Connected Vehicle Impacts on Transportation Planning

Technical Memorandum #3: Analysis of the Need for New and Enhanced Analysis Tools, Techniques, and Data

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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 identify 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 focuses 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 also considers the need for the development of entirely new tools and datasets when the existing ones cannot feasibly be enhanced or extended to enable C/AV analyses. This report follows four major themes, the first of which is a summary of existing data, tools and products currently used in transportation planning processes. The next area includes an evaluation and comparison of existing tools and their suitability 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 existing tools and data for use in analysis of C/AV technologies. The results show that data and analysis tools used in traditional long-term transportation planning would potentially be modified or overhauled to accommodate analyses of connected vehicle applications and technology. Finally a roadmap is provided that identifies 19 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 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
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
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
		VOLUME		
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		
		MASS		
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")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
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
		VOLUME		
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
		MASS		
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
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
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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1.0 Introduction

The principle 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.

While the focus is primarily on Connected Vehicle (CV) technology, it is clear that to incorporate the full range of planning products and activities, Automated Vehicle (AV) technology must be considered as well. As a result, the subject of this effort is referred to as Connected/Automated Vehicle (C/AV) technology in the document. Additional background information regarding both types of driving technologies is provided later in this chapter.

To fulfill the objectives of this project, four analysis tasks are being conducted:

1. Identifying how C/AV technology should be considered in transportation planning processes and products under a variety of circumstances (Task 2);
2. Identifying the need for new or enhanced tools, techniques, and data to support various C/AV planning activities and approaches for how to meet those needs (Task 3);
3. Developing a number of illustrative scenarios of C/AV planning, based on real-world planning environments, that highlight the various ways that C/AVs can be addressed, including how new or enhanced tools, techniques, and data can be applied to address a number of specific C/AV issues (Task 4); and
4. Identifying the roles and responsibilities of stakeholders and organizational and workforce skills, expertise, and capabilities needed to carry out C/AV planning (Task 5).

The results of these tasks will be summarized in a final report that will document the findings of the project and actions that planning agencies can take to address C/AV Vehicle impacts.

1.1 Analysis of the Need for New and Enhanced Analysis Tools, Techniques, and Data

This technical memo is being prepared in support of Task 3. It focuses 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 also considers the need for the development of entirely new tools and datasets when the existing ones cannot feasibly be enhanced or extended to enable C/AV analyses. This report follows a logical progression through four major themes:

1. **Summary of existing data, tools, and products.** This section identifies and summarizes the data, tools, and products currently used in transportation planning processes in a variety of contexts such as statewide and regional short- and long-range transportation plans in large/small states and urban areas.
2. **Evaluation and comparison of existing tools.** This section evaluates and compares existing transportation analysis tools with respect to their input/output interfaces, usability, modeling

features, and calibration requirements. It also begins to explore how these tools might be used to analyze connected vehicle strategies.

3. **Gap analysis for existing tools and data.** This section considers the current limitations of existing tools and data regarding the representation and analysis of connected vehicle technologies and applications. Data and analysis tools used in traditional long-term transportation planning would potentially be modified or overhauled to accommodate analyses of connected vehicle applications and technology.
4. **Roadmap for addressing the gaps.** This section identifies 19 research topics to target these needs (from Part 3), identifies which agency would be best suited for addressing these needs, establishes priority levels for each topic, and discusses the expected availability of potential data sources to inform those topics.

1.2 Connected and Autonomous Vehicle Technology

(*State DOT CEO Leadership Forum: A Focus on Transportation Futures.* Final Report, ITS World Congress. Submitted to NCHRP 20-24 (100) Panel by Cambridge Systematics, Inc., October 10, 2014.)

The next wave of vehicle innovation from the perspective of the operator or driver will come in the form of Connected Vehicles—first connected to each other (Vehicle-to-Vehicle, or V2V), then to roadway and infrastructure devices (Vehicle-to-Infrastructure, or V2I), then to other road users such as pedestrians, motorcyclists, and bicyclists. However, although the first CV technologies are expected to begin appearing first in vehicles rather than on the infrastructure side (and therefore marketed as emerging V2V technologies rather than V2I technologies), it is also expected that the first widespread applications of significance will largely be V2I applications. This is due to the fact that V2V applications typically require high penetration rates before their benefits accrue to any measurably significant degree. In contrast, V2I applications can often be achieved for all properly-equipped vehicles even with low penetration rates in the public vehicle fleet, as long as the supporting roadside infrastructure is in place. Because agencies may have an easier time justifying V2I roadside infrastructure investments only after there are some CV-enabled vehicles in the public fleet that would benefit from those installations, it is expected that CV technologies will begin appearing in vehicles first, with V2I technology deployments following.

Advances in Autonomous Vehicle technologies are expected to occur in parallel to these advances in CV technology. Although it is expected that both AV and CV technologies will provide the vehicle and driver with a greater awareness of the surroundings, they are fundamentally different in that AVs—unlike CVs—rely completely on onboard sensors to collect information about the vehicle's surroundings and to operate the vehicle without any dependence on direct communication with other vehicles or roadway infrastructure. In this way, the deployment of AV technology is largely influenced by private automobile manufacturers rather than by public agencies and departments of transportation, which are expected to initially have more of a regulatory or supervisory role regarding AVs. Furthermore, while V2I—and to a lesser extent, V2V—applications are dependent on public agencies and departments to provide the necessary enabling infrastructure, AV deployment may occur without involvement by or technological dependence on the public sector.

Given that these technologies are currently only in their initial/pilot deployment stages, there is some non-trivial degree of uncertainty regarding:

- Which technologies will eventually achieve full deployment;
- What capabilities will ultimately be available with those technologies;
- On what timeline those technologies will be deployed; and
- How the public will respond to these technologies, including (but not limited to) changes in adoption rates and market penetration rates over time.

In this section, we discuss general expectations regarding these technologies, such as what specific applications might be realized in the near term and what broader CV and AV characteristics may be realized in the long term. However, 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. Therefore, the reader is advised that the guidance and direction provided by this report, though based on widely accepted current forecasts regarding the future of CVs and AVs, is subject to continual refinement and revision moving forward, in response to the future availability of additional data regarding the development and deployment of CV/AV technologies.

Connected Vehicles

V2V applications use wireless technologies that can allow vehicles to “talk” to each other, enabling a variety of safety, mobility, information, and—eventually—vehicle automation applications. The data exchanged between vehicles would include speed, location, and direction of travel, braking, and loss of stability. This data allows for sensing threats and hazards with a 360 degree awareness of the position of other vehicles and the threats or hazards they present; calculating risk; issuing driver advisories or warnings; or taking preemptive actions to avoid and mitigate crashes. Much of the current U.S. DOT research and testing program related to V2V has been focused on emerging safety applications. According to the U.S. DOT, the deployment of V2V communications will enable safety systems that can assist drivers in preventing 76 percent of the crashes on the roadway, thereby reducing fatalities and injuries. Examples of those early safety applications include the following:

- Emergency electronic brake lights;
- Forward collision warning;
- Blind spot warning and lane change warning;
- Do-not-pass warning;
- Intersection movement assist; and
- Left turn assist.

In addition to communicating with other vehicles, wireless technologies can allow vehicles to exchange information with the roadway infrastructure, including signal cabinets and roadside receiver/transmitter units. Referred to as V2I communication, this enables several applications that would not be possible through V2V technology alone, including warnings about low volume roadway surface conditions, advance notification to vehicles of anticipated signal phase changes, and transit signal priority applications based on detailed vehicle information (e.g., occupancy, schedule adherence). Additional applications include security credentialing for freight, mapping and asset tracking systems, vehicle positioning services, and automated infrastructure data collection. Table 1-1 lists several of the early applications that leverage existing ITS deployments, as identified by AASHTO in its Footprint Analysis. (*National Connected Vehicle Field Infrastructure Footprint Analysis: Final*

Report Executive Summary. American Association of State Highway and Transportation Officials, Washington, D.C., December 2013.)

Table 1-1. Potential V2I Near-Term Applications for State DOTs and Other Agencies

Safety Applications	Mobility Applications	Agency Operations and Maintenance
• Red Light Violation Warning • Curve Speed Warning • Stop Sign Gap Assist • Spot Weather Impact Warning • Reduced Speed/Work Zone Warning	• Motorist advisories and warnings (emergencies, weather, variable speeds, curve speed, oversize vehicle) • Real-time route-specific weather information for motorized and nonmotorized vehicles • Advanced Traveler Information System • Freight operator real-time information with performance monitoring • Transit signal prioritization • Emergency vehicle prioritization	• Enhanced maintenance decision support • Information for maintenance and fleet management systems

Source: Cambridge Systematics, Inc.

Autonomous Vehicles

Autonomous vehicles act independently of V2V or V2I communication. Vehicle automation relies on robotics, artificial intelligence, machine learning, machine vision, and computer processing to control mechanical processes for vehicle movements. Lane striping, sign reflectivity, and other infrastructure cues are used in combination with navigational technology. The vehicles generally use sensors to operate—to varying degrees—without human input or control.

To address the changing nature of the driving experience, the National Highway Traffic Safety Administration (NHTSA) proposed a regulatory framework that uses five descriptive levels of automation. These levels range from Level 0 to Level 4, with Level 4 requiring no active “driver” role, as shown in Figure 1-1.

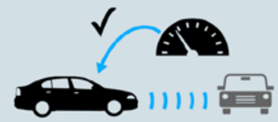
LEVEL	DESCRIPTION	EXAMPLES	
Driver Warning Systems 0	Provides guidance to the driver, but makes no decisions and does not take away control.	▪ Forward collision warning ▪ Lane departure warning ▪ Blind spot monitoring	
Automation of Isolated Driver Functions 1	Manages individual driver functions, but requires a human driver to continue performing other essential functions.	▪ Adaptive cruise control ▪ Dynamic brake support ▪ Lane Keeping Assist	
Automation of Several Driver Functions 2	Manages several driver functions simultaneously, but still requires a human driver to handle some essential functions.	▪ Combinations of items from (1) above.	
Limited Self-Driving Capability 3	Limited autonomous operation in certain environments, with supervision from human driver to handle complex situations.	▪ Handling inclement weather ▪ Interpreting traffic signals ▪ Reacting properly to pedestrians ▪ Handling railroad crossings	
Fully Autonomous Operation 4	Capable of handling more advanced driving situations and environments, for fully autonomous operation from origin to destination.	▪ Interpreting and avoiding animals/obstacles ▪ Obeying instructions from flaggers and peace officers ▪ Reacting properly to bicyclists	

Figure 1-1. Graphic. Five levels of vehicle automation
(Source: [National Highway Traffic Safety Administration](#).)

While a transportation system consisting primarily of fully automated-capable vehicles may be decades away, partially automated solutions such as vehicle platooning are expected to be in operation in the nearer future. For example, V2V can provide for safer, closer headways between trucks and for communications to nearby trucks that will allow “virtual trailering” between them. This would allow even closer spacing between trucks, thereby increasing capacity and reducing energy consumption.

Table 1-2 provides a summary of the benefit categories expected to be affected by each level of vehicle automation.

Table 1-2. Expected Benefits by Level of Vehicle Automation

Automation Level	Increased Capacity	Delay Reduction	Safety Improvements	Emissions/Fuel Improvements
Level 0	Little or no benefit	Moderate benefits	Significant benefits	Little or no benefit
Level 1	Little or no benefit	Moderate benefits	Significant benefits	Little or no benefit
Level 2	Little or no benefit	Moderate benefits	Significant benefits	Little or no benefit
Level 3	Significant benefits	Significant benefits	Significant benefits	Significant benefits
Level 4	Significant benefits	Significant benefits	Significant benefits	Significant benefits

Source: Cambridge Systematics, Inc.

Note: The anticipated benefits accompanying the five NHTSA levels of automation are in consideration of both autonomous vehicle technologies (i.e., AVs) and automation achieved through connected vehicle technologies (i.e., automation of CVs). Current research indicates that significant safety and mobility benefits will be achieved through a connected vehicle environment at NHTSA Levels 1 and 2 of vehicle automation. The amount of benefits achieved at NHTSA Levels 3 and 4 are subject to more detailed study.

2.0 Summary of Existing Analysis Products and Tools

This section provides an overview of existing analysis tools and techniques used in transportation planning processes in a variety of contexts, such as statewide and regional short- and long-range transportation plans in large/small states and urban areas. (Krista Jeannotte, Andre Chandra, Vassili Alexiadis, Alexander Skabardonis. *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools.* Federal Highway Administration Publication Number FHWA-HRT-04-039. July 2004.) It also provides a summary of existing data and findings related to connected vehicle field tests, pilots, case studies, and other analyses.

2.1 Different Categories of Analysis Tools

The following is an introduction to the different classes of analysis tools available to transportation professionals and practitioners, including a general description of these characteristics:

- The precision of the results;
- Intended applications;
- Fundamental principles or approach to the analysis; and
- Advantages and limitations, both in general and from a CV/AV analysis perspective.

The basic classes of tools reviewed in this section include the following:

- Planning tools—used for short-term and long-term state, regional, or local transportation plans. These include master plans, strategic plans, congestion management plans, and the like:
  - Sketch planning tools; and
  - Travel demand models.
- Design, construction, and operations tools—used to develop design guidance for new facilities or to evaluate and optimize existing facilities:
  - Highway Capacity Manual methods; and
  - Traffic simulation models.

Sketch Planning Tools

These are used to evaluate common transportation improvement projects without necessitating a detailed analysis, making them useful for preliminary budgets and proposals. They rely on aggregated data and outcomes from past projects to produce estimates based on essential input variables.

- **PRECISION:** Order of magnitude.
- **ADVANTAGES:** Are simple to perform and require relatively low investment of money, time, and resources. More approachable than other tools in terms of cost, level of effort, and ease of use.

- **LIMITATIONS:** Results are imprecise approximations and lack analytical robustness.

Travel Demand Models

By projecting future travel demands based on current conditions, demographic forecasts, and employment trends, these models can be used to predict benefits and impacts of major transportation improvement projects.

- **PRECISION:** High for capital improvement projects, but limited for TSM&O (transportation system management and operations strategies, such as intelligent transportation systems).
- **ADVANTAGES:** Have the capacity to consider various modes, routes, destinations, and departure times.
- **LIMITATIONS:** As travel demand models do not consider vehicle dynamics, they are poorly suited for evaluating the impacts of operational strategies and cannot readily provide detailed operational outputs (e.g., detailed speed or delay data). They do not explicitly consider queue spillback effects, traffic weaving impacts, or other effects that require modeling of individual vehicles.

Highway Capacity Manual (HCM) Methods

The methods in the HCM are widely accepted and understood and are based on analytical deterministic models using operational and performance data for existing facilities. Procedures for analyzing different facility types are available (e.g., freeway weaving sections, unsignalized intersections, bicycle facilities), though unlisted facility types cannot be analyzed (e.g., two-way left turn lanes, truck lanes on grades, auxiliary lanes at signalized junctions). Outputs are deterministic, aggregated, and generally focus on performance measures, such as level of service. More detailed information about HCM methods is provided later in this chapter.

- **PRECISION:** Outputs are generally provided for facilities (not vehicles), in 15-minute or 1-hour time increments. Performance metrics such as expected delays or volume-to-capacity ratio are typical outputs.
- **ADVANTAGES:** Requires relatively few inputs and little initial configuration effort. More approachable than other tools in terms of cost, level of effort, and ease of use.
- **LIMITATIONS:** HCM methods generally require stationary traffic conditions and are best suited for isolated facility analyses rather than system wide analysis. They are poorly suited for analyzing queue spillback effects.

Traffic Simulation Methods

These can be used to evaluate a wide range of operational strategies or roadway modifications across an entire network. Outputs are based on stochastic behaviors of drivers in the simulation and can be aggregated or disaggregated by link, driver, node, etc. The network is first constructed within the simulation environment, including facility and infrastructure configuration parameters such as node properties, link properties, and signal timing plans. It is loaded with appropriate levels of traffic and often calibrated to replicate real-world conditions as closely as possible within the needs and constraints of the analysis. Once prepared, the simulation model can be reconfigured or otherwise modified to gauge the operational and performance impacts of various strategies, adjustments, or improvements. More detailed information about traffic simulation methods is provided later in this chapter (see Section 2.3).

- **PRECISION:** Fine time-step resolution, with the possibility for simulation of individual vehicles and driver behaviors.
- **ADVANTAGES:** Can capture non-stationary traffic states including congestion growth or dissipation. Individual vehicles can be simulated with different driver parameters, commonly drawn from a specified statistical distribution. Impacts of queue spillback can be modeled.
- **LIMITATIONS:** Cannot be used to model many realistic driver behaviors or situations, such as inattention or collisions. Requires a significant level of input data. Preparation of the model, including calibration, can be time consuming. Simulations can be computationally expensive to execute.

2.2 More Detailed Descriptions of HCM Methods

Tools and procedures in the Highway Capacity Manual can be classified as either performance assessment/evaluation tools (analytical and deterministic tools) or performance optimization tools (traffic signal optimization tools).

To account for multiple vehicle classes, characteristics, and associated flow fractions, the HCM reports flows and densities in terms of passenger-car equivalents. In this way, trucks, buses, and other vehicles are effectively treated as an equivalent number of passenger cars that would be expected to have similar impacts on capacity.

Analytical/Deterministic Tools (HCM Methods)

These are typically used to estimate performance of a single location or facility, over a set of predefined analysis periods. Analytical, closed-form, deterministic procedures are used to estimate various performance outcomes based on input facility and operational characteristics. These procedures are informed by empirical data, test bed research, and small-scale field experiments. Outputs may include predictions of capacity, density, speed, delay, and queues.

- **PRECISION:** Macroscopic averages of expected facility performance across a 15-minute or 1-hour analysis interval.
- **ADVANTAGES:** Available procedures enable analysis of a variety of facility types and characteristics. Results may be obtained relatively quickly with few inputs.
- **LIMITATIONS:** Poorly suited for assessing network effects or system-wide performance.

Traffic Signal Optimization Tools (HCM Methods)

As the name implies, this class of tools is generally used to develop optimized signal timing plans for intersections and corridors. This is done using deterministic numeric methods and procedures taken from the Highway Capacity Manual.

- **PRECISION:** Results can be applied directly in the field.
- **ADVANTAGES:** Simpler and faster than simulation. Provides optimized cycle lengths, splits, and offsets for coordination.

- **LIMITATIONS:** Can only be used to optimize simpler signalization situations. Better suited for smaller networks due to the use of manual procedures.

2.3 More Detailed Descriptions of Traffic Simulation Methods

Generally, microscopic simulation models are better-suited for detailed analyses of strategies or conditions in which individual vehicle interactions are significant, while macroscopic simulation is more appropriate for larger networks that would be too time-consuming to simulate with the fine precision of a microscopic analysis. As a result of their greater attention to detail for both drivers and the infrastructure, microsimulation models also require more input data and initial configuration than macroscopic models. While microscopic simulators assign individual driver parameters to each vehicle, macroscopic simulators rely on assumptions of regularity regarding such behavioral parameters among drivers to simplify the simulation.

Mesoscopic models combine many of the characteristics of both microscopic and macroscopic models in order to achieve a balance between feasible network scale and degree of realism/precision in the simulation.

One limitation of traffic simulation models compared to the HCM is that delays upstream of bottlenecks or signalized junctions are not easily calculated, as the simulator software generally performs the aggregation at the roadway link or section level. Delays generally must be manually combined across all links that carry the queued traffic for a particular bottleneck.

Macroscopic Simulation Models

These rely on macroscopic traffic flow theory relationships (such as those between speed, flow, and density) to model traffic in specific systems, such as a freeway network, arterial grid, or rural highway system.

- **PRECISION:** Produces estimates of facility performance across entire segments at a time.
- **ADVANTAGES:** Allows for analysis of large-scale networks; not as computationally demanding as more detailed simulation models.
- **LIMITATIONS:** Individual vehicle behaviors are not simulated; consequently, strategies that impact vehicle-level interactions are not readily evaluated using macroscopic simulation models. Trip generation, trip distribution, and mode choice are not explicitly considered.

Mesoscopic Simulation Models

As a balance between microscopic and macroscopic simulation models, these enable the simulation of large networks while maintaining a higher degree of realism than is available in macroscopic models. With mesoscopic models, individual vehicles are simulated on the network, which can have detailed parameters defined for individual elements (though to a lesser extent than is possible with microscopic models). Movements and behaviors are governed by macroscopic relationships rather than lane-changing and car-following models.

- **PRECISION:** Models individual vehicles, but in a less-precise manner than microscopic models.
- **ADVANTAGES:** Can simulate larger networks while being less computationally demanding than microscopic models yet still providing vehicle-level precision.
- **LIMITATIONS:** Not well equipped to handle the simulation of intersection operations, weaving zones, operational strategies, and facilities that require a high level of vehicle-to-vehicle interaction.

Microscopic Simulation Models

Using car-following and lane-changing models to simulate driver behaviors and vehicle trajectories in time steps measured on the order of one second, these high-resolution simulations provide operational insight and detailed performance measures for a variety of strategies that affect demand, capacity, or facility operations.

- **PRECISION:** Provides detailed outputs at the segment, vehicle, intersection, or aggregate level. Can be configured to simulate traffic several times to capture certain stochastic effects.
- **ADVANTAGES:** Enables the analysis of a wide range of transportation improvement projects and operational strategies. Allows input parameters to be specified on a fine scale; for example, individual links can be assigned their own lane widths, grade, visibility distance, or other attributes.
- **LIMITATIONS:** Larger networks can become very computationally demanding. Model setup and calibration can be time-consuming as well.

2.4 Expected Impacts of Connected Vehicles

Several studies have been performed to date on the realized or potential impacts of connected vehicles across several benefit categories. This section serves as a brief literature review of such studies. The discussion is organized by benefit category, rather than by study or project, including the following:

- Capacity impacts;
- Emissions and fuel consumption impacts; and
- Crash reduction potential.

This section ends with an overview of the Connected Vehicle Safety Pilot Program—a set of research tracks sponsored by the U.S. DOT with the goals of providing data on CV technologies, associated driver responses, and resultant potential safety benefits in real world driving environments. The two relevant outcomes from the pilot program arise from the driver clinics (which explore driver acceptance and response to the technologies) and the model deployment in Ann Arbor, Michigan (which explores the performance and outcomes of the technology as deployed in a real world urban setting).

Potential Capacity Impacts of Connected Vehicles

In an article published by *American Scientist*, Steven Shladover of the University of California, Berkeley, points out that computer-controlled vehicles could double or triple the maximum allowable traffic density on freeways at their peak performance. In an experiment on I-15 in San Diego in 1997, a platoon of eight vehicles was maneuvered down a freeway using V2V technologies at a separation of 6.5 meters at highway speeds. This corresponded to an effective lane carrying capacity of 5700 vph with inter-platoon spacings of 60 meters for safety. When the maneuvering of entering and exiting vehicles was considered, this capacity was estimated at 4300 vph—still substantially higher than the standard lane capacity of 2000 vph without connected vehicle assistance. (Intellimotion) The CHAUFFEUR automation system in Europe, designed to provide electronic platooning of heavy freight vehicles, has been estimated to yield a potential capacity increase of 8%.

In a joint investigation of Cooperative Adaptive Cruise Control (CACC) by Nissan Motor Co. and the California Partners for Advanced Transportation Technology (PATH) at U.C. Berkeley, simulation models and field testing indicated that CACC could increase lane capacities to 3970 vph, nearly double the capacity achieved using only adaptive cruise control alone. (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, Berkeley.)

A conceptual analysis of lane capacity using automated vehicle platoons can be applied to achieve insight into the potential capacity increases afforded by different sets of platooning parameters. Table 2-1 provides the theoretical lane capacities achieved for selected combinations of parameters, assuming a travel speed of 72 kph. Note that the first row effectively represents no platooning, as each platoon is defined as one vehicle.

Table 2-1. Lane Capacity for Different Platooning Scenarios

Number of vehicles per platoon	Gap spacing between vehicles	Spacing between platoons	Assumed length of each vehicle	Lane capacity
1	N/A	30 meters	5 meters	2100 vph
5	2 meters	60 meters	5 meters	3840 vph
15	2 meters	60 meters	5 meters	6600 vph
20	1 meter	60 meters	5 meters	8000 vph

Source: Cambridge Systematics, Inc.

Potential Emissions and Fuel Consumption Benefits of Connected Vehicles

Testing in a wind tunnel facility at the University of Southern California found that drag forces could be reduced by 50% for vehicle spacings of approximately half a car length, while researchers at the University of California, Riverside, equated this reduction in drag force to a savings of 20% to 25% in fuel economy and vehicle emissions. (Intellimotion) The CHAUFFEUR program in Europe has the estimated potential to increase vehicle fuel economy by as much as 20%.

Between 2009 and 2012, the SARTRE Project (Safe Road Trains for the Environment) examined the impacts of five-vehicle platoons (two leading trucks and three following passenger cars) using V2V technologies and automatic control of steering and acceleration/braking. From tests conducted at 90 kph on a high-speed test track in Spain, fuel savings for the lead truck were found to range from approximately 1.5% at a spacing of 25 meters to as much as 8% at a spacing of 5 meters. The following truck achieved an approximate fuel savings of 7.5% at a spacing of 25 meters and over 12% at a spacing of 5 meters. For the three passenger cars at the back of the platoon, fuel savings ranged between 4.5% and 11.5% at a gap spacing of 15 meters and ranged between 11.5% and 15% for a gap spacing of 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.)

In another study by Japan Automobile Research Institute (JARI) and four truck manufacturers, V2V technologies were used to operate platoons of three trucks using either CACC or an automated driving system. The CACC approach employed a 20-meter spacing between vehicles and resulted in an average measured fuel consumption improvement of 8%. The automated driving system operated with inter-vehicle spacings of 10 meters and 4.7 meters and was measured to achieve an average fuel consumption improvement of 14% at 10 meters and 16% at 4.7 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.) In a 2013 California PATH study using a platoon of three trucks on a straight test track in Nevada, fuel savings of 4.5% (lead truck), 11.9% (middle truck), and 18.4% (last truck in platoon) were measured. The vehicles were operated using DSRC V2V communication at a spacing of 6 meters at 53 mph. (X. Lu and S. Shladover. *Original Automated Truck Platooning with DSRC as V2V.* California PATH, UC Berkeley. December 6, 2013.)

One analysis by the GSW Strategy Group, an energy and environmental strategy consulting firm, estimates that vehicle platooning and collision avoidance technologies could reduce fuel demand by 2%.

Incident and Crash Reduction Potential

A crash analysis sponsored by the Crash Avoidance Metrics Partnership (CAMP) and headed by Cambridge Systematics, Inc. and Jim Misener looked at California collision data for 2013 and found that roughly 78% of all crashes could be avoided by the use of V2V technologies based on the underlining determinant of crashes. This was based on a sample of 175,709 crash records from CHP data. (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.) Additionally, U.S. DOT has asserted that connected vehicle technologies can “reduce, mitigate, or prevent 81% of light-vehicle crashes by unimpaired drivers.” (Motor Authority)

Connected Vehicle Safety Pilot Model Deployment

Research Track 1 of the U.S. DOT Connected Vehicle Safety Pilot Program included several driver clinics at six different test sites across the United States between August 2011 and January 2012. The purpose of these clinics, each with over 100 drivers performing behind-the-wheel tests, was to gauge driver acceptance and response to various connected vehicle technology interfaces and systems. Results from these clinics are already available, and the responses provide insight into which technologies and C/AV technologies drivers are most interested in seeing deployed. For example, intersection movement assist scored the highest on several dimensions including usefulness and desirability. Questions regarding cost acceptance and motivation for adoption were also asked of the respondents, with over half of the respondents indicating that they would pay at least $250 for V2V technology in their vehicles.

Research Track 3 of the USDOT Connected Vehicle Safety Pilot Program involved the deployment of approximately 3,000 vehicles with CV technology on public streets in Ann Arbor, Michigan, to determine the effectiveness of such technology at reducing crashes. This one-year program sponsored by USDOT and led by the University of Michigan Transportation Research Institute (UMTRI) took place between 2012 and 2013 with the intent of yielding real-world data on DSRC communications in the context of connected vehicles and examining the potential safety benefits of CV technology through field-based testing and evaluation. In addition to safety applications, the pilot deployment was also designed to highlight other strategies that can be informed, improved, or made possible by V2V and V2I technology, including the following (Connected Vehicle Safety Pilot Program):

- Transit vehicle signal priority and emergency vehicle signal preemption;
- Pavement maintenance data collection;
- Pedestrian traffic density data; and
- Traffic signal timing applications.

Research Track 2 was concerned with determining specifications for devices and establishment of a qualified products list. It did not produce any C/AV data that would be directly relevant to this analysis of the need for new and enhanced planning tools, techniques, and data.

3.0 Evaluation and Comparison of Existing Tools

This chapter evaluates and compares existing transportation analysis tools in terms of their general inputs, outputs, usability, and modeling features/capabilities. It also compares their abilities to model connected vehicle applications and strategies.

3.1 Overall Tool Summary and Comparison

Figure 3-1 provides a summary assessment of existing transportation analysis tools in terms of their roles in the planning process (ranging from preliminary screening to alternatives analysis to operational design), cross-referenced against the tools' analytical sensitivity and/or resolution. Every tool type represents a tradeoff between geographic scope and level of sensitivity/resolution (scale versus complexity). Less detailed tool types are tractable for large networks, while more detailed tool types are restricted to smaller networks.

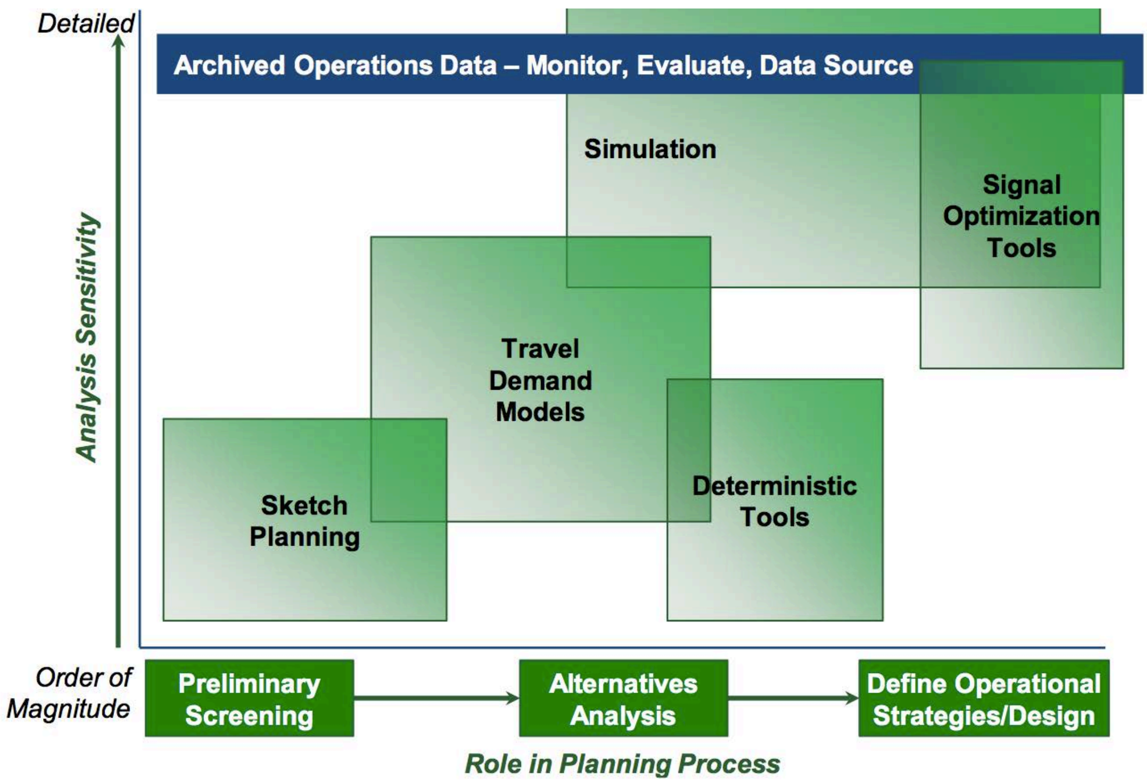


Figure 3-1. Graphic. Roles of existing transportation analysis tools in the planning process
(Source: Cambridge Systematics, Inc.)

It can be argued that the analysis of the impact of connected vehicle strategies will require more detailed, higher-resolution data and tools. This hypothesis 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 ITS, ICM, and ATDM strategies. The following paragraphs describe the three current classes of simulation tools used by planners, as well as a new emerging connected vehicle simulation capability:

- **Travel Demand 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 support CV analysis.
- **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 (such as ramp metering or traffic signal preemption), these tools show substantial promise for modeling CV applications and strategies.
- **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 do not consider dynamic speed/volume relationships and therefore provide less fidelity than microsimulation tools. They are, however, superior to travel demand models in that they can evaluate dynamic traveler diversions on large-scale networks. Thus, these tools are useful in the modeling of regional CV applications and strategies.
- **CV-Specific Simulation Models.** This emerging class of tools can simulate all types of sensors, vehicle, V2V, and V2I technologies at a microscopic level. A challenge will be to develop versions of these engineering tools that are approachable for practitioners, responsive to their needs, and accommodating of the desired level of precision for planners. In addition, developers and planning agencies will both want to integrate the capabilities of these models into their existing miso- and meso-based simulation tools, corridor planning workflows, and infrastructure assessments.

All of the above existing and emerging tools show promise regarding the analysis of various CV strategies; however, such analyses will require a number of tool enhancements, including modifications to the car-following and lane-changing logic and algorithms embedded in existing analysis tools. In some cases, it is furthermore possible that major restructuring of current analysis frameworks will be necessary to fully provide the following information:

1. The systemwide impacts of CV strategies.
2. The travelers' behavioral responses to imperfect, latent, and multi-resolution real-time traveler information.
3. Improved transit, freight, parking, and pedestrian analysis capabilities.
4. Enhanced land use planning capabilities.
5. Risk analysis capabilities to address ranges of potential impacts.

Overall, these enhanced or new analysis frameworks must be capable of evaluating the cost effectiveness of CV strategies individually, in combination with each other, and in combination with other ITS strategies in the near-term, mid-term, and long-term. In pursuit of this overall objective, additional requirements for these frameworks include the following capabilities:

1. Modeling both the transportation and communications impacts of CV strategies.
2. Identifying the operational conditions under which CV strategies will be most beneficial.

3. Distinguishing between different communications technologies and resolutions.
4. Testing different market penetrations for CV strategies.
5. Evaluating the impacts of communications errors, loss, or latency.

3.2 Comparisons of Tool Capabilities

This section compares the capabilities of the different classes of analysis tools across several dimensions:

- Geographic scale of analysis (Table 3-1).
- Usability and technical considerations (Table 3-2).
- Facility types available for analysis (Table 3-3).
- Travel modes available for analysis (Table 3-4).
- Traveler response types available for analysis (Table 3-5).
- Performance measure outputs available (Table 3-6).

Geographic scope is generally a constraint that must be satisfied by any tool under consideration for a particular analysis, making this one of the initial factors to be considered when selecting an appropriate tool for a specific need. Isolated locations, typically single junctions, are the smallest in scale. Segment-sized analyses also include small grid networks, while a corridor-sized model typically includes both a primary roadway and neighboring parallel routes as well. Regional models are the largest, generally having a coverage area of 200 square miles or more.

Table 3-1. Scale of Analysis Capabilities by Tool Category

Geographic Scope	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Simulation Models
Isolated location	Poorly suited	Poorly suited	Highly relevant	Highly relevant
Segment	Limited applicability	Poorly suited	Highly relevant	Highly relevant
Corridor or small network	Limited applicability	Limited applicability	Limited applicability	Highly relevant
Regional	Limited applicability	Highly relevant	Poorly suited	Limited applicability

Source: Cambridge Systematics, Inc.

Usability and technical considerations emphasize the level of effort required to learn, configure, and run the particular tool type and also include some of the auxiliary technical aspects of the approach, including results visualization and support for custom workflows/analyses.

Table 3-2. Usability and Technical Considerations by Tool Category

Technical requirement/characteristic	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
Level of effort required to learn	Minor	Extensive	Minor	Extensive
Usability and user-friendliness	Easy	Moderate to Challenging	Easy	Moderate to Challenging
Hardware requirements	Low	High	Low	High
Data input requirements (roadway, geometry, and traffic characteristics)	Low	High	Low to Moderate	High
Computational time	Low	Moderate	Low to Moderate	Moderate to High
Data post processing effort required (to obtain usable performance metrics)	Moderate	High	Moderate	Low to Moderate
Documentation (includes coverage in reports and existing analyses)	Moderate	Moderate	Thorough	Thorough
Customization capabilities (including customization of key parameters)	Limited	Available	Limited	Available
Default values for parameters provided	Most provided	Few/none provided	Most provided	Most provided
Integration with other software (e.g., geographic information system (GIS) software, database software)	Unavailable	Available	Limited support	Available
Animation/presentation output capabilities	None	Limited support	None	Available

Source: Cambridge Systematics, Inc.

Different tool types have varying capabilities to account for the effects of certain network elements in their analyses. The commonly available building blocks that can be incorporated into each type of analysis are shown in Table 3-3.

Table 3-3. Facility Types that Can Be Accommodated by Each Tool Category

Facility Type	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
Isolated intersection (single junction)	Limited applicability	Limited applicability	Highly relevant	Highly relevant
Roundabout	Poorly suited	Poorly suited	Limited applicability	Limited applicability
Arterial (signal spacing of 2 miles or less)	Limited applicability	Highly relevant	Highly relevant	Highly relevant
Highway/expressway (few signals or flow interruptions)	Limited applicability	Limited applicability	Limited applicability	Highly relevant
Freeway (uninterrupted flow)	Limited applicability	Limited applicability	Limited applicability	Highly relevant

Facility Type	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
High Occupancy Vehicle (HOV) Lane (dedicated lane for certain classes of vehicles only)	Limited applicability	Highly relevant	Limited applicability	Highly relevant
HOV Bypass Lane (HOV freeway entrance lane to bypass a ramp meter)	Poorly suited	Limited applicability	Limited applicability	Limited applicability
Ramp (entrance/exit from a roadway facility)	Limited applicability	Highly relevant	Highly relevant	Highly relevant
Auxiliary Lane (additional lane on a freeway joining an entrance and exit)	Poorly suited	Limited applicability	Highly relevant	Highly relevant
Reversible Lane (lane that changes direction according to a schedule)	Poorly suited	Limited applicability	Poorly suited	Highly relevant
Truck Lane (lane reserved for use by commercial vehicles)	Poorly suited	Limited applicability	Limited applicability	Highly relevant
Bus Lane (lane generally reserved for use by transit vehicles)	Poorly suited	Limited applicability	Limited applicability	Highly relevant
Toll Plaza (location where vehicles must stop for a brief period, e.g., to pay a toll)	Poorly suited	Limited applicability	Limited applicability	Highly relevant
Light-Rail Line (rail with a partially exclusive right-of-way)	Poorly suited	Highly relevant	Poorly suited	Limited applicability

Source: Cambridge Systematics, Inc.

While all classes of tools are able to consider single occupancy vehicles in their analyses, they are able to account for other vehicle types to varying degrees, as shown in Table 3-4.

Table 3-4. Travel Modes that Can Be Included in Analysis

Travel Mode	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
Single occupancy vehicle	Highly relevant	Highly relevant	Highly relevant	Highly relevant
High occupancy vehicle (includes taxis, buses, carpools, and vanpools)	Limited applicability	Highly relevant	Limited applicability	Highly relevant
Bus (can operate on streets or highways)	Limited applicability	Highly relevant	Limited applicability	Highly relevant
Rail (shared or exclusive right of way)	Limited applicability	Highly relevant	Limited applicability	Limited applicability
Truck (heavy freight vehicles)	Limited applicability	Limited applicability	Limited applicability	Highly relevant
Motorcycle	Limited applicability	Limited applicability	Limited applicability	Limited applicability
Bicycle	Limited applicability	Limited applicability	Limited applicability	Limited applicability
Pedestrian	Limited applicability	Limited applicability	Limited applicability	Limited applicability

Source: Cambridge Systematics, Inc.

When operational or infrastructure changes are analyzed, it is often reasonable to expect that the resultant changes in performance will produce additional changes in underlying demand as a result of the following:

- Route diversion—travelers changing from more congested routes to less congested ones.
- Mode shift—travelers shifting to modes with higher utility value to them, such as switching from transit to a single-occupant vehicle.
- Changes to departure time—travelers changing the times they start their trips in response to the changes in conditions and peak behavior throughout the analysis period.
- Induced demand—Occurrence of entirely new trips that travelers were previously not taking because the utility value was too low before the infrastructure improvements and/or operational strategies were deployed.

Induced demand is generally difficult to capture with any tool, though the more detailed methods tend to be the most challenging in this regard; furthermore, the HCM methods related to traffic signal optimization generally assume a constant demand.

Table 3-5. Traveler Responses that Can Be Captured in Analysis

Traveler Response	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
Route diversion, pre-trip	Limited applicability	Poorly suited	Poorly suited	Highly relevant
Route diversion, en route	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Mode shift	Limited applicability	Highly relevant	Poorly suited	Limited applicability
Departure time choice	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Induced/foregone demand	Limited applicability	Limited applicability	Poorly suited	Poorly suited

Source: Cambridge Systematics, Inc.

Available analysis outputs vary depending on the type of analysis tool used, as shown in Table 3-6. This reflects the native capabilities of each tool category, without consideration of additional outputs obtained through post-processing. Accuracy of the outputs is dependent on several factors, including reliability and resolution of the input data, assumptions inherent in the particular tool being used, and quality of the model calibration (if applicable).

Table 3-6. Performance Measures Available for Output

Performance Measure	Sketch Planning	Travel Demand Models	Highway Capacity Manual	Traffic Simulation Models
Level of Service	Poorly suited	Limited applicability	Highly relevant	Limited applicability
Speed	Highly relevant	Highly relevant	Highly relevant	Highly relevant
Travel time (including control delay)	Limited applicability	Limited applicability	Highly relevant	Highly relevant
Volume (expressed as a flow)	Highly relevant	Highly relevant	Highly relevant	Highly relevant
Travel distance (from origin to destination)	Poorly suited	Highly relevant	Poorly suited	Highly relevant
Ridership	Poorly suited	Limited applicability	Poorly suited	Limited applicability
Average vehicle occupancy (includes transit)	Poorly suited	Limited applicability	Poorly suited	Limited applicability
Volume to Capacity Ratio	Poorly suited	Highly relevant	Highly relevant	Highly relevant
Density	Poorly suited	Poorly suited	Highly relevant	Highly relevant
Vehicle-miles traveled or person-miles traveled	Limited applicability	Highly relevant	Limited applicability	Highly relevant
Vehicle-hours traveled or person-hours traveled	Limited applicability	Highly relevant	Limited applicability	Highly relevant
Delay (additional travel time beyond free flow travel time)	Limited applicability	Limited applicability	Limited applicability	Highly relevant
Queue lengths	Poorly suited	Poorly suited	Limited applicability	Highly relevant
Number of stops (based on a threshold speed)	Limited applicability	Poorly suited	Poorly suited	Highly relevant
Incidents	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Incident duration	Poorly suited	Limited applicability	Poorly suited	Highly relevant
Travel time reliability (quantification of the uncertainty regarding travel times, e.g., as an extra time buffer that travelers must build into their schedules).	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Emissions	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Fuel consumption	Limited applicability	Limited applicability	Poorly suited	Highly relevant
Noise	Limited applicability	Poorly suited	Poorly suited	Poorly suited
Mode split	Poorly suited	Highly relevant	Poorly suited	Limited applicability
Benefit/Cost Ratio (comparison of annualized, monetized benefits and costs).	Limited applicability	Limited applicability	Poorly suited	Limited applicability

Source: Cambridge Systematics, Inc.

Although Table 3-6 indicates which performance metrics are generally currently available from each type of analysis tool, future research may make additional outputs available for the combinations in the table that currently have a “poor” rating. Consequently, this table should not be interpreted as a representation of what each analysis tool type is inherently suitable or unsuitable for, but rather as a summary of what outputs are currently typically offered. When selecting a particular tool type for an analysis, the outputs offered by that tool do not necessarily have to enter into the choice as a constraint; if they do, this would indicate an opportunity for future research, so that the tools may be updated to more properly address the performance measurement needs of its users. By design, the analysis tool classification is not intended to be one of the determining factors for what performance measures the analyst or researcher will choose to use; it is often the case that these tools can be updated—or new tools developed—to provide analysts with the performance measures they require.

These performance measurement output considerations are especially important to take into account as the tools are updated according to the roadmap presented in Chapter 5 to include the effects, impacts, and outcomes associated with individual CV and AV applications. If any particular analysis tool category does not offer the proper outputs desired for a given CV or AV analysis, this may represent an opportunity for additional research or development regarding the offerings in that tool category. Alternatively, if suitable modifications cannot be made to existing tools to enable them to provide the desired outputs for a common type of analysis, this may reveal an opportunity for the development of an entirely new class of tool for those CV and AV application analyses. As CV and AV technologies continue to be developed and deployed, it is expected that existing analysis tools and their capabilities will be continually revisited, revaluated, refined, or extended—and that new ones will be developed as appropriate—to ensure that analysts continue have access to tools that meet their needs and expectations, particularly with respect to the types of outputs available.

3.3 Potential for Connected Vehicle Modeling

Given that connected vehicle applications naturally impact individual vehicles, microsimulation modeling presents itself as a well positioned class of tools for modeling the impacts and outcomes of connected vehicle technologies. 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.) Table 3-7 provides examples of how some CV strategies might be incorporated into a microsimulation model, on a conceptual/simplified level.

Table 3-7. Example Methods for Simulating Selected CV 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

Connected Vehicle Strategy	Sample Method for Incorporation into Simulation Model
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 following 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	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
Dynamic speed harmonization	Change in target speed distribution parameters on affected segments, based on prevailing traffic characteristics (e.g., average speed, average density)
Pre-clearance and expedited screening of cars and trucks 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)
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 information systems (and dynamic route guidance)	Enable dynamic vehicle routing based on real-time conditions, for a greater proportion of traffic

Source: Cambridge Systematics, Inc.

4.0 Gap Analysis for Existing Tools and Data

This section anticipates how data and analysis tools used in traditional long-term transportation planning would be modified or overhauled for use in near-term prediction for active management of the transportation system's performance. The section starts with a description of general gaps in available data and analysis methods/tools, followed by detailed lists of more specific capability and data gaps organized by analysis tool type. These detailed lists by tool type include descriptions of the following:

- The current need or gap to be addressed, along with additional background or explanation if applicable.
- Relevant research topics (see Chapter 5 for details regarding each topic) that seek to address these gaps.

4.1 Overall Gaps in Data and Analysis Tools

The following is a list of general data and analysis tool shortcomings and gaps that are common to a broad range of analysis tools, rather than being specific to only a particular tool category.

- Changes to infrastructure that will become possible (or even necessitated) by the advancement and spread of CV technologies are currently unaccounted for in analysis tools. These include the potential for narrower design tolerances (e.g., narrower lanes) or a reduced need for traveler information systems (e.g., guidance signage, traffic alerts via changeable message signs) as these become integrated directly into the vehicle.
- Optimization tools, such as those for signal timing with transit vehicle considerations, must be revisited and revised to account for the changes in driver behaviors that CV technology will produce, such as faster reaction times to phase changes, reduced need for clearance intervals, and reduced need for dedicated protected left turn phases due to changes in gap acceptance patterns.
- Decision support tools for operational decisions (e.g., incident management), maintenance activities, and freight management need to be updated to reflect the new capabilities afforded by CV technologies.
- Actual gains (in capacity, emissions, delays, etc.) achieved for various penetration rates of CV technology have not yet been thoroughly measured, investigated, or even estimated for C/AV strategies, including platooning, merge assistance, weaving assistance, or intersection movement assistance. These benefits must also be considered in the context of roadway types/environments (e.g., freeway, urban arterial) and traffic conditions (e.g., oversaturated). These analyses are a prerequisite to proper incorporation of these CV strategies into all classes of analysis tools.
- Guidance is needed regarding the suitability of various traffic analysis tools for analyzing each CV strategy in various contexts (e.g., platooning on freeways, intersection movement assistance on signalized arterials). It is anticipated that some classes of tools will be better suited for evaluating certain C/AV strategies than others (e.g., sketch-

planning tools for safety impacts, or traffic microsimulation models for weaving section capacity improvements).

- The upcoming field tests of CV systems represent a good opportunity to explore the potential outcomes associated with CV technology. To ensure the utility of these deployments is maximized, an analysis and data collection methodology is needed to ensure the proper data are collected in each case, including sufficient data for model calibration and validation against real-world CV data.

4.2 Sketch Planning Tools

The following table summarizes specific gaps in tool capabilities and data that affect the ability of sketch planning tools to properly analyze C/AV strategies and presents proposed research topics to address gaps.

Table 4-1. Gaps in Sketch Planning Tool Capabilities Regarding C/AV Strategies

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
Inability to estimate the performance and capacity impacts of connected vehicle technology, which would need to be informed by literature and past studies.	**TOPIC 1:** Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates. **TOPIC 2:** Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments.
Failure to account for the infrastructure modifications that will follow connected vehicle technologies, including the possible replacement or supplementation of human interface devices (signage, signal heads, rumble strips, roadway markings, etc.) with roadside units that communicate directly with the vehicle itself	**TOPIC 3:** Cost analysis of C/AV strategies from an agency perspective, informed by past C/AV deployments. **TOPIC 4:** Analysis of suitable predictor variables for C/AV costs of Topic 3, informed by past C/AV deployments.
Many of the economic impacts of CV technologies and strategies are not yet accounted for in existing planning tools, such as changes to traffic incident rates and severity, changes to agency operations and maintenance costs, and the capacity impacts of various environmental and infrastructural changes in the connected vehicle context (e.g., the capacity decreases associated with narrow lanes or reduced visibility conditions may be substantially muted by connected vehicle technology)	**TOPIC 1:** Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates. **TOPIC 2:** Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments.
Lack of data on anticipated adoption and penetration rates for CV technologies in vehicles and integrated into infrastructure. Sensitivity analysis regarding these predictions will also be crucial to ensuring that all CV analyses built upon these forecasts are responsibly conducted and reported	**TOPIC 5:** Penetration rate analysis for C/AV technology, including forecasts of costs and adoption rates.

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
The benefits associated with safety improvements made possible by CV technology are not included in the outputs provided by sketch-planning tools	**TOPIC 1:** Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates. **TOPIC 2:** Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments. **TOPIC 11:** Analysis of safety impacts of C/AV strategies; best methods for modeling these impacts.

Source: Cambridge Systematics, Inc.

4.3 Travel Demand Models

The following table summarizes specific gaps in tool capabilities and data that affect the ability of travel demand models to properly analyze C/AV strategies and presents proposed research topics to address gaps.

Table 4-2. Gaps in Travel Demand Model Capabilities Regarding C/AV Strategies

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
Inability to provide approximations of the capacity impacts associated with connected vehicle strategies	**TOPIC 6:** Methods and algorithms for modeling macroscopic impacts of C/AV strategies for application to TDM and HCM tools. **TOPIC 7:** Incorporating results from Topic 6 into TDM; validation using real-world data and microsimulation methods.
Data on the anticipated changes to mode split associated with CV technology is needed. Mode choice is impacted by utility of each mode, and the growth and spread of CV technologies would increase the utility of the private automobile and transit (given potential impacts on schedule adherence and transfer protection) and subsequently impact modal split	**TOPIC 16:** Analysis of driver response to and acceptance of C/AV strategies, including C/AV mode choice analysis.
Lack of a set of widely accepted and validated methods for estimating capacity impacts associated with C/AV strategies	**TOPIC 7:** Incorporating results from Topic 6 into TDM; validation using real-world data and microsimulation methods.

Source: Cambridge Systematics, Inc.

4.4 Highway Capacity Manual Methods

The following table summarizes specific gaps in tool capabilities and data that impact the ability of deterministic tools and HCM methods (including optimization routines) to properly analyze C/AV strategies and presents proposed research topics to address gaps.

Table 4-3. Gaps in HCM/Deterministic Tool Capabilities Regarding C/AV Strategies

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
Performance-related analyses available through HCM methods (including LOS and capacity assessment) cannot be used to evaluate projects or facilities that would utilize connected vehicle technology, as the impacts of C/AV strategies are not included in HCM methods	**TOPIC 8:** Methods for including capacity impacts of individual C/AV strategies in HCM tools, using models developed in Topic 6. **TOPIC 10:** Updating HCM performance analysis procedures to include C/AV capacity impacts from Topic 8.
Signal timing optimization procedures may produce non-optimal results due to their failure to consider the operational/capacity gains afforded by CV technology (tighter gap acceptance, closer following distances, reduced reaction times, etc.)	**TOPIC 9:** Updating HCM signal timing optimization procedures to include C/AV capacity impacts from Topic 8.
Inability to estimate the safety impacts associated with various strategies, including connected vehicle technology (e.g., curve speed warnings, blind spot warnings, stop sign violation warnings)	**TOPIC 11:** Analysis of safety impacts of C/AV strategies; best methods for modeling these impacts. **TOPIC 12:** Modification of HCM performance analysis methods to include C/AV safety impacts from Topic 11.

Source: Cambridge Systematics, Inc.

4.5 Traffic Simulation Software

The following table summarizes specific gaps in tool capabilities and data that affect the ability of traffic simulation tools to properly analyze C/AV strategies and presents proposed research topics to address gaps.

Table 4-4. Gaps in Traffic Simulation Software Capabilities Regarding C/AV Strategies

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
Inability to represent the communications and sensing aspects of connected vehicle technologies	**TOPIC 17:** Adding support for communications and sensor modeling of C/AV technologies into microsimulation.
Formal guidance is not widely available regarding how modifications should be made to car following and lane changing algorithms to simulate CV behaviors	**TOPIC 13:** Analysis of lane changing and car-following behavior associated with C/AV strategies/technologies.
Simulation software is not natively capable of representing specific CV strategies and their impacts, including dynamic transit capacity assignment, transfer connection protection, dynamic lane use (e.g., incident-related blockages), eco-speed harmonization, or intersection movement assistance	**TOPIC 14:** Adding support for C/AV operations of individual strategies into microsimulation software packages.
Probabilistic models that capture driver responses to in-vehicle warnings (e.g., queue warnings) and route guidance (e.g., dynamic rerouting) are not included in traffic simulation models	**TOPIC 16:** Analysis of driver response to and acceptance of C/AV strategies, including C/AV mode choice analysis.

Gap in Existing Tool Capabilities	Proposed Research Topics to Address It (Summarized)
Existing simulation tools do not have the aerodynamic analysis capabilities needed to evaluate the energy and emissions impacts associated with vehicle platooning	**TOPIC 15:** Adding support for modeling aerodynamic effects of C/AV into microsimulation software packages.

Source: Cambridge Systematics, Inc.

5.0 Roadmap for Addressing Gaps for Analysis Tools and Data

The focus of this chapter is on establishing a proposed research roadmap for addressing the gaps and needs discussed in Chapter 4. The roadmap is comprised of 19 research topics that are designed to provide researchers and practitioners with the transportation planning tools they need to conduct C/AV analyses as the associated technologies mature and are deployed. The organization of this chapter is as follows:

- **DESCRIPTION OF THE PROPOSED RESEARCH ROADMAP.** Overview of the 19 research topics that comprise the proposed research roadmap, described in Table 5-1.
- **RESEARCH TOPIC PRIORITIZATION.** Categorical prioritization for the 19 research topics, presented in Table 5-2.
- **SCHEDULE FOR THE RESEARCH ROADMAP.** Schedule for the 19 research topics, presented in Figure 5-1. This is followed by a discussion of the need to continually update the outcomes and findings associated with each research topic after the initial results are obtained.
- **BENEFIT TYPES CAPTURED BY EACH RESEARCH TOPIC.** Discussion about the capture of specific C/AV technology impacts by research topic, as summarized in Table 5-4.
- **FACTORS AFFECTING THE PROPOSED RESEARCH TOPICS.** Discussion of the significance of empirical data and penetration rates in the context of the proposed research roadmap.

5.1 Description of the Proposed Research Roadmap

Table 5-1 introduces each of the 19 research topics in the proposed roadmap and expands upon their characteristics, including:

- **RESEARCH TOPIC.** The fundamental objective and scope of the proposed topic. Unless otherwise specified for a particular topic, the outcomes and impacts of individual C/AV applications are to be captured, analyzed, and treated separately.
- **RESOURCE NEEDS AND AVAILABILITY.** A discussion of the expected data needs for the research topic, the expected availability of potential data sources to inform the topic's activities in the near future, and the anticipated level of effort associated with obtaining these data.
- **POTENTIAL LEAD ORGANIZATIONS.** A listing of potential lead agencies for sponsoring, overseeing, and/or supervising the topic. These are based on the strength of alignment between the organization's focus/objectives and the goals of the research topic, as well as past involvement in similar research activities.
- **RELEVANCE.** An overview of the relevance of the topic in the context of enabling or enhancing C/AV analysis capabilities for the tools used in traditional long-term transportation planning.

Details about the expected time frames—including relative start times and approximate durations—for each research topic are found later in this chapter, in the section titled, "Schedule for the Research Roadmap."

Table 5-1. Potential C/AV Research Topics to Address Existing Gaps in Data and Tools

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
1. Quantitative assessment of categorical **benefits** for C/AV deployments from pilot programs and real-world field tests, measured at various penetration rates and for different impact types.	This topic requires collecting detailed performance data from each of the pilot project deployments in 2015 and 2017 and from other similar large scale field tests in the past or anticipated for the near future. Some additional data may be available from U.S. DOT Connected Vehicle Safety Pilot Program in 2012-2013.	• USDOT Office of the Assistant Secretary for Research and Technology (OST-R). Its predecessor, the Research and Innovative Technology Administration (RITA), maintains a database of benefits for various ITS strategies. • FHWA, as it will be sponsoring the pilot deployments and providing direction and oversight to the individual agencies running the pilot projects. It is also the sponsoring agency of the Tool for Operations Benefit Cost Analysis (TOPS-BC), which performs a similar function.	Informs benefit estimation tools by providing ranges of typical benefits separately by CV strategy and by benefit category.
2. Analysis of suitable **predictor variables** for the degree of **benefits** achieved by C/AV deployments from pilot programs and real-world field tests, measured at various penetration rates and for different impact types.	Generally the same as for Topic 1. However, additional covariate data may need to be collected alongside the benefit information from Topic 1, which may prove challenging to obtain.	Same as Topic 1	Enables more precise estimation of benefits associated with a particular project under consideration, by including predictor variables in the models. As with Topic 1, each CV strategy is treated separately.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
3. **Cost** analysis of CV deployments by strategy type from an agency perspective, using cost information associated with past deployments of the same strategies.	This topic requires detailed cost information, which is not always reported by agencies following pilot deployments. When this happens, the information must be requested or tracked down before it can be aggregated and analyzed. Transit and freight fleet data (anticipated to be among the first datasets available) may provide initial insights into the costs for select CV strategies. Data spanning a broader range of strategies are anticipated from FHWA's CV Pilots Deployment Project in 2015-2017. Additional data will be incorporated on an ongoing basis as agencies deploy V2I and V2V.	• USDOT OST-R (see Topic 1). • FHWA (see Topic 1). • Major transit operators in the U.S. (such as LA Metro or New York MTA), as they are expected to be early adopters of CV technologies. • Major freight fleet managers in the U.S., as they are expected to be early adopters of CV technologies.	Allows for approximate cost estimation for budgeting and funding purposes. Economic analysis of CV deployments is also possible in conjunction with estimated benefits for the strategies under consideration.
4. Analysis of suitable **predictor variables for the costs** associated with CV deployments by strategy type from an agency perspective, using cost information associated with past deployments of the same strategies.	Generally the same as Topic 3. However, additional covariate data may need to be collected alongside the cost information from Topic 3, which may prove challenging to obtain. There is potential for data sharing between this research topic and the earlier analysis of predictor variables for benefit categories (see Topic 2). More detailed cost information may be needed for this topic than for Topic 3.	Same as Topic 3	Enables more precise estimation of costs associated with a particular project under consideration, by including independent predictor variables in the models. As with Topic 3, each CV strategy type is treated separately.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
5. C/AV adoption/penetration rate analysis based initially on user surveys/focus groups in conjunction with cost forecasts for in-vehicle equipment. These results would subsequently be used to inform surveys of the public regarding acceptance and adoption of such technologies, as a source for forecasts of market penetration and end user cost trends for specific C/AV technologies. Over time, these projections can be supplemented by data from automobile OEMs regarding actual purchase rates for C/AV-equipped and non-equipped vehicles.	Data regarding purchasing rates for C/AV-equipped and non-equipped vehicles will become available in the coming years, as automobile manufacturers have already begun to include C/AV technology offerings in their vehicle lineups. Cost forecasts for C/AV technologies must be gathered by the researchers as well. This topic will also benefit greatly from driver survey data regarding C/AV perceptions and desirability, which are already available from U.S. DOT Connected Vehicle Safety Pilot Driver Acceptance Clinics. Researchers may perform additional surveys to augment this dataset as needed, to enable evaluation and forecasting of penetration rates for individual C/AV technologies. This is essential, as it is reasonable to expect that public perceptions and reactions to different types of C/AV equipment will depend on the specific details of each technology, which suggests that the true C/AV adoption and penetration rates will be technology-specific.	• The Crash Avoidance Metrics Partnership (CAMP)—this consortium has already taken the lead on other connected vehicle analyses, and the high representation of automobile manufacturers in its membership makes it well suited for working with OEMs to conduct CV adoption analyses. CAMP was also involved with the Connected Vehicle Safety Pilot Driver Acceptance Clinics. • FHWA and U.S. DOT, as they sponsored the similar investigations of driver response through other projects and the Connected Vehicle Safety Pilot Driver Acceptance Clinics.	Enables more precise forecasting of anticipated benefits associated with different C/AV strategies by providing more reliable estimates of C/AV penetration rates.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
6. Analysis of **methods and algorithms for modeling macroscopic impacts** (including capacity gains) of C/AV strategies in travel demand models and HCM/deterministic tools using higher-level roadway and traffic characteristics, for different levels of C/AV penetration rates, using parameters (e.g., car following distance, reaction time, gap acceptance) from the C/AV systems designed and sold by automobile manufacturers.	Data from large-scale deployments and field tests will be useful for assessing the capacity and operational impacts of connected vehicles on the traffic stream and on various transportation facilities. Data anticipated from FHWA's CV Pilots Deployment Project in 2015-2017 thus will be highly relevant. Additional data can be collected and incorporated on an ongoing basis. Modeling of these impacts will likely require new models or significant modifications to existing ones, and may also require substantial amounts of covariate data and measured outcomes from pilot deployments for both calibration and validation. The effort to collect and prepare these data may be significant.	• National Cooperative Highway Research Program (NCHRP) and TRB, as common bridges between researchers and practitioners, are well positioned for developing new models to capture the large-scale impacts of connected vehicles on traffic.	Before the impacts of C/AV technology can be incorporated into travel demand models or HCM/deterministic tools, their impacts as a function of other variables must be well understood. By exploring and evaluating such models separately for individual connected vehicle strategies, this research topic supports the availability of such models for later incorporation into existing commercial transportation demand models (see Topic 7) and into HCM/deterministic tools as well (see Topic 8).

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
7. **Methods and techniques for including C/AV impacts in travel demand models**, with customizable parameters (e.g., penetration rates) and the ability to enable or disable specific C/AV strategies. This includes an analysis of the **accuracy** of these methods through comparison to other, more precise models (e.g., traffic simulation software) and **comparison to real-world** before-and-after data from large-scale deployments. Recommendations regarding the modeling viability and best approach for each strategy based on the accuracy would also be provide.	It is a significant effort to change the underpinnings of travel demand models to include the impacts of a wide range of C/AV strategies, with each one potentially requiring its own model. Models must first be developed (see Topic 6) before they can be considered for inclusion in software packages, possibly through plug-ins, extensions, or fundamental changes to the software core. Furthermore, an understanding of mode choice behavior in the context of C/AV applications (see Topic 16) is expected to be integral to accurately capturing their impacts in travel demand models. Developing and validating the underlying models involves collecting and preparing the necessary real-world data, requiring substantial effort by researchers and agencies. It is also possible that different data sets will be needed for each of the C/AV strategies. These data will become available over time as C/AV technology becomes more prevalent in coming decades.	• TRB and the Strategic Highway Research Program (SHRP2) implementation program, which may begin including requirements for consideration of C/AV strategies in planning documents, proposals, etc. as a mechanism for encouraging software makers to include such functions in their offerings. TRB is also a common bridge between researchers and practitioners and a frequent provider of model validation efforts. • FHWA, as a major sponsor of CV-related research and one of the agencies leading the early deployments of C/AV strategies. • Software developers, as they will be best suited to incorporating these models into their own software offerings.	This research topic focuses on getting the analysis methods and models identified previously for C/AV strategy operational and capacity impacts (see Topic 6) integrated into the software used by planners and practitioners for forecasting, programming, planning, and other functions. It also focuses on reliability of the modeling results, which can be affected by both the underlying theoretical model and the method of implementing it in the software. Consequently, this research topic also examines the overall model outputs to assess how reliably they align with microsimulation results and real-world datasets regarding connected vehicle technology, as a validation procedure for modeling C/AV strategies in travel demand models.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
8. Investigation into **methods and techniques for including the capacity improvements associated with various C/AV strategies into deterministic analysis tools.** The effects of each strategy will need to be treated separately so that the tools can be used for facility and project analyses based on a specific set of C/AV strategies under consideration for that facility/project.	This research topic requires as an input the models from Topic 6. For tractability, this topic is not simultaneously concerned with identifying or validating the underlying models (see Topic 6). HCM methods generally seek a balance between precision and simplicity of procedures, such that a method for incorporating a potentially wide range of C/AV strategies may be challenging.	• The TRB and HCM) subcommittee, as they have been key leaders in the development and advancement of deterministic analysis methods to date.	In this research topic, researchers take the models for capacity and performance impacts associated with C/AV strategies (see Topic 6) and modify or adapt them to make them suitable and compatible with existing HCM methods and techniques to the greatest extent possible. This leads naturally to Topics 9 and 10, which focus on incorporating these models into the HCM.
9. Modification of **signal timing optimization procedures** to include the capacity impacts of specific C/AV strategies identified in Topic 8.	Once suitable methods have been identified in Topic 8, this topic is concerned with implementing those methods and publishing the necessary modifications to the HCM and documenting the associated procedures. Software components of the HCM must be updated as well.	Same as Topic 8.	This research topic focuses on getting the analysis methods and models identified previously for C/AV strategy capacity and performance impacts (see Topic 8) integrated into the HCM signal timing optimization procedures used by planners and practitioners.
10. Modification of HCM performance analysis procedures to include the capacity impacts of specific C/AV strategies identified in Topic 8.	Same as Topic 9 (this research topic can be done in parallel with Topic 9).	Same as Topic 8.	This research topic focuses on getting the analysis methods and models identified previously for C/AV strategy capacity and performance impacts (see Topic 8) integrated into the HCM performance analysis procedures used by planners and practitioners.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
11. Analysis of the **safety impacts** associated with various C/AV strategies (e.g., curve speed warnings, blind spot warnings), as well as the best methods for modeling these impacts. The first wave of C/AV applications entering the market now focuses on safety applications rather than automated driving systems or strategies primarily oriented toward capacity improvements. These include rear-end collision warnings, lane changing assistance, and intersection movement guidance/warnings.	Incidents are rare events, and as such, a large portion of this research effort will likely focus on obtaining a sufficiently large sample of crash data and associated covariate data. Obtaining these necessary data will likely require large-scale deployments of C/AV technology across several facility types spanning various traffic conditions. Such data will potentially be available from the U.S. DOT Connected Vehicle Safety Pilot Program in 2012-2013, with additional data anticipated from FHWA's CV Pilots Deployment Project in 2015-2017. Additional data are expected to be collected and incorporated on an ongoing basis. This research topic focuses only on direct safety benefits, such as reductions in incident severity or frequency. Other secondary benefits, such as delay savings, travel time reliability improvements, and emissions reductions that occur as a result of reduced incident severity, occurrence, or duration are beyond the scope of this research topic, as these secondary effects are already well documented and understood in existing literature. (Tools for Operations Benefit Cost Analysis) An additional challenge associated with this topic is that the models must be designed in such a way that they are suitable for—and compatible with—existing methods and frameworks (e.g., time interval constraints, available input parameters, expected outputs).	• The TRB. • FHWA and U.S. DOT are good candidates, given their sponsorship of similar benefits assessments in the past and their involvement with several early C/AV pilot deployments. • CAMP, which has played a major role to date in the investigation of safety impacts of C/AV strategies.	This research topic focuses on identifying methods for modeling the safety impacts of C/AV technologies so that those indirect performance impacts can subsequently be incorporated into the HCM analysis tools (see Topic 12). This would be focused on evaluating and analyzing the distribution of the level of benefit achieved separately for each of the various C/AV strategies. Whenever possible, this research topic would also explore the relationship between level of benefit and other predictor covariates, such as penetration rate or level of congestion. Congestion leads to reduced travel time reliability and higher occurrence of incident-related delays. As C/AV strategies have the ability to both reduce incident occurrence and increase capacity (thereby reducing the prevalence of conditions that make incidents more likely), they can be expected to improve facility performance indirectly through reductions in incident-related delays.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
12. Modification of performance analysis procedures to include the safety impacts of the specific C/AV strategies examined in Topic 11.	Once suitable models have been identified in Topic 11, this current activity is concerned with implementing, publishing, and reviewing the necessary modifications to the HCM and documenting the associated procedures. Software components of the HCM must be updated as well. This topic, therefore, will depend upon the outcomes from Topic 11.	• The TRB and HCM subcommittee, as they have been key leaders in the development and advancement of deterministic analysis methods to date.	This research topic takes the collision/incident reduction models from Topic 11 and integrates them into the HCM tools so that the performance benefits associated with these incident reduction rates can be captured in HCM analyses.
13. Analysis of lane changing and car following behavior that arises with C/AV technologies enabled, for different penetration rates.	Much of the data required for this research topic are already available: algorithm parameters and logic for lane changing and car following systems from automobile manufacturers and their C/AV in-vehicle systems, and existing lane changing and car following models from microsimulation software. This research topic would largely focus on merging these separate data sources in a coherent and reasonable way. Validation of these models will be performed in Topic 14, and is therefore beyond the scope of the current research topic.	• FHWA, as it has already taken the lead on projects such as Next Generation SIMulation (NGSIM) to validate microsimulation model car following and lane changing behavioral algorithms. • Traffic simulation software developers, as they will be the ones who ultimately benefit from the improved/enhanced models, through increased sales to MPOs and other transportation agencies that require such modeling and analysis capabilities.	Lane changing and car following algorithms are a core element of microsimulation models, making them strategically positioned to simulate the impacts of C/AV strategies (see Topic 14) if the impacts of these C/AV technologies can be properly translated into changes to car following and lane changing behavior. This research topic makes such changes possible by exploring the effects that C/AV deployment would have on these behaviors. Although empirical data are relevant for validation of the models and their predicted effects (see Topic 14), the primary objective of this task is to develop the theoretical models (including parameters and model structures) necessary to enable modeling of C/AV operations in microsimulation models.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
14. Building **native support** for C/AV operations in commercial **simulation software** packages, with customizable parameters (e.g., penetration rates) and the ability to enable or disable specific C/AV strategies.	This research topic will use the outcomes from Topic 13, which focused on lane changing and car following models. Input will be required from automobile manufacturers and V2I OEMs regarding the basic specifications of their equipment, such as default following distances or signal timing algorithms based on V2I communications; these inputs are anticipated to be available incoming years, as equipment manufacturers begin to develop mature product designs with these parameters specified. Although making software modifications to gap acceptance, car following, and similar algorithms is not an excessively challenging task, other modifications must be made to the software as well, which could contribute significantly to the effort required to complete this research topic. For example, signal operations may need to be updated to include consideration of vehicles equipped with C/AV technology, while additional parameters may need to be added for specifying driver acceptance/response behaviors. This research topic will also rely on empirical data from past and future C/AV deployments to perform validation of the simulated outcomes associated with C/AV applications, as predicted by microsimulation models.	• FHWA (see Topic 13). • Traffic simulation software developers (see Topic 13). • TRB and the SHRP2 research program, which may begin including requirements for consideration of C/AV strategies in operations plans, strategies, frameworks, proposals, etc. as a mechanism for encouraging software developers to include such functions in their offerings.	Microsimulation models are well suited for evaluating the anticipated impacts of C/AV deployments for various penetration rates. This research topic puts these analysis tools in the hands of practitioners, researchers, and agencies who are already using microsimulation tools in their workflows and analyses.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
15. Building native support for **aerodynamic impacts** of C/AV operations in commercial simulation software, as an extension of the C/AV operations described above.	Aerodynamic models exist that can accomplish these objectives already, as do the traffic simulation models that would need to be integrated with them. However, the data to validate these models will not be available until sufficient data on the fuel savings and aerodynamics of platooning via C/AV technologies are collected. Furthermore, existing models may prove inadequate for the purposes of this research topic, thereby necessitating the development of new methods and models for estimating the impacts of aerodynamics in the specific context of microscopic traffic simulators.	• Automobile manufacturers, who already perform aerodynamic analyses of their own vehicles and would be able to provide valuable insight into and experience with this research topic. The Volvo group, for example, has already modeled and analyzed the impacts of connected vehicles on fuel economy at highway speeds. (Jan Hellaker, Christian Grante, Stefan Bergqvist. *EARP Topic 1D – Partial Automation for Truck Platooning.* Volvo Group Advanced Technology and Research (Presentation).) • FHWA, as it has already sponsored initial efforts to analyze the aerodynamics of vehicle platoons at close spacings and the resultant impacts on fuel economy. (Steven Shladover. *EARP Topic 1D – Partial Automation for Truck Platooning: Project Work Plan.* University of California PATH Program (Presentation). December 6, 2013.) • Traffic simulation software developers (see Topic 13).	Fuel savings and emissions reductions obtained through C/AV technologies can be more precisely estimated through vehicle-level simulations than through other higher-level analysis tools. This research topic enables such fuel consumption and emissions analyses by taking into consideration the impacts of closer vehicle headways on fuel economy.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
16. Analysis of **driver behavior, response, and acceptance** in connection with in-vehicle C/AV technologies. This includes both an assessment of **mode choice** preferences with respect to various penetration rates (which affect utility) and cost points and an analysis of driver reactions to warnings, information, and other data/outputs provided by C/AV systems.	The necessary data for this analysis can be obtained through surveys, driver simulators, field tests, and other localized data gathering. Suitable driving simulators are available, and the concepts that drivers will be presented with during surveys and simulations are already becoming familiar to them via mainstream media and automobile manufacturers. Data on driver acceptance and response to C/AV systems may also be extracted from existing datasets such as the U.S. DOT Connected Vehicle Safety Pilot Driver Acceptance Clinics. These data may be used to augment data collected by the researchers for this effort. Integration of these data into existing mode choice models is not expected to be excessively challenging, as these models are mature, well understood, and capable of handling new or hypothetical alternatives.	• FHWA, as it has sponsored similar investigations of driver behavior and response in other projects (for example, the San Diego Integrated Corridor Management Analysis, Modeling and Simulation Project (ICM AMS). • NCHRP and TRB as common bridges between researchers and practitioners with the depths of resources and funds to accomplish such a research topic; furthermore, a signification portion of TRB's membership is already focused on driver behavior and human interface/factors design. • Major metropolitan planning organizations and other agencies responsible for long-term planning.	This research topic enables more accurate representation of C/AV outcomes by incorporating the driver response element along with more precise mode choice modeling. This enables analysts to more reliably represent the mode split between connected vehicles and other transportation options in their models and to more accurately model driver behaviors and reactions, which is particularly relevant to Topic 7. Each C/AV application will likely need to be analyzed separately, as it is not expected that driver response will be invariant across the different application types.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
17. Inclusion of **communications and sensing aspects of specific C/AV technologies in commercial simulation software**, for performing virtual load testing, bandwidth needs analyses, and scenario analyses (e.g., equipment failures, comparisons of different V2I equipment placement strategies).	Software already exists to support the simulation of different vehicle hardware components including onboard sensors, and conventional traffic simulation software has the capability of being extended through plugins or application programming interfaces (APIs) to enable the needed enhancements for simulating C/AV equipment. However, although these capabilities exist, the level of effort required to develop these tools and implement them is not trivial. Furthermore, if validation were desired using real-world data, the identification or collection of suitable datasets would require a significant additional effort.	• CAMP, as it has already led an effort to use simulation software and detailed real-world traffic data to estimate the number of vehicles within range of V2I roadside units for different facilities. • Traffic simulation software developers, as they will be the ones who ultimately benefit from the improved/enhanced models, through increased sales to MPOs and other transportation agencies that require such modeling and analysis capabilities.	Researchers will be concerned not only with the operational and capacity impacts of C/AV technology, but also the demands that such technologies will place on V2I, V2V and I2V equipment. This research topic enables researchers to analyze the potential loads placed on various pieces of field equipment, leading to potential use as an optimization tool for equipment placement and specifications development. Sensor-level simulation capabilities also allow researchers to examine the impacts of component failures and various scenarios that might arise.
18. Development of tools that provide **decision support** for various operational activities that can be **informed by C/AV data,** including maintenance scheduling, dynamic fleet rerouting, and incident detection/management.	Decision support tools already exist already and would only require updating to include data from C/AV systems; however, additional research may be required to evaluate the best methods for aggregating the data and transforming them into a format that is relevant to each decision support tool, as well as modifying the tools themselves to accommodate these new data streams. Regarding the required input data, real-world data feeds for these applications will become available only as C/AV technologies are deployed. Such data will potentially be available from the U.S. DOT Connected Vehicle Safety Pilot Program in 2012-2013, with additional data anticipated from FHWA's CV Pilots Deployment Project in 2015-2017. Transit and freight fleet data (anticipated to be among the first datasets available) may prove to be valuable initial probe vehicle datasets to support this research topic, though their penetration rate (as a fraction of the entire traffic stream) will be limited.	• AASHTO, as a unifying organization for State DOTs, who are expected to already have their own decision support systems and workflows for specific purposes. • FHWA, as a consistent sponsor of the development of decision support tools (e.g., the incident management component from the San Diego ICM project).	This research topic takes advantage of the large volume of data that are expected to accompany the deployment of C/AV technology in coming years by utilizing these data to inform both real-time operational decisions and offline planning/logistics.

Research Topic	Resource Needs and Availability	Potential Lead Organizations	Relevance
19. Establish a **modeling framework/methodology for capturing C/AV impacts and outcomes** in existing analysis tools. This would include assessment of which strategies are reliably captured by each analysis tool category and the recommended methods for representing each of those strategies.	This research topic depends on much of the experience and knowledge obtained from research Topics 1 through 17, which focus on updating various aspects of analysis tools to include C/AV strategy impacts and outcomes. The researchers will likely need to conduct comparative studies of different analysis methods and tools in those situations where sufficient data are not already available to enable recommendations regarding the suitability of various analysis/modeling approaches by strategy and context (e.g., facility type).	• The TRB, as it is a significant, consistent contributor to modeling guidance (e.g., the traffic simulation subcommittee). • FHWA and U.S. DOT are good candidates, given their potential sponsorship of the majority of the individual research topics (i.e., Topics 1 through 17) that would inform this one.	The core objectives of this topic are: to synthesize the outcomes and results from all of the preceding research topics into a coherent, consistent, and rational analysis framework; and to identify any new/unresolved research needs and gaps that require additional work and attention, along with potential strategies for addressing them. This research topic unifies the preceding ones that target individual analysis and data needs and provides overall direction for analysts and practitioners regarding the best methods and techniques for analyzing the outcomes and effects of C/AV strategies. It is largely focused on aggregating all insights obtained, lessons learned, best practices identified, and contributions to the state of practice from all other tool enhancements and modifications associated with C/AV strategy analysis. The expected outcome from this research topic is in many ways a C/AV analogue to FHWA's Traffic Analysis Toolbox, in that it: promotes consistency of techniques, methods and criteria; consolidates a breadth of knowledge on a particular subject into a single reference resource; and provides best practices and general guidance for a wide range of common analyses.

Source: Cambridge Systematics, Inc.

5.2 Research Topic Prioritization

This section establishes a suggested priority classification for each research topic, based on the topic's breadth, relevance to other topics in the roadmap, and impact on C/AV modeling capabilities.

Background and Prioritization Criteria

There is an inherent hierarchy to the research topics with respect to their dependencies, the expected breadth of their results, and the extent to which the topic's outcomes address the objectives established in Chapter 1. Consequently, it is reasonable to assign different priority levels to each of the research topics, based on which are anticipated to have broader impacts on the ability and availability of tools to model and analyze the impacts of C/AVs and on which ones provide required inputs, data, or necessary resources to other research topics. More precisely, qualitative prioritization guidance for the 19 research topics described in Table 5-1 is provided based on the following criteria:

- **TOOL CATEGORIES IMPACTED:** The topic's breadth of relevance, reflected by the number of analysis tool types to which the research topic applies.
- **OTHER DEPENDENT TOPICS:** The degree to which the research topic informs or applies to other topics.
- **SIGNIFICANCE LEVEL:** The extent to which the research topic enables or enhances C/AV analysis capabilities for the associated tool types.

Following the above criteria, each research topic is assigned to one of two priority levels:

- **FIRST PRIORITY TOPICS:** the ones that need to be done first because they are prerequisites for other research topics and/or are very broadly impactful, and do not themselves require many inputs from other research topics.
- **SECOND PRIORITY TOPICS:** the ones that require inputs from other research topics before they can be initiated, or are relatively narrow in scope.

Prioritization Results

The results of this qualitative prioritization process are shown in Table 5-2. This table also provides details regarding each of the three evaluation criteria listed above.

Table 5-2. Priority Classification for Each Research Topic

Research Topic (Summarized)	Tool Categories Impacted—*Sketch Planning Tools*	Tool Categories Impacted—*HCM Tools*	Tool Categories Impacted—*Travel Demand Models*	Tool Categories Impacted—*Traffic Sim. Tools*	Significance of This Research Topic for Enabling C/AV Analysis	Topics That Depend on This One	Overall Priority Level *(1=Highest)*
1. Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates.	Yes				Sketch planning tools are widely used for initial project filtering, screening, and analysis.	Topic 2	Level **1**
2. Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments.	Yes				This research topic supplements benefit estimation at a sketch-planning level.	*None*	Level **2**
3. Cost analysis of C/AV strategies from an agency perspective, informed by past C/AV deployments.	Yes				Sketch planning tools are widely used for initial project filtering, screening, and analysis.	Topic 4	Level **1**
4. Analysis of suitable predictor variables for C/AV costs of Topic 3, informed by past C/AV deployments.	Yes				This research topic supplements cost estimation at a sketch-planning level.	*None*	Level **2**
5. Penetration rate analysis for C/AV technology, including forecasts of costs and adoption rates.	Yes	Yes	Yes	Yes	Essential to accurately estimating the extent to which the benefits of each strategy will be realized.	*None*	Level **1**
6. Methods and algorithms for modeling macroscopic impacts of C/AV strategies for application to TDM and HCM tools.		Yes	Yes		Travel Demand Models and HCM/Deterministic tools cannot include C/AV considerations without this research topic.	Topics 7, 8, 9, and 10	Level **1**
7. Incorporating results from Topic 6 into TDM; validation using real-world data and microsimulation methods.			Yes		Travel Demand Models cannot include capacity-influencing C/AV effects without this research topic.	*None*	Level **2**

Research Topic (Summarized)	Tool Categories Impacted—*Sketch Planning Tools*	Tool Categories Impacted—*HCM Tools*	Tool Categories Impacted—*Travel Demand Models*	Tool Categories Impacted—*Traffic Sim. Tools*	Significance of This Research Topic for Enabling C/AV Analysis	Topics That Depend on This One	Overall Priority Level *(1=Highest)*
8. Methods for including capacity impacts of individual C/AV strategies in HCM tools, using models developed in Topic 6.		Yes			Deterministic tools cannot include capacity-influencing C/AV effects without this research topic.	Topics 9 and 10	Level **2**
9. Updating HCM signal timing optimization procedures to include C/AV capacity impacts from Topic 8.		Yes			This research topic enhances a specific subset of HCM tools only.	*None*	Level **2**
10. Updating HCM performance analysis procedures to include C/AV capacity impacts from Topic 8.		Yes			This research topic enhances a specific subset of deterministic tools only.	*None*	Level **2**
11. Analysis of safety impacts of C/AV strategies; best methods for modeling these impacts.		Yes			Safety impacts are only a subset of the total impacts associated with C/AVs.	Topic 12	Level **2**
12. Modification of HCM performance analysis methods to include C/AV safety impacts from Topic 11.		Yes			Safety impacts are only a subset of the total impacts associated with C/AVs.	*None*	Level **2**
13. Analysis of lane changing and car-following behavior associated with C/AV strategies/technologies.				Yes	Enables more realistic modeling of C/AV operations in simulation models.	Topics 14 and 15	Level **2**
14. Adding support for C/AV operations of individual strategies into microsimulation software packages.				Yes	Enables more realistic modeling of C/AV operations in simulation models.	Topic 15	Level **2**

Research Topic (Summarized)	Tool Categories Impacted—*Sketch Planning Tools*	Tool Categories Impacted—*HCM Tools*	Tool Categories Impacted—*Travel Demand Models*	Tool Categories Impacted—*Traffic Sim. Tools*	Significance of This Research Topic for Enabling C/AV Analysis	Topics That Depend on This One	Overall Priority Level *(1=Highest)*
15. Adding support for modeling aerodynamic effects of C/AV into microsimulation software packages.				Yes	This research topic focuses on enabling more accurate estimation of specific benefit category outcomes for simulation models.	*None*	Level **2**
16. Analysis of driver response to and acceptance of C/AV strategies, including C/AV mode choice analysis.	Yes	Yes	Yes	Yes	Mode choice and driver acceptance of C/AV technologies are both crucial to accurately modeling the anticipated impacts of C/AV strategies.	Topic 7	Level **1**
17. Adding support for communications and sensor modeling of C/AV technologies into microsimulation.				Yes	This research topic focuses on modeling specific aspects of C/AV technology in simulation models.	*None*	Level **1**
18. Decision support tools informed by C/AV data; modifying existing tools, and developing new ones as needed.					This research topic enhances decision support tools with additional data, but does not provide analysis support for C/AV technology.	*None*	Level **2**
19. Comprehensive modeling framework or methodology for C/AV strategies; guidance regarding best practices.	Yes	Yes	Yes	Yes	This research topic establishes modeling and analysis guidance for planners, operators, and practitioners.	*None*	Level **1**

Source: Cambridge Systematics, Inc.

5.3 Schedule for the Research Roadmap

This section provides an overview of the expected timing for each of the research topics in the proposed roadmap, as shown in Figure 5-1. This research roadmap is designed to be a rational, tractable, and structured approach for addressing all of the needs and gaps identified in Chapter 4, and for providing 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. It has not yet been formally adopted or funded, and as such, the contents of this roadmap (including scope and timing) are tentative and subject to change.

The start time for a given research topic is based on the expected availability of required data to support the topic (see Table 5-1, "Resource Needs and Availability" column), and on the timing of other pre-requisite research topics on which the given topic depends (see Table 5-2). 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 (see Table 5-1, "Resource Needs and Availability" column). The "approximate level of effort" color labels in the figure facilitate rapid identification of the research tasks that have the shortest (green) and longest (red) durations, and are consequently expected to require relatively less or more resources to complete.

Unless otherwise noted, all research topics are also expected to require an additional 6-12 months for project development, including preparation of a request for proposal, collection of proposals, evaluation of received materials, negotiation with most promising candidates, and notification of awards.

Ongoing Nature of the Research Topics

The end dates for each research topic in Figure 5-1 are defined by their estimated start dates and durations, and are intended to suggest when initial results might be expected from those topics; they should not be interpreted as the final dates that any work would be performed on each of those topics. 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.

All of the research topics described in this chapter are concerned with CV technologies and applications; however, most are also expected to include AV considerations as well. Any research topics for which AV technology is relevant are indicated in Table 5-3, which furthermore provides information about the particular levels of automation that are expected to apply. Whenever one or more levels of automation are indicated for a given research topic, it is expected that those topics would be revisited and updated after each level of automation is achieved for relevant vehicle fleets (transit, freight, private automobile, etc.). Additional information about AV technologies and automation levels is provided in Chapter 1 and Figure 1-1.

For example, empirical data obtained from the FHWA Connected Vehicle Pilots Deployment Project waves in 2015 and 2017 will be highly relevant to several of the research topics (see Table 5-3, with emphasis on the columns for "Level 0" and "Level 1"), and 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 end date for that topic as shown in Figure 5-1 occurs prior to the release of these datasets.

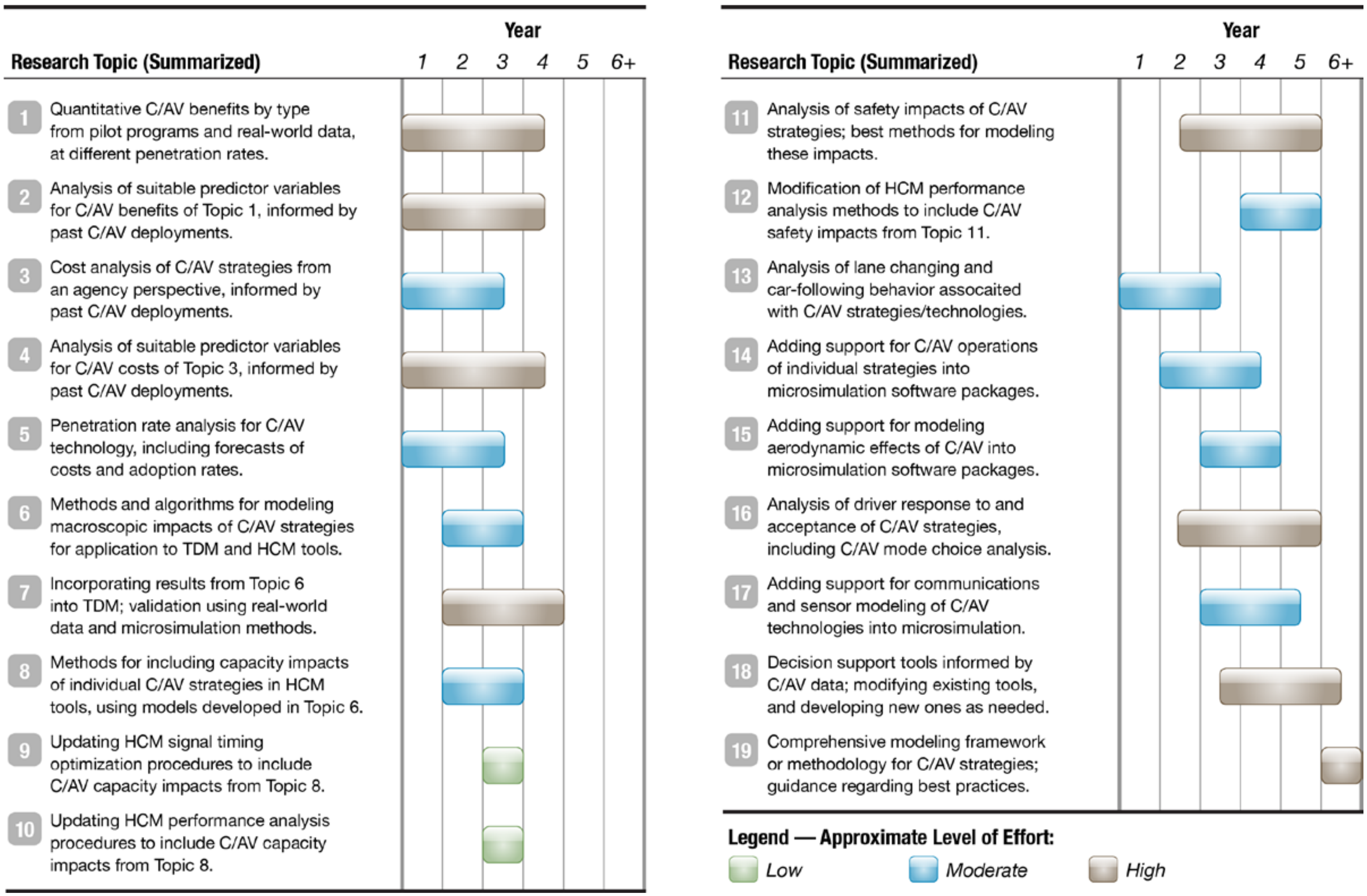


Figure 5-1. Graphic. Research roadmap for incorporating connected vehicles into analysis tool capabilities and datasets

(Source: Cambridge Systematics, Inc.)

Table 5-3. Autonomous Vehicle Levels of Automation that Apply to Each Research Topic

Research Topic (Summarized)	**Level 0:** *Driver Warning Systems*	**Level 1:** *Isolated Driver Functions Automated*	**Level 2:** *Several Driver Functions Automated*	**Level 3:** *Limited Self-Driving Capability*	**Level 4:** *Fully Self-Driving Operation*
1. Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates.	Yes	Yes	Yes	Yes	Yes
2. Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments.	Yes	Yes	Yes	Yes	Yes
3. Cost analysis of C/AV strategies from an agency perspective, informed by past C/AV deployments.					
4. Analysis of suitable predictor variables for C/AV costs of Topic 3, informed by past C/AV deployments.					
5. Penetration rate analysis for C/AV technology, including forecasts of costs and adoption rates.	Yes	Yes	Yes	Yes	Yes
6. Methods and algorithms for modeling macroscopic impacts of C/AV strategies for application to TDM and HCM tools.				Yes	Yes
7. Incorporating results from Topic 6 into TDM; validation using real-world data and microsimulation methods.				Yes	Yes
8. Methods for including capacity impacts of individual C/AV strategies in HCM tools, using models developed in Topic 6.				Yes	Yes
9. Updating HCM signal timing optimization procedures to include C/AV capacity impacts from Topic 8.					Yes
10. Updating HCM performance analysis procedures to include C/AV capacity impacts from Topic 8.				Yes	Yes

Research Topic (Summarized)	**Level 0:** *Driver Warning Systems*	**Level 1:** *Isolated Driver Functions Automated*	**Level 2:** *Several Driver Functions Automated*	**Level 3:** *Limited Self-Driving Capability*	**Level 4:** *Fully Self-Driving Operation*
11. Analysis of safety impacts of C/AV strategies; best methods for modeling these impacts.	Yes	Yes	Yes		
12. Modification of HCM performance analysis methods to include C/AV safety impacts from Topic 11.	Yes	Yes	Yes		
13. Analysis of lane changing and car-following behavior associated with C/AV strategies/technologies.				Yes	Yes
14. Adding support for C/AV operations of individual strategies into microsimulation software packages.					
15. Adding support for modeling aerodynamic effects of C/AV into microsimulation software packages.					
16. Analysis of driver response to and acceptance of C/AV strategies, including C/AV mode choice analysis.	Yes	Yes	Yes	Yes	Yes
17. Adding support for communications and sensor modeling of C/AV technologies into microsimulation.				Yes	Yes
18. Decision support tools informed by C/AV data; modifying existing tools, and developing new ones as needed.					
19. Comprehensive modeling framework or methodology for C/AV strategies; guidance regarding best practices.	Yes	Yes	Yes	Yes	Yes

Source: Cambridge Systematics, Inc.

Note: The relevance of the various research topics to each of the five NHTSA levels of automation considers both autonomous vehicle technologies (i.e., AVs) and automation achieved through connected vehicle technologies (i.e., automation of CVs). Current research indicates that significant safety and mobility benefits will be achieved through a connected vehicle environment at NHTSA Levels 1 and 2 of vehicle automation. The amount of benefits achieved at NHTSA Levels 3 and 4 are subject to more detailed study.

5.4 Benefit Types Captured by Each Research Topic

Table 5-4 provides additional detail regarding the scope of each research topic with respect to the C/AV impacts that it is intended to capture. When considered in conjunction with Table 5-2, this table establishes how the various research topics target the performance measures associated with C/AV applications for each analysis tool type. This illustrates both the relevance and usefulness of each research topic in achieving the fundamental objectives of the research roadmap. The different categories of C/AV impacts listed in Table 5-4 include:

- Mobility measures, including vehicle speeds, travel times, and delays.
- Travel time reliability measures, such as Travel Time Index.
- Capacity measures, including maximum achievable density, throughput, or transit occupancies.
- Emissions.
- Fuel consumption.
- Incident measures, including occurrence of primary incidents, occurrence of secondary incidents, duration, and severity.
- Costs, including both agency-incurred and user-incurred costs.
- Traveler behavior, including mode split.

Institutional Benefits

In addition to the benefit classes listed above, there are also institutional benefits associated with one research topic in particular: Topic 18. Unlike the majority of the research topics in the roadmap, which are directly concerned with capturing the effects of C/AV applications on various aspects of facility performance, this topic explores the development of new tools intended to enable agencies and institutions to take advantage of the increased availability of field data that is expected to occur as CV technologies are deployed. This is further illustrated in Table 5-2, which indicates that Topic 18 is not intended to have any direct impacts on the analysis capabilities of any of the four classes of planning tools.

Topic 18 offers several key benefits to agencies in particular, given its central objective of using C/AV data from probe vehicles as a valuable new source of information for their responsibilities and activities. For example, such probe data might prove useful as a supplement for speed/congestion measurements at various points on the network, or for monitoring of pavement data quality as part of a maintenance-needs assessment and prioritization program. It is expected that, as these new data streams become available with the deployment of CV technologies and equipment in the field, additional applications of these data will become apparent that were not predicted in advance; consequently, one of the ongoing objectives associated with Topic 18 is a regular reassessment of the various agency functions and activities that these data might have relevance to.

Table 5-4. Connected/Autonomous Vehicle Impacts Captured or Included in Each Research Topic

Research Topic (Summarized)	Mobility	Reliability	Capacity	Emissions	Fuel Usage	Safety	Costs	Traveler Behavior
1. Quantitative C/AV benefits by type from pilot programs and real world data, at different penetration rates.	Yes	Yes	Yes	Yes	Yes	Yes		
2. Analysis of suitable predictor variables for C/AV benefits of Topic 1, informed by past C/AV deployments.	Yes	Yes	Yes	Yes	Yes	Yes		
3. Cost analysis of C/AV strategies from an agency perspective, informed by past C/AV deployments.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
4. Analysis of suitable predictor variables for C/AV costs of Topic 3, informed by past C/AV deployments.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
5. Penetration rate analysis for C/AV technology, including forecasts of costs and adoption rates.	Yes	Yes	Yes	Yes	Yes	Yes	Yes (National Connected Vehicle Field Infrastructure Footprint Analysis, AASHTO, Executive Summary, 2014, pp. 7-9.)	Yes
6. Methods and algorithms for modeling macroscopic impacts of C/AV strategies for application to TDM and HCM tools.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
7. Incorporating results from Topic 6 into TDM; validation using real-world data and microsimulation methods.	Yes		Yes	Yes	Yes	Yes		Yes
8. Methods for including capacity impacts of individual C/AV strategies in HCM tools, using models developed in Topic 6.	Yes		Yes					

Research Topic (Summarized)	Mobility	Reliability	Capacity	Emissions	Fuel Usage	Safety	Costs	Traveler Behavior
9. Updating HCM signal timing optimization procedures to include C/AV capacity impacts from Topic 8.	Yes		Yes					
10. Updating HCM performance analysis procedures to include C/AV capacity impacts from Topic 8.	Yes		Yes					
11. Analysis of safety impacts of C/AV strategies; best methods for modeling these impacts.						Yes		
12. Modification of HCM performance analysis methods to include C/AV safety impacts from Topic 11.						Yes		
13. Analysis of lane changing and car-following behavior associated with C/AV strategies/technologies.	Yes	Yes	Yes	Yes	Yes	Yes		Yes
14. Adding support for C/AV operations of individual strategies into microsimulation software packages.	Yes	Yes	Yes	Yes	Yes	Yes		Yes
15. Adding support for modeling aerodynamic effects of C/AV into microsimulation software packages.				Yes	Yes			
16. Analysis of driver response to and acceptance of C/AV strategies, including C/AV mode choice analysis.	Yes	Yes	Yes	Yes	Yes	Yes		Yes
17. Adding support for communications and sensor modeling of C/AV technologies into microsimulation.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
18. Decision support tools informed by C/AV data; modifying existing tools, and developing new ones as needed.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
19. Comprehensive modeling framework or methodology for C/AV strategies; guidance regarding best practices.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: Cambridge Systematics, Inc.

5.5 Factors Affecting the Proposed Research Topics

This section discusses two significant factors that broadly affect the proposed research tasks in some capacity: the inclusion of empirical data, and the consideration of C/AV penetration rates.

Role of Empirical Data

It is sometimes the case that a new technology or innovation in transportation has unforeseen consequences on driver behavior, facility performance, or other areas. This was observed—for example—with pedestrian countdown timers, which were intended to warn pedestrians in crosswalks about the remaining time for crossing safely, but were found to result in additional pedestrians crossing during the "don't walk" phase and the slowing of vehicles prior to the onset of the amber signal. Similarly unforeseen and unintended outcomes are expected to occur with the deployment of CV and AV applications as well. By their nature, these types of effects are best captured by a careful analysis of empirical data that are collected post-deployment. Including such data allows these tools 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 research roadmap outlined in this chapter relies significantly on such empirical data. They are used in some capacity for each topic in the research roadmap, to protect against the possibility that any unexpected or unanticipated outcomes for a particular AV/CV strategy are missed by the analysis. Types of empirical data relevant to the research roadmap include: deployment costs data, C/AV application benefits data, safety outcomes data, fuel economy data, and driver behavioral response data. The majority of research topics in the roadmap utilize these data directly as part of their specific activities. Any remaining research topics that do not directly incorporate empirical data sources (i.e., Topics 8, 9, 10, 12, 13, 14, 17, and 19) utilize the outputs and outcomes from other topics that do; in this way, every research topic in the roadmap is informed by empirical data, either directly or indirectly.

Relevance of Empirical Data by Tool Type

Empirical data play a significant role in all the research topics concerned with sketch planning tools, deterministic/HCM tools, and travel demand modeling tools. For these tools, forecasting/estimation methods may be developed to project future impacts or outcomes of C/AV applications and deployments using available empirical data from existing deployments for model selection, calibration, and validation. Trend analysis methods can be suitable and valuable techniques for the purposes of model selection development, calibration, and validation. As additional data are collected over time, these models can be further refined and recalibrated to provide greater accuracy and reliability regarding the outcomes of CV and AV applications and deployments. Some empirical data are already available regarding the outcomes of smaller-scale CV pilot deployments and limited/isolated field tests of both AVs and CVs, and it is with these data that the objectives of the research topics may be achieved initially. However, there is also an expectation that as additional data are collected and made available through the FHWA Pilot Deployments and various other CV and AV programs, these research topics will be revisited for further analysis tool refinement, modification, and development as appropriate.

The role of empirical data for the research topics concerned with microsimulation tools is more limited, as the theoretical underpinnings and frameworks for these tools are generally more dependent on individual driver behaviors and microscopic interactions than on empirical measurements of broader, higher-level macroscopic outcomes. However, this also gives microscopic simulation tools the unique advantage of being suitable for the evaluation of AV and CV strategies that have not yet been deployed—either to the extent that the analyst wishes to evaluate, or at all. While all other tools rely on empirical data to inform their modeling and forecasting capabilities directly, microscopic tools are capable of providing theoretical projections about what impacts and outcomes may occur based on assumptions about how the technologies may work, without explicitly requiring empirical data obtained from field tests or previous deployments of those technologies (though such data are still highly relevant for calibration and validation).

Empirical Data from CV Pilots Deployment Project

The empirical data on outcomes of CV applications obtained through the evaluations associated with FHWA's CV Pilots Deployment Project will be highly relevant to many of the research topics in this proposed roadmap. Therefore, the CV Pilots Deployment Program is anticipated to be an essential source of data for the research roadmap being proposed here, and is identified as a potential data source for many of the individual research topics listed in Table 5-1 (see the "Resource Needs and Availability" column). To ensure that the full potential and utility of the datasets collected from the CV Pilots Deployment Program is realized, it would be valuable to consider the data needs of this research roadmap when designing the evaluation components for each of the individual CV deployment sites. One anticipated limitation associated with the pilot deployments that should be acknowledged is that the penetration rate of equipped vehicles is expected to be relatively modest.

Table 5-5 provides a categorical listing of several candidate CV applications that are expected to be incorporated into these pilot deployments (additional applications not listed in Table 5-5 may also be incorporated into the pilot deployments). Because the intent of these deployments is to address real-world problems with CV technologies, the emphasis will be on actual implementation of the applications of Table 5-5 and on deployment of prototype applications, rather than on the provision of enabling technologies alone.

FHWA is not placing a greater emphasis on either V2V or V2I applications for these deployment pilots, although it recommends focusing on those technologies that are expected to have meaningful impacts and outcomes even at low penetration rates. Because V2I strategies are generally not dependent on communication with other vehicles by design—in contract to V2V strategies, which are dependent on other vehicles being similarly equipped—the deployment pilots may initially be expected to focus more on V2I applications (refer to Chapter 1, in the section titled, "Connected and Autonomous Vehicle Technology"). Although AV applications are not explicitly being included in the CV pilot deployments program, FHWA recognizes that AV technologies often enhance or enable specific CV applications, and consequently encourages their inclusion in the pilot deployments when relevant for the advancement or implementation of CV strategies.

Table 5-5. Connected Vehicle Applications Identified for FHWA's CV Pilots Deployment Project

Connected Vehicle Application
V2I Safety • Red Light Violation Warning • Curve Speed Warning • Stop Sign Gap Assist • Spot Weather Impact Warning • Reduced Speed/Work Zone Warning • Pedestrian in Signalized Crosswalk Warning (Transit)

Connected Vehicle Application
V2V Safety • Emergency Electronic Brake Lights (EEBL) • Forward Collision Warning (FCW) • Intersection Movement Assist (IMA) • Left Turn Assist (LTA) • Blind Spot/Lane Change Warning (BSW/LCW) • Do Not Pass Warning (DNPW) • Vehicle Turning Right in Front of Bus Warning (Transit)
Agency Data • Probe-Based Pavement Maintenance • Probe-Enabled Traffic Monitoring • Vehicle Classification-Based Traffic Studies • CV-Enabled Turning Movement and Intersection Analysis • CV-Enabled Origin-Destination Studies • Work Zone Traveler Information
Environment • Eco-Approach and Departure at Signalized Intersections • Eco-Traffic Signal Timing • Eco-Traffic Signal Priority • Connected Eco-Driving • Wireless Inductive/Resonance Charging • Eco-Lanes Management • Eco-Speed Harmonization • Eco-Cooperative Adaptive Cruise Control • Eco-Traveler Information • Eco-Ramp Metering • Low Emissions Zone Management • AFV Charging/Fueling Information • Eco-Smart Parking • Dynamic Eco-Routing (light vehicle, transit, freight) • Eco-ICM Decision Support System
Road Weather • Motorist Advisories and Warnings (MAW) • Enhanced Maintenance Decision Support System (MDSS) • Vehicle Data Translator (VDT) • Weather Response Traffic Information (WxTINFO)

Connected Vehicle Application
Mobility
• Advanced Traveler Information System • Intelligent Traffic Signal System (I-SIG) • Signal Priority (transit, freight) • Mobile Accessible Pedestrian Signal System (PED-SIG) • Emergency Vehicle Preemption (PREEMPT) • Dynamic Speed Harmonization (SPD-HARM) • Queue Warning (Q-WARN) • Cooperative Adaptive Cruise Control (CACC) • Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG) • Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) • Emergency Communications and Evacuation (EVAC) • Connection Protection (T-CONNECT) • Dynamic Transit Operations (T-DISP) • Dynamic Ridesharing (D-RIDE) • Freight-Specific Dynamic Travel Planning and Performance • Drayage Optimization
Smart Roadside
• Wireless Inspection • Smart Truck Parking

Source: United States Department of Transportation, Intelligent Transportations Systems, Joint Program Office.

Capturing the Effects of Penetration Rates

The majority of the research topics in the roadmap are designed to address the relationship between C/AV application outcomes and penetration rates in the field (note that this is generally not equivalent to market availability rates). The topics that do *not* explicitly link penetration levels to C/AV deployment outcomes are:

- Topic 5—this topic is solely concerned with penetration rate forecasting and modeling.
- Topic 15—aerodynamic models will not need to consider penetration rates directly, since the microsimulation models in which they are integrated will handle these considerations instead.
- Topic 19—this topic is more concerned with an overall analysis methodology than with models for specific C/AV impacts.

For most C/AV applications, penetration rates are expected to rise incrementally over time once the technologies become publicly available and private owners make individual purchases of C/AV-equipped vehicles over time. However, certain fleets of vehicles, such as buses or company trucks, may experience large jumps in penetration rates of C/AV technologies among its vehicles. For example, a transit agency may deploy CV technologies across all its vehicles in a single comprehensive effort. Analysis tools must be capable of accounting for these variable, time-dependent and technology-specific penetration rates if they are to be continuously relevant to practitioners and agencies.

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