Connected Vehicle Impacts on Transportation Planning

Analysis of the Need for New and Enhanced Analysis Tools, Techniques, and Data—Briefing for Traffic Simulation Models

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Final Report—March 11, 2016

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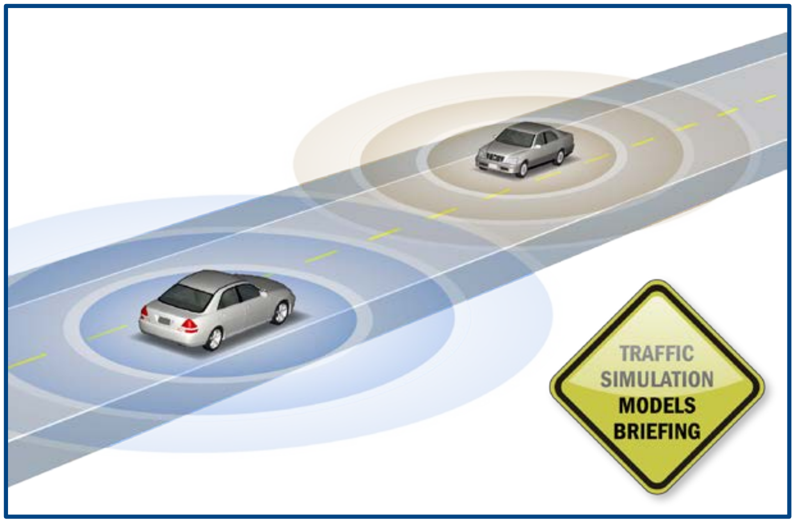

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16. Abstract

The principal objective of this project, “Connected Vehicle Impacts on Transportation Planning,” is to comprehensively assess how connected vehicles should be considered across the range of transportation planning processes and products developed by states, Metropolitan Planning Organizations (MPOs), and local agencies throughout the country. The purpose of this memorandum is to provide a summary of a larger report that identified the need generated by Connected and Automated vehicle (C/AV) technology for new or enhanced tools, techniques, and data to support various C/AV planning activities and approaches for how to meet those needs. It focused on identifying enhancements to existing transportation analysis data and tools used in transportation planning that will be needed to extend those tools to accommodate C/AV impacts and outcomes in the future. This report focuses on the research and activities that will need to take place in order to adapt existing transportation models for use in analyzing Automated and Connected Vehicles. This report includes a summary of existing data, tools and products currently used in transportation planning processes. The next area includes an evaluation of the suitability of existing simulation models for C/AV analysis with respect to input/output interfaces, usability, modeling features and calibration requirements. Following is a gap analysis that identifies the limitations of current simulation models for use in analysis of C/AV technologies. The results show that simulation models used in traditional transportation planning, analysis and design would potentially be modified or overhauled to accommodate analyses of connected vehicle applications and technology. The ability to incorporate data provided through Connected and Automated vehicle demonstration projects will be especially important in these modifications. Finally a roadmap/research plan is provided that summarizes research topics to target these needs and gaps, identifies which agency would be best suited for addressing these needs, establishes priority levels for each topic and a draft schedule, and discusses the expected availability of potential data sources to inform those topics.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
°C	Celsius	1.8C+32	Fahrenheit	°F
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Introduction

Connected and Automated Vehicle (C/AV) technologies are coming; and they will bring with them a wide range of operational, safety, environmental, and institutional impacts. However, relatively little has been done to modify existing transportation planning and analysis tools in preparation for the arrival of these technologies to the market—something that is already starting to happen with collision warning systems, lane keeping functions, and other driver assistance technologies (see figure 1).

The purpose of this research roadmap briefing is to examine the present state of traffic simulation models, to identify current connected vehicle (CV) analysis treatments and their limitations, and to propose a research roadmap that addresses these needs. This summary document is intended to be a companion to the full C/AV technical memorandum for new and enhanced analysis tools, techniques, and data with a focus on the current state of CV treatments for and capabilities of traffic simulation tools, and the specific aspects of the planning roadmap that seek to expand these capabilities for traffic simulation users and developers.

Role/Relevance of Traffic Simulation in Connected Vehicle Analyses

Many of the analysis tools currently employed by researchers and practitioners for the evaluation and optimization of transportation facilities are at risk of becoming outdated or limited in their relevance/usefulness as CV technologies become more prevalent on the market. While lacking many native tools for the analysis and handling of CV applications directly, traffic simulation software is uniquely positioned among transportation planning tools to be able to accommodate a wide range of future CV application analyses with the right modifications and enhancements.

Filling a crucial analytical role. The analysis of CV strategies is expected to require investigation of individual vehicle interactions, which traffic simulation software is ideally positioned to capture. This is supported by a review of the state of advanced transportation analysis practice in the last two decades, which reveals that simulation models have been increasingly used for the analysis of other intelligent transportation systems (ITS) strategies that depend on vehicle-level interactions and effects, such as active traffic management strategies.

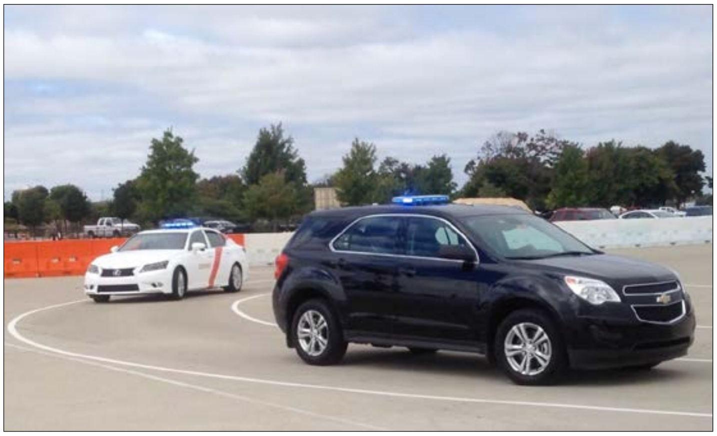


Figure 1. Photo. Demonstration of Vehicle-to-Vehicle technology by DENSO at the 2014 Intelligent Transportation System World Congress.
(Source: Cambridge Systematics, Inc.)

Note: The white vehicle receives position, steering, speed, and braking data from the leading black vehicle, and uses this information to automatically drive itself along the same path at a safe following distance.

Results based on properly conducted traffic simulation analyses are widely trusted among transportation professionals, and it is expected that simulation software will continue to grow in relevance as CV applications emerge in the market and its modeling capabilities are extended accordingly (with respect to performance metric outputs, CV modeling capabilities, supported facility types, etc.).

Timeframe considerations. This roadmap is intended to span only a period of a few years, during which time it will be prudent to investigate and evaluate to what extent traffic simulation models can (and should) be used to estimate the impacts of various CV strategies. It also is expected (and assumed for the purposes of this roadmap) that the penetration rates for most CV strategies will not reach 100 percent during the years spanned. It may take decades for CV technologies to reach the point where substantial changes and disruption to the current state of things occurs (e.g., when C/AV technologies make traditional lane markings and traffic signals irrelevant), and this roadmap for traffic simulation models is not intended to span that transition if/when it occurs. In the coming decades, when CV strategies begin to saturate the market, a new roadmap will need to be developed and implemented instead, and the ongoing relevance of traffic simulation models reevaluated in the context of these relatively disruptive changes to transportation operations and infrastructure analysis.

Recognizing limitations. Traffic simulation models are not intended to address all analysis needs; these tools already coexist with other tools that serve different purposes (e.g., traffic simulations models are well-suited for decision support for operations, while other tools are better equipped to assist with basic facility design and high-level alternatives analyses); and it is reasonable to expect that this trend of coexistence will continue as CV applications begin entering the market. Traffic simulation tools are anticipated to continue to complement other types of analysis tools, and not act as a functional replacement for them and their current roles.

Organization of this Briefing

The remainder of this briefing is organized as follows:

1. Primer on CV and AV technology, to familiarize the reader with this technology and to establish the background essential to understanding both the types of impacts that these technologies might have on the traffic simulation methods and the specific research roadmap items being proposed.
2. Summary of the current state of the traffic simulation models to reiterate their role and relevance to transportation planners and analysts.
3. Identification of potential methods for modeling selected CV applications with existing simulation tools, and assessment of the limitations regarding these methods with respect to CV analyses.
4. Overview of a proposed research roadmap to address these limitations.
5. Conclusions and next steps for implementing this research roadmap.

Primer on Connected and Automated Vehicles

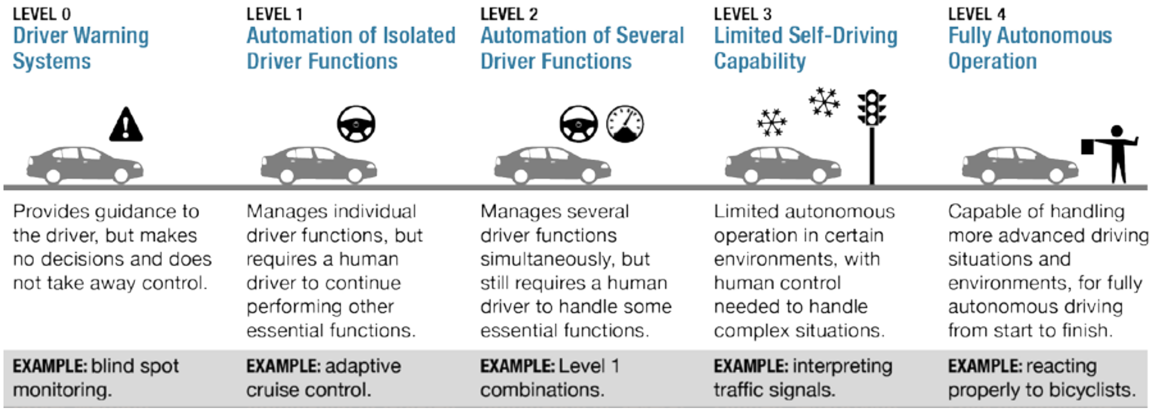
The next wave of vehicle innovation from the perspective of the operator or driver will come in the form of connected vehicles (CV) and automated vehicles (AV). This section provides an introduction to both technologies. (*State DOT CEO Leadership Forum: A Focus on Transportation Futures.* Final Report, Intelligent Transportation Systems (ITS) World Congress. Submitted to the National Cooperative Highway Research Program (NCHRP) 20-24 (100) Panel by Cambridge Systematics, Inc., October 10, 2014.)

Connected Vehicles are defined as those that wireless technologies that allow vehicles to "talk" to each other (i.e., vehicle-to-vehicle (V2V)), to the roadway infrastructure (i.e., vehicle-to-infrastructure (V2I), and to other nonmotorized roadway users (i.e., vehicle-to-X (V2X)) to achieve a greater awareness of the vehicle's surroundings, thereby, enabling a variety of safety, mobility, information, and—eventually—vehicle automation applications. Some of these potential applications are listed in table 1.

Table 1. Potential connected vehicle applications.

Vehicle-to-Vehicle	Vehicle-to-Infrastructure	Vehicle-to-Other
• Cooperative Adaptive Cruise Control • Do-Not-Pass Warnings • Intersection Movement Assistance • Queue Warnings • Lane Change Warnings	• Curve Speed Warnings • Roadway Surface Condition Warnings • Transit Signal Priority • Red Light Violation Warnings	• Reduced Speed Work Zone Warnings • Notification of Pedestrians in Signalized Crosswalks • Transit Stop Requests/Alerts

Source: Cambridge Systematics, Inc.



LEVEL 0 Driver Warning Systems	LEVEL 1 Automation of Isolated Driver Functions	LEVEL 2 Automation of Several Driver Functions	LEVEL 3 Limited Self-Driving Capability	LEVEL 4 Fully Autonomous Operation
Provides guidance to the driver, but makes no decisions and does not take away control.	Manages individual driver functions, but requires a human driver to continue performing other essential functions.	Manages several driver functions simultaneously, but still requires a human driver to handle some essential functions.	Limited autonomous operation in certain environments, with human control needed to handle complex situations.	Capable of handling more advanced driving situations and environments, for fully autonomous driving from start to finish.
EXAMPLE: blind spot monitoring.	**EXAMPLE:** adaptive cruise control.	**EXAMPLE:** Level 1 combinations.	**EXAMPLE:** interpreting traffic signals.	**EXAMPLE:** reacting properly to bicyclists.

Figure 2. Graphic. National Highway Traffic Safety Administration classification scale for vehicle automation.
(Source: U.S. Department of Transportation, National Highway Safety Administration.)

Automated Vehicles are defined as those that use onboard sensing technologies, rather than intervehicle communications, to provide the vehicle and driver with a greater awareness of the surroundings, thereby, enabling the automation of one or more driver functions through artificial intelligence, machine learning, machine vision, and computer processing. Intervehicle communications also can be used to achieve such vehicle automation, but when such technologies are used, the more widely used nomenclature refers to these as CVs (see above). These AV technologies are expected to arrive to the market in parallel with CVs over the coming years and decades, and are commonly ranked according to a 0 to 4 scale described by the National Highway Traffic Safety Administration (NHTSA). On this scale, level 0 identifies a technology that does not actively manage any of the vehicle's functions, while level 4 identifies a technology that handles all driving functions from origin to destination (see figure 2). The term **Autonomous Vehicle** is reserved specifically for level 4 vehicle automation. More detailed information about levels 1 to 4 of vehicle automation is provided in the full memorandum on C/AV Analysis Tools, Techniques, and Data.

Benefits

Field tests, simulation studies, and theoretical exercises have been conducted to evaluate the impacts of connected vehicles across several benefit categories. Table 2 provides samples of benefits across three key categories from selected studies in recent years. Additional impact analyses and results are available from other current data sources or expected from several future data sources, including the following:

- **Research Track 1 of the U.S. Department of Transportation (U.S. DOT) CV Safety Pilot Program** (August 2011 to January 2012), which provides survey data from hundreds of drivers at multiple locations in the U.S. on driver acceptance, cost preference, motivation for adoption, and behavioral response to CV technology interfaces and systems.
- **Research Track 3 of the U.S. DOT CV Safety Pilot Program** (2012 to 2013), which provides field data from 3,000 vehicles in Ann Arbor, Michigan, on the effectiveness of CV technology at reducing crashes. (Connected Vehicle Safety Pilot Program (Brochure).

U.S. DOT, Research and Innovative Transportation Administration. FHWA JPO-11-031. Accessed October 5, 2015.)

- **Federal Highway Administration (FHWA) CV Pilots Deployment Project** (2015 and 2017), which will implement several prototype CV applications to address real-world problems. (Hartman, Katherine. "Connected Vehicles Pilot Deployment Program." *ITS—CV Pilot Deployment Program*. ITS Joint Program Office, U.S. DOT. Accessed October 5, 2015.)

Note that Research Track 2 of the U.S. DOT CV Safety Pilot Program was concerned with establishing a qualified products list and did not produce any CV data that would be directly relevant to this research roadmap.

The Importance of Real-World Data

New technologies or innovations often have unforeseen consequences on driver behavior, facility performance, or other areas. For instance, pedestrian countdown timers were intended to inform pedestrians of the remaining time for crossing safely, but also were observed to influence some drivers who would begin to slow down in advance of the actual yellow signal activation, as the countdown approached zero. (Bundy, Brandon. *Modification of driver behavior based on information from pedestrian countdown timers.* Master's Dissertation, Department of Civil, Environmental and Architectural Engineering, University of Kansas. 2008. (Accessed October 5, 2015).) Similarly unforeseen and unintended outcomes are expected to occur with the deployment of CV and AV applications.

These types of effects are best captured by a careful analysis of empirical data from real-world deployments (for example, data from the FHWA CV Pilots Deployment Project). With such data, it is possible to account for both the theoretically expected outcomes, as well as other effects that may not have been anticipated beforehand, but were observed during actual deployments. The traffic simulation research roadmap relies significantly on such empirical data, including deployment costs data, CV application benefits data, safety outcomes data, fuel economy data, and driver behavioral response data.

Table 2. Examples of potential impacts of connected vehicle applications.

Category	Extent of Impacts
Capacity and Throughput	• Computer-controlled vehicles could increase in maximum traffic throughput by a factor of **200%-300%.** (Hayes, Brian. *Leave the Driving to It*. American Scientist, September/October 2011. Pages 362 to 366. (Accessed October 5, 2015).) • In an experiment on I-15 in 1997, researchers estimated vehicle-to-vehicle technologies could result in a lane capacity of **4,300 vehicles per hour,** compared to 2,000 vehicles per hour without vehicle-to-vehicle. (Shladover, Steve. *The GM-PATH Platoon Scenario*. "Intellimotion, Volume 6, Number 3, 1997. Page 2. (Accessed October 5, 2015).) • Truck platooning in Europe using the CHAUFFEUR system will provide an estimated **8% capacity increase.** (Bishop, Richard. *Whatever Happened to Automated Highway Systems?* Traffic Technology International, August/September 2001. (Accessed October 5, 2015).) • Simulation modeling and field testing by Nissan and California Partners for Advanced Transit and Highways (PATH) indicate that Cooperative Adaptive Cruise Control (CACC) could provide a lane capacity of **3,970 vehicles per hour.** (S. Shladover, C. Nowakowski, H. Kawazoe, and H. Tsuda. *Cooperative Adaptive Cruise Control to Stabilize Car Following (Second Generation).* Presentation by California PATH Program, University of California (UC), Berkeley.) • Depending on platooning parameters (e.g., gap spacing), lane capacities with vehicle platooning could reach a theoretical maximum of **8,000 vehicles per hour.**
Emissions and Fuel Consumption	• Wind tunnel tests indicate a 50% reduction in drag force for closely spaced platoons, which corresponds to a **20% to 25% reduction** in emissions and fuel consumption. (Shladover, Steve. (Shladover, Steve. *The GM-PATH Platoon Scenario*." Intellimotion, Volume 6, Number 3, 1997. Page 2. (Accessed October 5, 2015).) • The CHAUFFEUR truck platooning system will provide up to an estimated **20% increase** in fuel economy. (Bishop, Richard. *Whatever Happened to Automated Highway Systems?* Traffic Technology International, August/September 2001. (Accessed October 5, 2015).) • On a high-speed test track, fuel **savings of 8% to 15%** were measured in five-vehicle platoons at a vehicle spacing of 5-8 meters. (J. Hellaker, C. Grante, and S. Bergqvist. *EARP Topic 1D—Partial Automation for Truck Platooning.* Presentation by the Volvo Group Advanced Technology and Research.) • Platoons of three trucks in Japan were measured to achieve a fuel economy **improvement of 8%** with cooperative cruise control, and a fuel economy **improvement of 14% and 16%** with automated driving. (J. Hellaker, C. Grante, and S. Bergqvist. *EARP Topic 1D—Partial Automation for Truck Platooning.* Presentation by the Volvo Group Advanced Technology and Research.) • Platoons of three trucks in Nevada were measured to achieve a fuel economy **savings of 4.5% to 18.4%** depending on the truck position, using vehicle-to-vehicle technology. (X. Lu and S. Shladover. *Original Automated Truck Platooning with DSRC as V2V.* California PATH, UC Berkeley. December 6, 2013.)

Table 2. Examples of potential impacts of connected vehicle applications. (continued)

Category	Extent of Impacts
Traffic Incidents	• U.S. Department of Transportation estimates that connected vehicle technologies can reduce, mitigate, or **prevent 81%** of light-vehicle crashes by unimpaired drivers. (Read, Richard. *Dallas, Minneapolis, San Francisco Become Part of DOT's "Talking Car" Project*. Motor Authority, May 13, 2011. (Accessed October 5, 2015).) • A crash analysis of California 2013 collision data found that **78% of all crashes** could be addressed by vehicle-to-vehicle technologies, based on their causal factors. (Cambridge Systematics and Jim Misener. Interoperability Issues of Vehicle-to-Vehicle-Based Safety Systems Project Extension (V2V-I Phase 2): V2V Vehicle Density Analysis. December 10, 2014.)

Source: Cambridge Systematics, Inc.

Current State of Traffic Simulation Models

This section examines the current roles and applications of traffic simulation models, reviews their capabilities, and identifies the existing limitations regarding their ability to account for connected vehicle (CV) and automated vehicle (AV) effects. (Krista Jeannotte, Andre Chandra, Vassili Alexiadis, and Alexander Skabardonis. *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools.* FHWA Publication Number FHWA-HRT-04-039. July 2004.) A basic understanding of the traffic simulation models is assumed of the reader, including a familiarity with the types of adjustable parameters available through simulation models.

Role and Relevance

Traffic simulation models can be used to evaluate a wide range of operational strategies or roadway modifications at individual locations or across an entire network (see figure 3). The disaggregate approach used by simulation models allows them to more precisely and quantitatively capture the effects of advanced operational strategies at an individual vehicle level that other, lower-sensitivity methods are poorly designed to handle (e.g., strategies that affect gap acceptance or reaction times). Stochastic driver effects also are captured through the assignment of different combinations of driver parameters to each vehicle in the simulation.

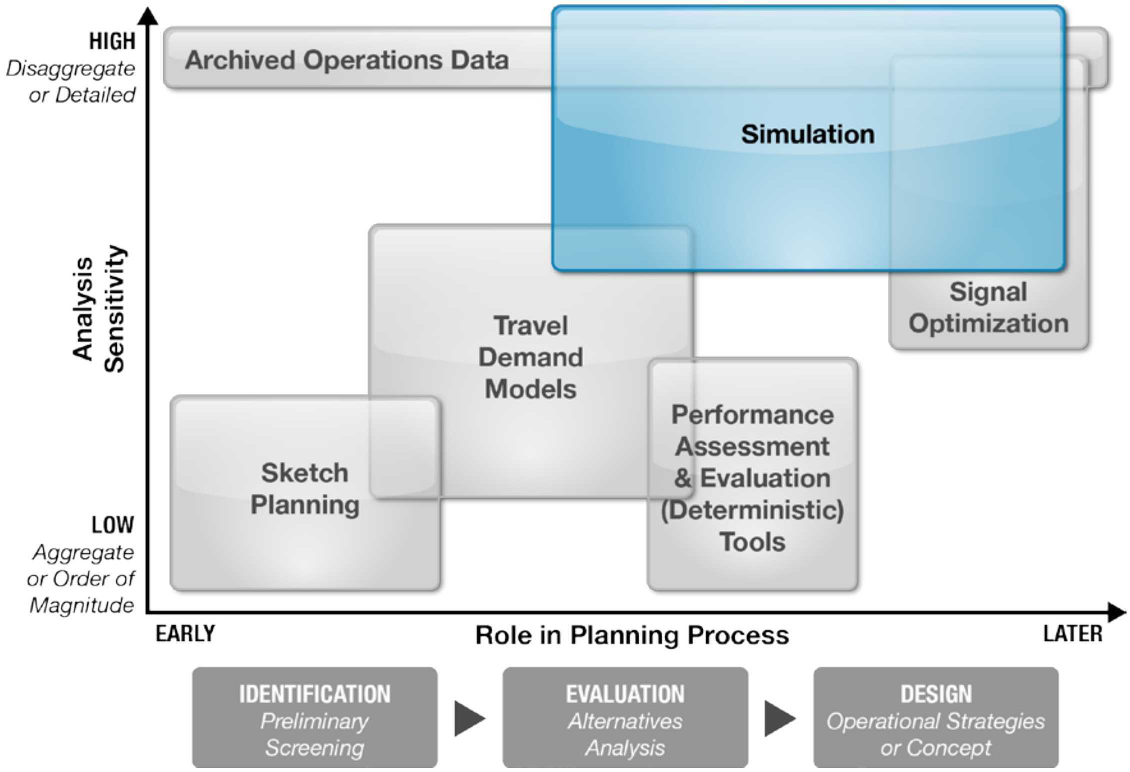


Figure 3. Graph. The role of traffic simulation models in the transportation planning process.
(Source: Cambridge Systematics, Inc.)

As shown in figure 4, the first step in traffic simulation analyses is generally to construct the base transportation network in the simulation environment, including links; nodes, their geometric characteristics (e.g., lane width); and configuration details (e.g., lane counts). The operational parameters for infrastructure are then defined (e.g., signalization parameters), and the network loaded with existing traffic volumes. These may include pedestrian, transit, automobile, and truck volumes (e.g., defined through origin-destination trip tables).

At this point, an initial simulation can be performed for comparison of the model performance against known real-world data, which commonly includes traffic speeds and volumes at specific locations on the network. Certain model parameters may be adjusted to calibrate the model in an attempt to more accurately replicate real-world conditions on the network.

Once the agreement between simulation output and observed traffic characteristics is sufficiently high, the model can be used for scenario analyses. For this, the simulation model parameters may be modified to reflect various hypothetical states (e.g., operational strategies or infrastructure alternatives under consideration), and the resultant outputs from the modified model compared against the outputs from the original model.

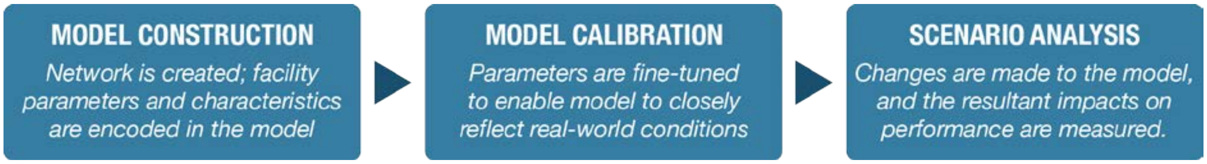


Figure 4. Flowchart. The general principle underlying typical traffic simulation models.
(Source: Cambridge Systematics, Inc.)

Traffic simulation models generally fall into one of three types according to their level of modeling precision:

1. **Macroscopic Models** rely on traffic flow theory relationships (such as those between speed, flow, and density) to model traffic in specific systems at an aggregate link level, but do not model individual vehicles and their interactions in a highly detailed manner. This type of analysis is suitable for larger geographic scales, such as a freeway network, arterial grid, or rural highway system.
2. **Microscopic Models** incorporate lane-changing and car-following algorithms to simulate driver behaviors and vehicle trajectories in time steps measured on the order of seconds or fractions of seconds. These high-resolution simulations provide valuable operational insight and detailed performance measures for a variety of strategies that affect the interactions between individual vehicles.
3. **Mesoscopic Models** blend the characteristics of both microscopic and macroscopic models to achieve a balance between larger network size and realism/precision in the simulation model. For example, a mesoscopic model may assign a full set of driver parameters to each vehicle in the simulation and apply basic lane-changing and car-following models to capture interactions, but may also apply macroscopic models from traffic theory to represent behaviors at nodes in an effort to reduce processing time.

Strengths of traffic simulation models include:

- Fine time-step resolution, with the ability to simulate individual vehicles and driver interactions.
- Ability to model nonstationary traffic states, such as congestion growth or dissipation.
- Ability to simulate stochastic traffic effects by assigning a different set of driver parameters to each vehicle in the simulation, typically taken from a user-specified statistical distribution.
- Accounting for physical queue lengths and properly representing queue spillback conditions in the model.

However, traffic simulation models also are limited by the fact that they:

- Cannot be used to model certain real-world driver behaviors or situations, such as inattention or collisions.
- Require a significant level of input data (e.g., origin-destination tables for each travel mode).
- Require a substantial investment of time and effort, including the time needed for the software to perform the simulation once the model is ready.

Analysis Capabilities

Table 3 summarizes the capabilities and limitations of traffic simulations models across several dimensions. Figure 3 compares the suitability of traffic simulation models to other types of analysis tools (e.g., sketch planning tools) for different applications/tasks at various stages of the planning process. As shown in the table, Traffic Simulation tools generally treat demand as an exogenous variable (i.e., one that is explicitly specified for the software) and are not suitable for estimating induced demand effects, as might be expected over time as C/AV technologies enter the market. Therefore, although simulation tools currently are unable to capture demand-side impacts of C/AV strategies, this is considered to be a limitation by design.

Table 3. Analysis capabilities and general limitations of traffic simulation models.

Category	Traffic Simulation Models Suitable for:	Other Tools More Suitable for:
Scale	Most small- to medium-scale analyses	Regional analysis
Usability and Technical Requirements	Can generally be extended, customized, and integrated with other software	Situations where comprehensive traffic data are not available, or where staff do not have the time to prepare and run a full traffic simulation model
Facility Types	Most roadway facilities for vehicular traffic	Some specialized roadway features (e.g., roundabouts) and facilities involving other modes (e.g., at-grade light rail)
Travel Modes	Common vehicle types	Nonvehicular traffic (e.g., pedestrians, bicyclists, rail)
Changes in Demand	Route shifts, departure time shifts, some mode shift effects (indirect)	Mode shift (direct modeling), induced demand
Performance Measures	Most mobility performance measures (aggregated and disaggregated), and some environmental metrics	Vehicle occupancy metrics, mode split metrics (in conjunction with mode shift), and benefit-cost ratio estimates

Source: Cambridge Systematics, Inc.

Current Connected Vehicle Analysis Capabilities and Limitations of Traffic Simulation Tools

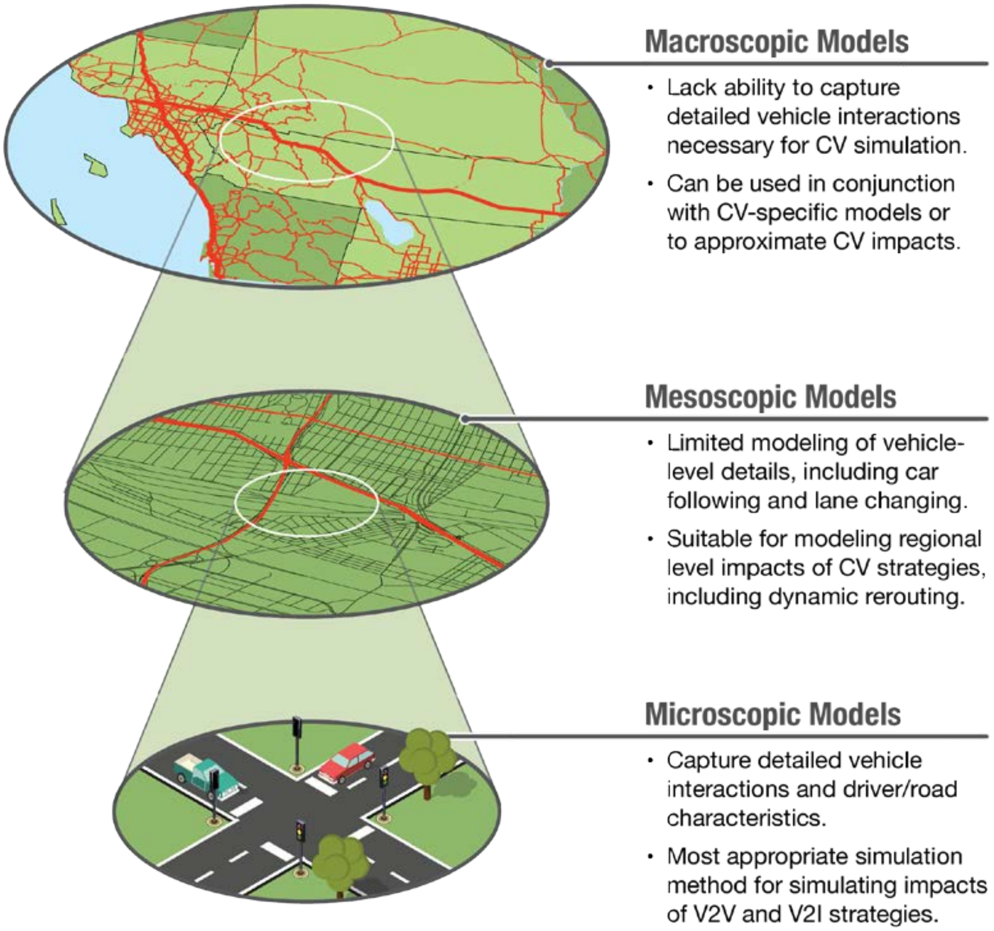
Simulation tools are often better equipped to address planning and analysis questions related to connected and automated vehicle (C/AV) technologies than other tools at present, as other tools require empirical data for development of the models themselves; whereas, simulation tools can estimate many C/AV outcomes through modification of their existing models. Microscopic simulation models, in particular, incorporate a high degree of detail associated with the traffic and roadway characteristics, allowing for the simulation of hypothetical connected vehicle (CV) strategies and operational characteristics even before empirical data become available. Mesoscopic and macroscopic simulation models can be used to evaluate operational strategies across large-scale networks in an approximate manner.

Furthermore, many CV strategies (e.g., platooning, wireless freight inspection) have impacts and outcomes that are expected to scale with penetration rates, and these effects can be precisely modeled through direct adjustment of the penetration rates in the models themselves, even when supporting empirical data are not yet available for validation.

Current Options for Modeling Connected Vehicle and Automated Vehicle Technologies

The analysis of CV strategies generally requires detailed, high-resolution data and tools, as evidenced by a review of the state of advanced transportation analysis practice in the last two decades which revealed that simulation models have been increasingly used for the analysis of Intelligent Transportation Systems (ITS), Integrated Corridor Management (ICM), and Active Transportation and Demand Management (ATDM) strategies. The following list describes the three current classes of simulation tools used by planners and their potential relevance to CV analyses, with a general summary provided in figure 5. The list below also includes a fourth class, CV-specific simulation models, which is an emerging specialized type of model specifically developed for certain CV analyses.

- **Macroscopic Simulation Models.** These have only limited capabilities to accurately estimate changes in operational characteristics (such as speed, delay, and queuing) resulting from implementation of operational strategies; they were not designed to evaluate travel management strategies, such as CV, ITS, and other operational strategies. Because of these inadequacies, they are generally not suited for use for CV analysis, but they can potentially be used in conjunction with other tools and methods to achieve it.



Macroscopic Models

- Lack ability to capture detailed vehicle interactions necessary for CV simulation.
- Can be used in conjunction with CV-specific models or to approximate CV impacts.

Mesoscopic Models

- Limited modeling of vehicle-level details, including car following and lane changing.
- Suitable for modeling regional level impacts of CV strategies, including dynamic rerouting.

Microscopic Models

- Capture detailed vehicle interactions and driver/road characteristics.
- Most appropriate simulation method for simulating impacts of V2V and V2I strategies.

Figure 5. Potential modeling support for connected vehicle strategies by simulation type.
(Source: Cambridge Systematics, Inc.)

- **Microscopic Simulation Models.** Because of the detailed representation of the traffic and road networks found in these models and because of their ability to model individual vehicles and traffic control strategies (e.g., traffic signal preemption), these tools show substantial promise for modeling a wide range of CV strategies. In some cases, these simulation models can be customized or extended to emulate either the basic principles/logic or assumed effects of specific CV applications.
- **Mesoscopic Simulation Models.** These combine properties of both microscopic and macroscopic simulation models; and although they can capture the effects of queue lengths and the temporal distribution of congestion, they generally do not consider dynamic speed/volume relationships and, therefore, provide less fidelity than microsimulation tools. They are, however, capable of evaluating dynamic traveler diversions on large-scale networks, and are therefore potentially useful for modeling regional CV applications and strategies.
- **CV-Specific Simulation Models.** This emerging class of tools can simulate individual sensors, vehicles, and CV equipment at a microscopic level. However, recognizing that institutions that use and rely on more popular traffic simulation

software will not have the time, resources, or motivation to migrate/adapt their systems, processes, training, and staffing to incorporate/accommodate these relatively purpose-specific CV models, it is expected that there will be substantial market pressure to integrate the capabilities of these CV-specific models into existing general-purpose microscopic and mesoscopic simulation software for added flexibility, extensibility, and workflow integration (which this research roadmap accomplishes).

As mentioned in the above list, microsimulation models are a promising class of tools for modeling the impacts and outcomes of CV technologies, given that CV applications operate at the level of individual vehicles (which are an inherent element of a microsimulation approach). In some cases, these simulation models can be customized or extended to emulate either the basic principles/logic or assumed effects of specific connected vehicle applications (*National Connected Vehicle Field Infrastructure Footprint Analysis: Applications Analysis.* American Association of State Highway and Transportation Officials. July 31, 2013)—for example, through dynamic interaction with application programming interfaces (APIs) at simulation runtime, or through the adjustment of user-accessible parameters. Table 4 provides examples of how a wide range of CV strategies might be incorporated into a microsimulation model, on a conceptual/simplified level.

Table 4. Example methods for simulating selected connected vehicle applications.

Connected Vehicle Strategy	Sample Method for Incorporation into Simulation Model
Intelligent traffic signals (and eco-traffic signal timing)	Custom programming code that modifies approaching vehicle speeds in conjunction with anticipated/upcoming traffic signal states.
Work zone alerts	Custom programming code that reduces vehicle speeds in advance of work zones.
Transfer connection protection	Custom programming code that holds transit vehicles at specified stops when certain criteria are met for pending or anticipated transfers.
Queue warnings	Custom programming code that reduces vehicle speeds in advance of queued traffic.
Disabled vehicle warnings	Custom programming code that reduces vehicle speeds in advance of disabled vehicles.
Dynamic transit capacity assignment	Custom programming to adjust the current occupancy or capacity of a transit vehicle to control whether passengers board at a particular stop depending on factors, such as bus schedule lateness, time until the next bus arrives, and occupancy of the following bus.
Driver Gap Assist at signalized intersections	Change to the gap acceptance parameters of the drivers at the affected junctions (e.g., less conservative parameters).
Speed zone warnings	Change the speed limit compliance parameters or the speed distributions on the affected segments (e.g., increased adherence to posted speed limits).
Cooperative adaptive cruise control (i.e., vehicle platooning)	Change in speed variation (reduction) and following distance (reduction) on affected segments; alternatively, custom programming a specialized car-following model, such as the Intelligent Driver Model.

Table 4. Example methods for simulating selected connected vehicle applications. (continued)

Connected Vehicle Strategy	Sample Method for Incorporation into Simulation Model
Dynamic speed harmonization	Change in target speed distribution parameters on affected segments, based on prevailing traffic characteristics (e.g., average speed, average density).
Preclearance and expedited screening at border crossings	Change in wait time distribution parameters for some vehicle classes/types at the ports of entry.
Emergency electronic brake lights (advance notice of braking ahead)	Modification of “look ahead” parameters on affected segments, or custom programming to slow vehicles down even when an intermediate vehicle is between the subject vehicle and the obstacle, obscuring the view.
Freight/transit signal priority	Custom programming code that modifies signal control logic/timing to accommodate priority traffic (e.g., freight, transit).
Emergency vehicle preemption	Custom programming code that modifies signal control logic/timing to ensure that the equipped vehicles safely receive a green signal in advance of arrival at the intersection.
Intersection movement assist	Custom programming code that temporarily eliminates driver headway requirements for vehicles approaching equipped intersections and organizes vehicles into short platoons by approach. The code would then send these platoons through the intersection without stopping (to the extent possible), such that alternating streets receive the right-of-way in quick succession.
Left turn assist	Change to the left-turn gap acceptance parameters of the drivers at the affected junctions (e.g., less conservative parameters).
Advanced automatic crash notification relay (and automatic incident detection)	Reductions in the clearance times for manually encoded lane blockages in the model due to specified incidents.
Advanced traveler info (and dynamic route guidance)	Enable dynamic vehicle routing based on real-time conditions for a greater proportion of traffic.

Source: Cambridge Systematics, Inc.

Limitations of Traffic Simulation Models with Connected Vehicle and Automated Vehicle Analyses

Despite the potential relevance that traffic simulation tools exhibit for CV modeling and analysis, they will still generally require a number of tool enhancements, such as:

1. Modifications to the car-following and lane-changing logic and algorithms.
2. Methods for capturing:
    a. Transportation and communications impacts of CV strategies.
    b. Impacts of communications issues (e.g., errors, loss, or latency).
    c. Impacts of different communications technologies and resolutions.
3. Consideration of travelers’ behavioral responses to imperfect, latent, real-time traveler information.
4. Providing the ability to test different market penetrations for CV strategies.

Figure 6. Photo. This truck, designed by Volvo, uses onboard sensors and vehicle-to-vehicle technology to form platoons with other equipped vehicles.
(Source: Cambridge Systematics, Inc.)

Note: This allows for much shorter headways than would otherwise be possible through manual control alone.

In considering these and other analysis needs discussed in the memorandum on C/AV Analysis Tools, Techniques, and Data, five high-level major limitations with traffic simulation models can be identified:

1. **CV equipment is not directly simulated**, making it difficult to evaluate the anticipated effects of various connected vehicle scenarios (e.g., equipment failures, latency issues, typical loads, and resource demands) and operations (e.g., the effects of different implementations or algorithms for a particular CV application). Instead, the equipment functions are often approximated through high-level assumptions about their overall effect on high-level driver decision and behaviors (e.g., reaction time, gap acceptance).
2. **Lane-changing algorithms, car-following algorithms, and other aspects of simulated vehicle logic are specifically designed to emulate *human* behavior**, and may be a poor reflection of how vehicles will operate when CV technologies and various levels of automation become prevalent (see figure 6). Analysts also lack guidance regarding what, if any, changes are appropriate to make to the simulation algorithms and logic when CV applications are considered.
3. **Individual CV applications are not natively supported**, making the simulation of such applications more time-intensive and less consistent across different analyses, as each strategy must be manually captured through custom code and logic added by the analyst to support a particular context/situation. In some cases, access to the necessary components of the model is not provided, making it impossible for the analyst to simulate some strategies altogether. With native support for CV applications built in, analysts would be able to more quickly and consistently implement and justify methods for simulating different CV applications in their models.
4. **Driver responses to CV applications are not directly captured in the models**, including driver acceptance of vehicle guidance and the effects that those applications have on mode choice. Though these may be indirectly captured in simulation models using other high-level

parameters, such methods inherently limit the degree of realism that can be achieved through simulation models in representing the operation and character of CV applications when deployed. For example, it becomes more challenging when driver acceptance and mode choice effects become linked to other factors (e.g., frequency of alerts).

5. **Aerodynamic analysis capabilities currently are not supported**, meaning that simulation models are unable to produce direct estimates for the energy-related impacts of CV applications. These include changes in fuel consumption, emissions, and acceleration, which can be expected to follow the operational and behavioral changes that accompany CV applications (e.g., closer following distances associated with vehicle platooning). These impacts are expected to be most pronounced for larger-profile vehicles, such as trucks, recreational vehicles, and buses.

In addition to the above limitations specific to traffic simulation models in the context of CV applications, additional broader issues exist that may be expected to limit the reliability and accuracy of traffic simulation analysis results involving CV strategies. These include:

1. **No accounting for the changes to infrastructure** that will become possible (or even necessitated) by the advancement and spread of CV technologies, such as narrower lanes (which may not have the same effect on an automated vehicle as it would on a human driver).
2. **No existing analysis guidance** regarding the suitability of traffic simulations models for conducting various types of analyses involving specific CV applications.
3. **Limited data on penetration/adoption rates** and the adoption patterns and forecasts they are expected to follow as CV technologies enter the market.

Proposed Research Roadmap

This section presents a set of seven research topics designed to address the limitations identified in the previous section with respect to the handling of CV effects in traffic simulation models. These topics are a subset of the 19 described in the full memorandum on C/AV Analysis Tools, Techniques, and Data, and have been selected for their relevance to traffic simulation models.

Overview

Table 5 lists and briefly describes the seven topics proposed for traffic simulation modeling research. Each one may be considered its own potential project or contract, for which additional specifications (e.g., deliverables, tasks, project milestones) would need to be developed in pursuit of the topic's overall objectives.

Table 5. Summary of proposed research roadmap topics specific to traffic simulation models.

Topic	Title	Summary
1	Forecasting penetration and adoption rates	Analysis of user attitudes and perceptions about connected vehicle applications, combined with data on the expected availability of supporting technologies from automobile Original Equipment Manufacturers (OEM), to enable forecasts of adoption and penetration rates for each strategy moving forward. This is not necessarily a single forecast of general connected vehicle adoption and penetration, but may take the form of several forecasts or classes based on potential future scenarios, specific connected vehicle strategies/markets, and several other factors.
2	Updating lane-changing and car-following algorithms for connected vehicle contexts	Exploring the effects connected vehicle applications have on lane-changing and car-following behaviors, and incorporating appropriate parameters and logic into the corresponding control algorithms in simulation software to account for these differences when connected vehicle applications are engaged.
3	Adding support for connected vehicle operations	Building native support for connected vehicle operations and applications in commercial simulation software packages, with user-defined penetration rates and other configurable parameters. This functionality is dependent on the outcomes from topic 2, and enables the analyst to engage or disengage connected vehicle applications within the simulated environment quickly, easily, and consistently across analyses.

Table 5. Summary of proposed research roadmap topics specific to traffic simulation models. (continued)

Topic	Title	Summary
4	Adding support for native aerodynamic modeling	Integration of models and methods to estimate aerodynamic impacts of vehicle movements (e.g., headways, acceleration behavior), which allows for more precise estimation of fuel savings and emissions reductions achieved through various connected vehicle strategies that operate on a microscopic (i.e., vehicle-to-vehicle) level. The relevance of this topic is dependent on the completion of topics 2 and 3.
5	Investigating driver acceptance and response to connected vehicle applications	Analysis of the range and distribution of driver reactions to individual connected vehicle technologies, such as acceptance of warnings and route guidance, to more accurately model outcomes as they relate to penetration/adoption rates, and to more reliably model the mode split for connected vehicles as a function of penetration rates.
6	Adding support for connected vehicle communications and sensing equipment	Modeling the basic functions of connected vehicle equipment, such as communications between field units and on-board sensors, in simulation software enables analysts to achieve a deeper, crucial understanding of what to expect when those technologies arrive to the market.
7	Providing connected vehicle analysis guidance	Developing an analysis framework/methodology for accurately capturing the effects/outcomes of connected vehicle applications in traffic simulation and other tools, which would include recommended approaches, best practices, and known limitations, and would promote consistency among analysts. Also, identifying the limitations of traffic simulation and discussing where it fits in an overall connected vehicle analysis toolbox/framework.

Source: Cambridge Systematics, Inc.

Figure 7 indicates each topic's timing, expected duration, dependencies, and relevance to the eight CV-specific limitations of traffic simulation models identified earlier. More information about figure 7 is listed below:

- **Subject to change.** As with any forecast regarding the future driving environment and future availability of technologies, there is an inherent and unavoidable uncertainty with respect to the assumptions about what the future will hold, the outcomes that will be achieved, and the optimal research path to follow as a result.
- **Topic start times.** The start times are estimated based on the expected availability of required data and on the timing of other prerequisite research topics.
- **Topic durations.** The duration for a given research topic is estimated based on the resources required to complete the topic, and on the expected level of effort required to obtain the necessary supporting data.
- **Availability of initial results.** The end dates suggest when initial results might be expected from those topics, but should not be interpreted as the final dates that any work would be performed. It is expected that there will be ongoing work for all of these topics even after their objectives have been initially accomplished, as the topic outcomes will continue to benefit from an infusion of new datasets as they become

available over time (e.g., data from Federal Highway Administration (FHWA) Connected Vehicle Pilots Deployment Projects).

- **Topic prioritization.** Each topic is given one of two priority classifications, based on its breadth, relevance to other topics in the roadmap, and impact on CV modeling capabilities. *First priority topics* may be considered the higher priority, either because they are prerequisites for other research topics or because they are very broadly impactful.

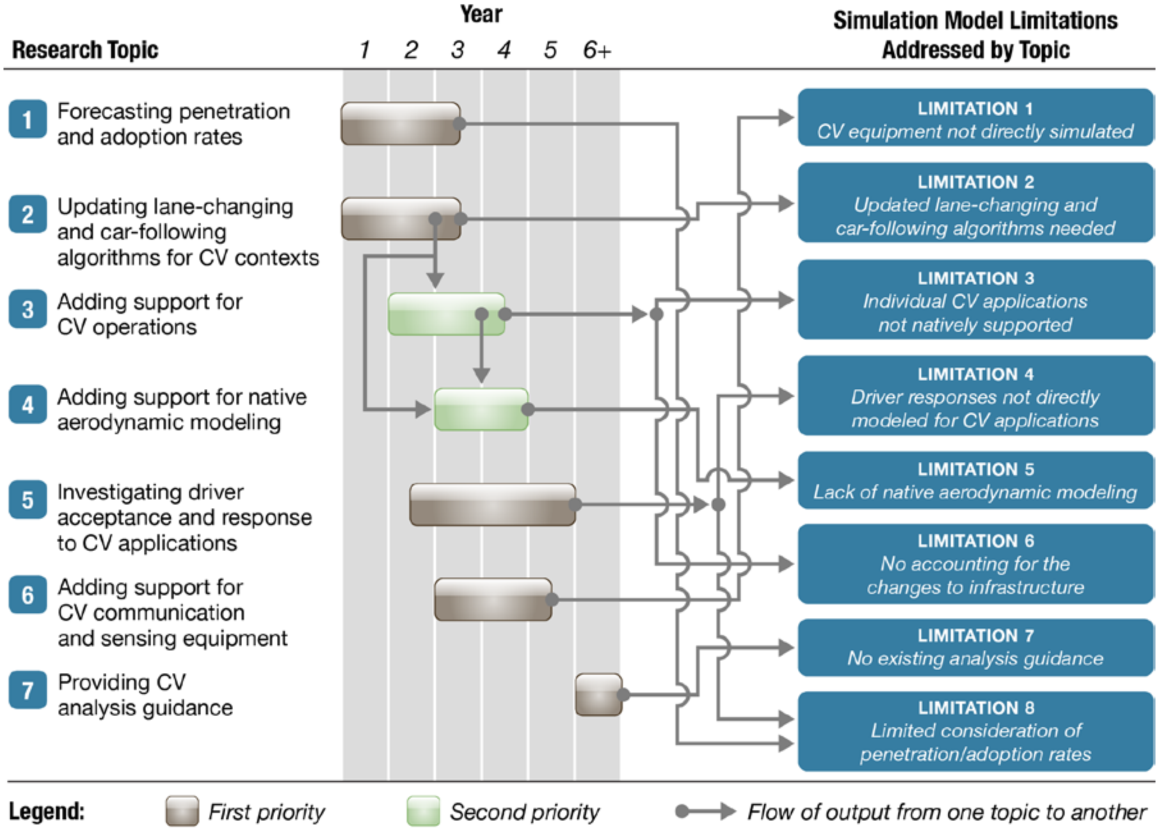


Figure 7. Chart. Research roadmap for addressing connected vehicle analysis limitations of traffic simulation models.

(Source: Cambridge Systematics, Inc.)

Conclusions and Next Steps

Connected vehicle (CV) and automated vehicle (AV) technologies are widely varied with respect to their character, the resultant impacts, and even the questions that analysts seek answers to (such as decisions about the form and structure that those applications should take in a given context). When supporting empirical data are not available or are limited, simulation tools show substantial promise for addressing these questions. Microscopic simulation models incorporate a high degree of detail associated with the traffic and roadway characteristics, allowing for the simulation of hypothetical CV strategies and operational characteristics even before empirical data become available.

This research roadmap outlines a strategy for bringing CV-specific modeling capabilities to the broad population of existing traffic simulation modeling tools. The roadmap is an approach for addressing all of the needs and gaps identified previously that is both structured and flexible enough to adapt to changing needs. The ultimate goal is not to implement a specific roadmap, but to provide analysts and practitioners with the tools and resources they need to capture the impacts and outcomes associated with CV and AV applications as they are deployed in the future.

The remainder of this section focuses on key activities, divided into three stages, for addressing research needs in the roadmap: near-term activities, medium-term activities, and long-term activities. Figure 8 summarizes the major themes and the approximate timing of each of these three phases.

Figure 8. Flowchart. Summary of the three general phases for fulfillment of the connected vehicle research roadmap.

(Source: Cambridge Systematics, Inc.)

Near-Term Next Steps

The following is a list of possible key near-term activities to support the adoption, advancement, and implementation of the proposed research. This list is intended to facilitate planning and discussion regarding the next steps, but should not be considered a comprehensive list of near-term activities.

- **Internal review and consultation with stakeholders and partner agencies.** Soliciting feedback and comments from key internal and external stakeholders/staff raises awareness of the relevance, scope, and value of the proposed research among planners and analysts; and encourages a unified vision and approach among all partners/agencies.

- **Definition of roles and responsibilities for key staff and partners.** Ownership of the research activities must be clearly defined, along with the roles of contributing staff and partner agencies. This includes, for example, establishing and implementing strategies for identifying needed changes in the research program, tracking progress as the tasks are performed, and fostering clear communication of expectations and methods for coordinating efforts among all involved partners.
- **Identification of potential funding sources.** This includes funding and staffing support for both the individual research topics and the overall program, such as coordination, logistics, progress tracking, and updates. Some topics may be eligible for partial or full funding through specific sources that align with the topic scopes. However, the interdependent nature of the various topics means that all research activities and topics must receive necessary levels of funding and staffing support for the needs and gaps to be successfully addressed. Potential methods for accomplishing this include establishing a dedicated agency budget line item, meeting some or all funding needs through planning-related programs, and seeking executive-level support for the research program through its alignment with various CV initiatives.
- **Selection of lead organizations or agencies for each topic.** It is expected that, while one agency or organization may have responsibility for the management, maintenance, and implementation of the overall research program, responsibility for each component topic may be delegated to a different entity that has the specific knowledge, experience, and resources to properly supervise progress and perform quality control functions. Possible lead entities for each of the topics in figure 7 are shown in table 6. More information is available in the full memorandum on connected and automated vehicle (C/AV) Analysis Tools, Techniques, and Data.
- **Formal adoption of the research program.** Once consensus is achieved among all major stakeholders and partners regarding the core elements of the research program and its implementation (e.g., vision, roles, responsibilities, potential funding mechanisms), it may be formally adopted to acknowledge this agreement and commitment among the key contributing parties. However, it should be noted that an informal agreement may be adequate to advance the program.
- **Project development tasks.** Once a funding source and lead agency/organization have been identified for a research topic, the project development work can be performed to establish specific details associated with the topic's implementation, including timeline, scope, budget, and deliverables (see figure 9). These can then be used to craft requests for proposals, evaluate the responses received, and select a preferred respondent for executing the work.

Table 6. Potential lead organizations for the proposed research roadmap topics.

Topic	Title	Potential Lead Organizations
1	Forecasting penetration and adoption rates	• The Crash Avoidance Metrics Partnership • Federal Highway Administration/U.S. Department of Transportation
2	Updating lane-changing and car-following algorithms for connected vehicle contexts	• Federal Highway Administration • Traffic simulation software developers (or related consortium)
3	Adding support for connected vehicle operations	• Federal Highway Administration Traffic simulation software developers (or related consortium) • Transportation Research Board and the Strategic Highway Research Program 2
4	Adding support for native aerodynamic modeling	• Automobile manufacturers (or related consortium) • Federal Highway Administration Traffic simulation software developers (or related consortium)
5	Investigating driver acceptance and response to connected vehicle applications	• Federal Highway Administration • National Cooperative Highway Research Program and Transportation Research Board • Major Metropolitan Planning Organizations
6	Adding support for connected vehicle communications and sensing equipment	• The Crash Avoidance Metrics Partnership • Traffic simulation software developers (or related consortium)
7	Providing connected vehicle analysis guidance	• Transportation Research Board • Federal Highway Administration/U.S. Department of Transportation

Source: Cambridge Systematics, Inc.

Figure 9. Graphic. Typical activities in the project development process.
(Source: Cambridge Systematics, Inc.)

Medium-Term Considerations

Once the research roadmap is agreed upon and an implementation plan is established, the roadmap topics themselves can be performed. With the exception of Research Topic 7, this is expected to happen over an approximate five-year period after the near-term logistical and support tasks are complete. A key factor in determining the schedule will be the availability of data and analytical findings from C/AV demonstration projects and deployments. The following are key factors to consider for planning and implementation purposes during the performance period:

- **Research Topic Sequencing**. Figure 7 provides guidance regarding the prioritization and timing of the research topics. The start time for a given topic is based on the expected availability of required data to support the topic, and on the timing of prerequisite research topics on which the given topic depends. The duration for a given research topic is based on the resources required to complete the topic, and on the expected level of effort required to obtain the necessary supporting data. More information is available in the full memorandum on C/AV Analysis Tools, Techniques, and Data.
- **Research Topic Levels of Effort**. Research topics 5 and 7 are expected to require significantly more effort to accomplish than the other topics, based on the expected data and resource needs/availability associated with those topics. More information is available in the full memorandum on C/AV Analysis Tools, Techniques, and Data.
- **Integrating data from the CV Pilots Deployment Projects**. Empirical data obtained from the Federal Highway Administration (FHWA) Connected Vehicle Pilots Deployment Project waves in 2015 and 2017 will be highly relevant to several of the research topics—particularly topics 1, 5, and 7, which are expected to be impacted by earlier levels of automation (see figure 2). It is expected that all of the applicable research topics will be revisited and updated in response to any new insights or information obtained from these datasets, even if the topic’s end date, as shown in figure 7, occurs prior to the release of these datasets.

Long-Term Perspective

The successful fulfillment of the research proposed in this project is a milestone marking the point at which needs may be reevaluated, a follow-up gap analysis performed, and an updated research program produced as a result. The following list elaborates on three key activities that are likely to be required in the long term. (It should be noted that these activities are subject to greater uncertainty, given the rapid pace of changes in technology):

- **Keeping the research roadmap relevant.** As the state of CV technology deployment continues to evolve in the coming years and decades, the research program will need to be updated with new topics to reflect the latest data and expectations for CV applications, technological capabilities, and other dynamic factors.
- **Considering new tools and reevaluating existing ones**. In transportation planning and analysis, new tools often enter the market to supplement or displace existing ones. In the future, it will be crucial to revisit the set of major tool classes used by transportation planners and analysts, so that additional relevant ones may be

identified and added, as appropriate. Furthermore, existing tools may need to be reevaluated with respect to their ongoing relevance to CV analyses.

- **Revisiting the research roadmap topics as more data become available**. It is expected that there will be ongoing work for all of these research topics even after their objectives have been initially accomplished, as the topic outcomes will continue to benefit from an infusion of new datasets as they become available over time. In particular, data from advances in AV technology are expected to be relevant to research topics 1, 2, 5, and 6, especially at later levels of automation (see figure 2).

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