancy Prototype

Another concept to focus on is Vehicle Occupancy (Number of passengers per vehicle). Both AV and shared rides can significantly influence vehicle occupancy. Upstream factors that affect vehicle occupancy such as privacy, operating cost, and convenience are based upon user-defined input. The upstream elements feed into a mathematical formulation to calculate vehicle occupancy. Model formulation depends on vehicle type, number of seats, applicable area, probability of ZOV, private vs. shared, etc. The downstream elements include roadway capacity, congestion, and parking. This concept is illustrated in 4.

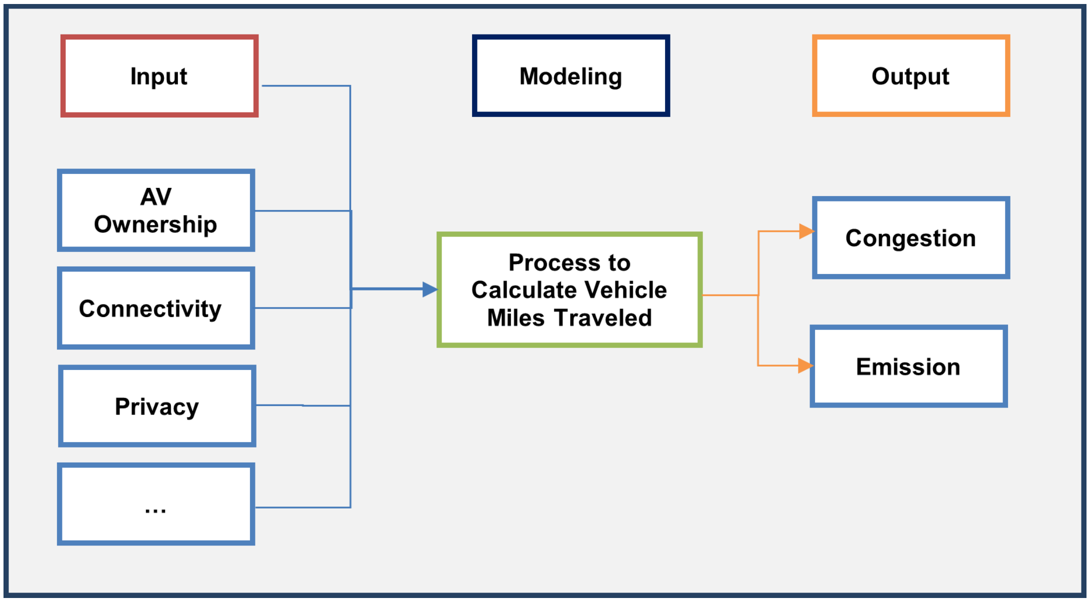


(Source: ICF)

Figure 4. Schematic Prototype Process – Vehicle Occupancy

Vehicle Miles Traveled Prototype

The third concept is Vehicle Miles Traveled (VMT), defined as the total annual miles of vehicle travel divided by the total population in a state or urbanized area. VMT can also be represented as a daily or hourly value. VMT calculation includes determining the daily traffic on a roadway segment and its length, then summing all the segments' VMT to reach a total for the geographical area. Upstream factors that affect vehicle occupancy such as privacy, operating cost, and convenience are based upon user-defined input. VMT affects emissions and climate change. This concept is illustrated in Figure 5.



(Source: ICF)

Figure 5. Schematic Prototype Process – VMT

Chapter 3. (Task 3): Prototype Models and Documentation

Building upon the Chapter 2 Model Specifications deliverable containing a wide variety of variables, processes, and performance indicators, this chapter serves as the first of the deliverables for Prototype Models. It provides a prioritized list of parameters and models to implement as prototypes during the next steps of research. This chapter also documents the process of developing the prototype models including documentation of inputs, outputs, and functions implemented, with ranked potential next steps, along with a sample of code. Since this chapter is implementing the Agile framework for development, this chapter is updated with each key feature of the prototype such that the current inputs, outputs, functions, and next steps reflect the latest version and are a complete in both a GitLab package and associated Microsoft Office or RStudio files.

Roadway Capacity Prototype

Roadway Capacity Prototype Overview

This section provides an overview of the roadway capacity adjustment function. The purpose of this function is to provide a framework that allows the user to adjust capacity of roadway facilities based on market penetration of AVs, percentage of the roadway facility that provides connectivity between vehicles, the changes to average size of vehicles relative to the standard Passenger Care Equivalent (PCE), and the potential of zero occupant vehicles (ZOVs). This function uses two different user input tables and two look-up tables to determine the appropriate capacity adjustment factor (CAF) to apply to each facility type. So, we have:

- AV market penetration rates by level of automation
- Roadway system inputs that provide details on the base capacity, connectivity, PCE, and ZOVs for each facility type
- Vehicle dynamics look-up table
- Capacity adjustment factor look-up table

The vehicle dynamics look-up table contains details related to how AVs behave on a specific roadway facility type. These behaviors are focused on the platoon capabilities of connected and autonomous vehicles (CAVs) and include the intervehicle gap (space between each AV), maximum platoon size, and CAV inter-platoon gap (space between each platoon). The capacity adjustment factor look-up table contains appropriate CAFs to use for each combination of facility type, vehicle dynamics, CAV percentage, and base roadway capacity. The use of these two look-up tables will allow users to add additional CAFs as new empirical or micro-simulation studies are conducted to better understand the impacts of AVs on roadway capacity, and to produce a CAV market adjusted CAF with resulting adjusted capacity. A PCE adjustment to account for the vehicle size is then applied to produce a second adjusted capacity. Each adjusted capacity is listed separately so the influence of each in isolation can be understood.

Model Functions

After completion of the Model Prototype List in Chapter 2, each of the parameters were expanded upon to document the type of input, the range of input, and a brief description to assist with the development of the pseudocode and implementation of the model prototype. The priority of functions discussed are summarized in the attached Chapter 3 – Structured Pseudocode V5 table. Each function has an associated ranking (0 is highest priority ranking). Table 6 summarizes the current thought process, priority order, and status for each function.

Table 6. Revised Prioritized List of Model Functions

Rank	Function	Influence of Function on Roadway Capacity Analyses	Status
0	Roadway Capacity	This is the agreed upon functionality to implement as the first module.	Completed
0	Roadway System	Capacity cannot be calculated without roadway attributes, so this is a required input.	
1	Market Penetration	This defines the levels of automation among the vehicles in the study area. It is a fundamental variable in most of the current methods for evaluating CAV impacts on transportation systems.	
1	Connectivity	This function is needed to distinguish between AV and CAV.	
1	Vehicle Driving Dynamics	Roadway capacity is directly influenced by the manner in which vehicles are operated. Parameters such as gap acceptance, platoon size, and inter-platoon gap are those currently used in draft version of the Highway Capacity Manual and we will start with those.	
2	Vehicle Size	The physical space occupied by a vehicle has an impact on the vehicles per hour per lane metric.	
3	Zero Occupant Vehicle (ZOV)	The vehicle dynamics and/or vehicle size may differ if there are no passengers or contents in the vehicle.	

Roadway Capacity Model Prototype Pseudocode

The pseudocode for the roadway capacity model prototype in the general implementation order is shown below organized by prototype functions in terms of inputs, outputs, and calculations needed for evaluation and the harness that implements the functions in this specific model prototype. This code is implemented in GitLab repository files to run the model prototype.

Prototype Functions

1. Define the input files and values in the appropriate CSV files for each scenario. Descriptions and sample data for each user input are described below.

- AV market penetration rates by level of automation are defined as a global input for the market penetration for all vehicles traveling within the study area. A sample input table for the AV market penetration lookup is below. The values shown below are arbitrary to demonstrate the format of the data, and that the values should sum to 100. (Table 7)

Table 7. Sample AV Market Penetration rates Lookup Table

AV Market Penetration	Percent
Level 0	0
Level 1	50
Level 2	20
Level 3	0
Level 4	20
Level 5	10

- Roadway system inputs provide details on the base capacity, connectivity, maximum AVs allowed the CAV passenger car equivalent for each facility type, and the percentage of ZOVs. (Table 8)

Table 8. Roadway System Inputs Lookup Table

Facility Type	Base Capacity	Connectivity Percentage	AV Allowed	Passenger Car Equivalent	Percent ZOV
Freeway	2400	100	100	0.90	0
Merge	1800	100	100	0.80	0
Weave	1900	100	100	0.80	0

- The vehicle dynamics look-up Table defines CAV operating conditions for each facility type. Current values are populated based on the draft Highway Capacity Manual simulation results (Table 4).

Table 9. Sample Vehicle Dynamics Lookup Table

Facility Type	Intervehicle Gap	Max Platoon	CAV Inter-platoon Gap
Freeway	0.71	10	2
Merge	0.71	10	2
Weave	0.71	10	2

- The capacity adjustment factor look-up Table can be based on microsimulation, empirical data, or asserted values. The factors included in the default input file are based on the Highway Capacity Manual, Chapter 26, the influencing factors of vehicle dynamics on base roadway capacity. (Table 9)

Table 10. Sample Capacity Adjustment Factor Lookup Table

CAV Percentage	ZOV Percentage	Facility Type	Intervehicle Gap	Max Platoon	CAV Inter-platoon Gap	Base Capacity	ADJ CAF
0	0	Freeway	0.71	10	2	2,400	1.00
0	0	Freeway	0.71	10	2	2,100	1.00
0	0	Freeway	0.71	10	2	1,800	1.00
0	0	Diverge	0.71	10	2	2,400	1.00
20	0	Diverge	0.71	10	2	2,400	1.02
20	0	Diverge	0.71	10	2	2,100	1.02
20	0	Diverge	0.71	10	2	1,800	1.15
20	0	Merge	0.71	10	2	2,200	1.02

2. Calculate the %CAV for each facility type for use in the CAF lookup. Calculate the total global %AV by adding Level 4 and Level 5. Multiply the minimum value of the global %AV and the AV Allowed for each facility type by the %Connectivity for each facility type.

3. Read in the Percent ZOVs: the percentage of CAVs by facility type that have zero occupants or parcels. This is used to apply different vehicle dynamic parameters by facility type, and to calculate metrics related to zero emissions vehicles (ZEVs) separate from vehicles with people or parcels.

4. Look up the CAF based on the %CAV and each individual vehicle dynamic factor for each facility type along with the percent ZOVs. If the user input Base Capacity is not a listed value in the CAF look-up table, interpolate the CAF based on the next closest base capacity for each facility type.

5. Calculate the CAV Market Adjusted Capacity for each facility type by multiplying the CAF for each facility type to the user input Base Capacity for each facility type.

6. Calculate the PCE Adjusted Capacity: the ratio of size of the CAV fleet relative to the existing fleet influences the amount of utilized roadway space. The ratio will be applied by dividing the CAV adjusted capacity by the PCE to account for vehicle size.

7. Output results of the look-up Table and the resulting calculation. Table 11 illustrates the structure of the output, showing the base facility type capacity, the %CAV, the CAF, the adjusted capacity, the PCE, and the PCE adjusted capacity for each facility type in the input data.

Table 11. Sample Completed Calculation of Roadway Capacity Model Prototype

Facility Type	Base Capacity	CAV Percentage	CAF	AV Market Adjusted Capacity	PCE	AV Market & PCE Adjusted Capacity	ZOV Percent-age	ZOV CAF	ZOV & AV Market Penetration Adjusted Capacity	ZOV, PCE, & AV Market Penetration Adjusted Capacity
Freeway	2,200	30.00	1.06	2,325.00	0.90	2,583.00	10	1.01	2,215.00	2,461.00

Merge	1,800	30.00	1.05	1,890.00	0.80	2,362.00	10	1.00	1,800.00	2,250.00
Diverge	1,900	30.00	1.16	2,204.00	0.80	2,755.00	10	1.10	2,096.00	2,620.00

Prototype Harness

The coding standard used for the prototype consists of an R script called by an RMarkdown file with user inputs and module parameters contained in CSV files. The process is described in this chapter, the RMarkdown file, and stored using GitLab. The GitLab repository contains an overview of the project, the past deliverables, and documentation with associated files.

The Scenario Management control file is the model "harness" that manages scenario names, descriptions, input files, and output files, serving a purpose akin to the toolbelt worn by a carpenter while s/he is completing a construction project. (Table 12). The RMarkdown allows the user to select scenarios dynamically and see the results update automatically. A subsequent step could be to develop scenario input files to demonstrate the influence of the inputs on the results.

Table 12. Example Prototype "Harness" (Scenario Management File)

Scenario	Description	Market Penetration	Roadway System Input	Vehicle Dynamics	CAF Lookup	Output Table
Alt A	Baseline Scenario	data\scenario_a\market_penetration.csv	data\scenario_a\RoadwaySystem.csv	data\lookup_tables\vehicle_dynamics.csv	data\lookup_tables \lookup.csv	data\output \alternative_a.csv
Alt B	Scenario with Higher AV Market Penetration Rate	data\scenario_b\market_penetration.csv	data\scenario_b\RoadwaySystem.csv	data\lookup_tables\vehicle_dynamics_V2.csv	data\lookup_tables\lookup.csv	data\output \alternative_b.csv

The user interface is updated dynamically in response to the scenarios selected from the Scenario Management file. The output results Table updates automatically for all facility types in the Roadway System input for the selected scenario. Figure 6 is a screen capture of the dropdown selection functionality for the scenario manager.

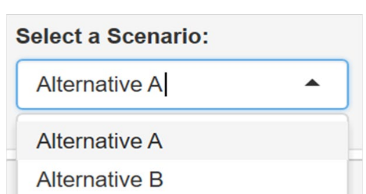


Figure 6. Scenario Selection Drop Down Menu

The following code snippet provides an example of how to use the roadway capacity adjustment function for multiple scenarios. The relative paths to the required input files are all contained in the scenario manager look-up Table. The information in Table 13 is then used to update a list that is passed to the function.

```
source("scripts/CalculateRoadwayCapacity.R")


# List to specifiy the input files
CalculateRoadwayCapacitySpecification  <- list(
  AVMarketPenetration = list(file="data/scenario_a/market_penetration.csv"
    , description="A file that summarizes the percentage of AV market penetration by level of automation (values should total to 100)"
    , column_names = c("av_level", "market_penetration")
    , data_types = c("character", "numeric")
    , column_description =c("Level of Automation", "Market Penetration Percentage"))
  , RoadwaySystem = list(file="data/scenario_a/RoadwaySystem_Input.csv"
    , description="A file that provides details on the specific roadway segment "
    , column_names = c("facility", "base_capacity", "connectivity_percentage", "percent_av_allowed", "pce", "percent_zov")
    , data_types = c("character", "numeric", "numeric", "numeric", "numeric", "numeric")
    , column_description =c("Facility Type", "Base Capacity", "Connectivity Percentage", "AV Allowed", "Passenger Car Equivalent", "Percent ZOV"))
  , VehicleDynamics = list(file="data/lookup_tables/vehicle_dynamics_table.csv"
    , description="A look table the summarizes the vehicle dynamics used in the scenario"
    , column_names = c("facility", "percent_zov", "intervehicle_gap", "max_platoon_size", "cav_interplatoon_gap")
    , data_types = c("character", "numeric","numeric", "numeric", "numeric")
    , column_description =c("Facility Type", "Percent ZOV","Intervehicle Gap","Max Platoon","CAV Interplatoon Gap"))
, CAFLookup = list(file="data/lookup_tables/lookup_table.csv"
    , description="The main lookup table used by the tool to determine which CAF to apply to the base capacity value."
    , column_names = c("cav_percentage", "facility", "intervehicle_gap", "max_platoon_size", "cav_interplatoon_gap", "base_capacity", "caf")
    , data_types = c("character", "numeric", "numeric", "numeric")
    , column_description =c("CAV Percentage", "Facility Type", "Intervehicle Gap", "Max Platoon Size", "CAV Interplatoon Gap", "Base Capacity", "CAF"))
  , ZOVCAFLookup = list(file="data/lookup_tables/lookup_table_zov.csv"
    , description="The main lookup table used by the tool to determine which CAF to apply to the base capacity value."
    , column_names = c("cav_percentage", "percent_zov","facility", "intervehicle_gap", "max_platoon_size", "cav_interplatoon_gap", "base_capacity", "caf")
    , data_types = c("character", "numeric", "numeric", "numeric", "numeric")
```

```
    , column_description =c("CAV Percentage", "ZOV Percent", "Facility Type", "Interve
hicle Gap", "Max Platoon Size", "CAV Interplatoon Gap", "Base Capacity", "CAF"))

  , output = list(file="data/output/scenario_a.csv"

    , description = "Scenario Specific Output File That will Be Generated with the Too
l is Run"

    , column_names = c("facility","base_capacity","cav_percentage", "caf", "adjusted_c
apacity", "pce", "pce_adj_capacity", "percent_zov", "zov_caf", "zov_adjusted_capacity"
, "zov_pce_adj_capacity")

    , data_types = c("character", "numeric", "numeric", "numeric", "numeric", "numeric
", "numeric", "numeric", "numeric")

    , column_description = c("Facility Type","Base Capacity","CAV Percentage", "CAF",
"AV Market Penetration Adjusted Capacity", "PCE", "AV Market Penetration and PCE Adjus
ted Capacity", "ZOV Percentage", "ZOV CAF", "ZOV and AV Market Penetration Adjusted Ca
pacity", "ZOV, PCE, and AV Market Penetration Adjusted Capacity"))

  )

# Run the function to calculate the adjusted Roadway Capacity

df <- CalculateRoadwayCapacityZOVPCE(CalculateRoadwayCapacitySpecification)


# Print the Results of the Function in a Formated Table

kable(df, format.args = list(big.mark=",")

      , digits = c(0, 0, 0, 2, 0, 2, 0, 0, 2, 0, 0)

      , align = c('l', 'c', 'c','c', 'c', 'c', 'c', 'c', 'c', 'c', 'c'))
```

Table 13. Interactive R Markdown for Each Scenario

Facility Type	Base Capacity	CAV Percentage	CAF	AV Market Adjusted Capacity	PCE	AV Market and PCE Adjusted Capacity	ZOV Percentage	ZOV CAF	ZOV and AV Market Penetration Adjusted Capacity	ZOV, PCE, and AV Market Penetration Adjusted Capacity
Freeway	2,200	30.00	1.06	2,325.00	0.90	2,583.00	10	1.01	2,215.00	2,461.00
Merge	1,800	30.00	1.05	1,890.00	0.80	2,362.00	10	1.00	1,800.00	2,250.00
Diverge	1,900	30.00	1.16	2,204.00	0.80	2,755.00	10	1.10	2,096.00	2,620.00

To compare results outside of the interactive R Markdown, the results for each scenario are displayed on screen and are also output to a CSV file located in the data\output directory with the scenario description as the file name.

Other Potential Prototypes

The roadway capacity prototype described above was implemented with multiple functions. As an outcome of Chapter 2, other prototypes were considered. Table 14 below contains the functions and prototypes for consideration beyond the roadway capacity model. These functions and prototypes are beyond the scope of the current project.

Table 14. Prioritized List of Other Prototype Model Functions

Rank	Function	Influence of Function on Roadway Capacity Analyses
4	Vehicle Occupancy	This would be the difference between total vehicle fleet and ZOVs and would influence the person throughput and possibly vehicle size. The number of people and parcels per auto for each market penetration percentage for each facility type. This will be used to calculate the size of vehicle. a. 1 or 2 people or parcels per auto b. 3 or more people or parcels per auto
5	Vehicle Miles Traveled (VMT)	VMT is an output and does not directly influence roadway capacity. Metrics within VMT such as miles driven by ZOV may be of interest, however.
6	AV Ownership	Evidence does not currently show that operating characteristics of personally owned versus shared vehicles would be substantively different in terms of their impact on the behavioral dynamics that influence roadway capacity. This may be a future module that may influence vehicle usage and VMT.
7	Land Use and Related Activity	Land use contextual variables influence baseline roadway capacity because of their relationship to friction factors (e.g. parking, driveways) associated with dynamic driving behaviors. At present, there is no research to suggest that substituting traditional human-operated vehicles with CAVs would engender a dramatic change in the friction factors associated with land use contexts.
8	Mobility Services	Although widespread use of Mobility Services vehicles could affect variables such as overall demand, mode choice, vehicle ownership, and VMT, it is not anticipated that it would influence roadway capacity directly.
9	Cooperation	The ability to change modes seamlessly would influence mode choice and activity, but not roadway capacity.
10	Fuel Alternatives	Although fuel types have some relationship to driving dynamics such as acceleration, it does not significantly impact roadway capacity assessments. Variations in fuel types could influence other variables not directly associated with roadway capacity including vehicle range, mode selected, VMT, energy consumption, cost of travel, and emissions.
11	In-AV Activity	Being able to perform activities while traveling in a vehicle may influence mode choice, cost of travel, and VMT but would most likely

Rank	Function	Influence of Function on Roadway Capacity Analyses
		not influence driving behaviors or vehicle dynamics that impact roadway capacity.
12	Employment Telework	Changes in commuter travel patterns associated with telework can impact variables such as travel modes, time of day, and overall activity, but do not have a direct impact on roadway capacity.

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