Connected Vehicle Impacts on Transportation Planning

Analysis of the Need for New and Enhanced Analysis Tools, Techniques, and Data—Highway Capacity Manual Briefing

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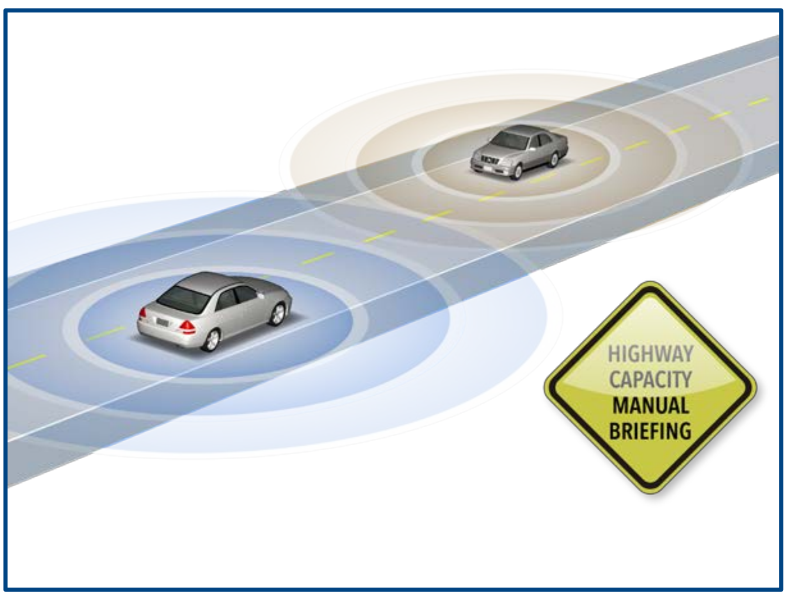
Final Report—March 2, 2016
FHWA-JPO-16-365



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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 a summary of a larger report that identified the need generated by Connected and Automated vehicle (C/AV) technology for new or enhanced tools, techniques, and data to support various C/AV planning activities and approaches for how to meet those needs. It focused on identifying enhancements to existing transportation analysis data and tools used in transportation planning that will be needed to extend those tools to accommodate C/AV impacts and outcomes in the future. This report focuses on the research and activities that will need to take place in order to adapt the Highway Capacity Manual for use in analyzing Automated and Connected Vehicles. This report includes a summary of existing data, tools, and products currently used in transportation planning processes. The next area includes an evaluation of the the suitability of the Highway Capacity Manual 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 the HCM for use in analysis of C/AV technologies. The results show that HCM used in traditional transportation planning and analysis would potentially be modified or overhauled to accommodate analyses of connected vehicle applications and technology. Finally a roadmap is provided that summarizes research topics to target these needs and gaps, identifies which agency would be best suited for addressing these needs, establishes priority levels for each topic, and discusses the expected availability of potential data sources to inform those topics.

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

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

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The Need for a Research Roadmap

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

The purpose of this research roadmap briefing is to examine the present state of the Highway Capacity Manual (HCM), to identify current limitations that will need to be addressed to enable appropriate consideration/analysis of upcoming CV/AV applications, and to propose a research roadmap that addresses these needs. This summary document is intended to be a companion to the full CV Research Roadmap tech memo for new and enhanced analysis tools, techniques, and data (available separately), with a focus on the specific aspects that are relevant to HCM users and contributors.

Role/Relevance of the HCM and this Research Roadmap

Many of the analysis tools currently employed by researchers and practitioners for the evaluation and optimization of transportation facilities are at risk of becoming outdated or limited in their relevance/usefulness as CV/AV technologies become more prevalent on the market, and the HCM is no exception. While it may be tempting to simply conclude that the arrival of CV/AV applications will mark the end of the HCM and its relevance, a deeper consideration of the manual's longstanding role within the transportation community reveals that the HCM will continue to fill a crucial role in planning and operations moving forward, and therefore cannot be neglected during the advent of CVs and AVs**.**

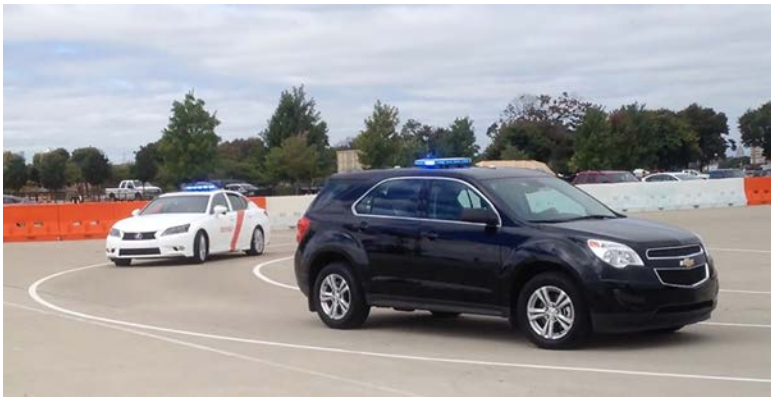

Figure 1. Photo. Demonstration of V2V technology by DENSO at the 2014 ITS World Congress.
(Source: Cambridge Systematics, Inc.)

Filling a crucial analytical role. The HCM is a uniquely positioned tool for planning and operations: it can be used to conduct a more quantitative and precise analysis than would be possible with sketch planning tools, without requiring the resource-intensive investment of labor and data required for simulation modeling. Even if the updated HCM methods for CV and AV analyses ultimately diverge from the traditional HCM methods of using equations to fit observed data, there is still a place for modifications to the HCM to ensure that analysts continue to have access to this time-tested and widely trusted analysis toolset.

CV and AV technologies are widely varied in character, impacts, and even the questions that analysts would want answered regarding their deployment (such as decisions about the form and structure that those applications take in a given deployment). When supporting data are not available or are limited, simulation tools—rather than the HCM—may be better equipped to address these questions. When agencies or decisionmakers want to estimate tradeoffs between alternatives before going into the level of effort required for a detailed modeling/simulation effort, they instead turn to the HCM (in the case of design alternatives or basic operational decisions) or to sketch planning tools (for very quick and relatively generic outcomes estimates).

Performance measurement will continue to be a crucial aspect of transportation facility evaluations, and this generally translates into the metrics that the HCM is strategically positioned to report. The HCM is one of the hallmarks of performance measurement and prediction, and one that benchmarks and evaluation baselines have been based on for decades. Many C/AV strategies (e.g., platooning, wireless freight inspection) have impacts and outcomes that are expected to scale with penetration rates, and these are consequently expected to be well suited for inclusion in the HCM through adjustment factors and similar modifications. The HCM has become a widely known and trusted tool, and it is expected that the manual will be adapted as conditions warrant (e.g., updated to reflect the impacts of CV technologies, and modified to include new performance measures and facility types), rather than simply being abandoned and dismissed as obsolete.

The risks of not updating the HCM. Not pursuing this HCM-oriented research roadmap would only add to the challenges facing analysts in the future, as it would leave a critical gap between sketch planning and detailed simulation/modeling tools. It is expected that institutions and frameworks that use and rely on the HCM will not have the time, resources, or motivation to migrate/adapt their systems, processes, training, and staffing to new tools, especially when those new tools are as demanding and resource-intensive as simulation. Rather than dismiss the HCM now as something that may not be able to accommodate some CV strategies in the distant future, this research roadmap outlines a strategy for updating the HCM to support its continued relevance and usefulness.

While it also is possible that the HCM and its relatively simplified equation-based analysis approach will turn out to be unsuitable for CV analyses in general, that is something that cannot be known without first attempting to update the HCM in response to CV/AV developments and data. It would be inappropriate to start off with an expectation that the HCM simply cannot be used for CV analyses, as this invites the opportunity for a type of self-fulfilling prophecy regarding its fate.

Timeframe considerations. This roadmap is intended to span only a period of a few years, during which time it will be prudent to investigate and evaluate to what extent the HCM can (and should) be used to estimate the impacts of various C/AV strategies. It also is expected (and assumed for the purposes of this roadmap) that the penetration rates for most C/AV strategies will not reach 100 percent during the years spanned. It may take decades for C/AV technologies to reach the point where substantial changes and disruption to the current state of things occurs (e.g., when CV technologies make traditional lane markings and traffic signals irrelevant), and this roadmap for the HCM is not intended to span that transition if/when it occurs. In the coming decades, when C/AV strategies begin to saturate the market and the transportation infrastructure, a new roadmap will need to be developed and implemented instead; it is at that time, rather than now, that a decision will be needed regarding whether to update/adjust the HCM or retire it instead.

Recognizing limitations. The HCM is not intended to address all analysis needs, and transportation professionals understand that. The HCM already coexists with other tools that serve different purposes (for example, the HCM assists with facility design and basic performance estimation, while other tools are often better equipped to handle decision support for operations), and it is reasonable to expect that this trend of coexistence will continue as CVs start appearing on transportation facilities, just as the HCM has maintained relevance through the arrival of ATM and other potentially “disruptive” technologies.

It is true that the HCM may never be suitable for some CV applications (particularly those that require near universal deployment before they can be implemented), but others that have incremental effects on capacity or performance as they are deployed are still expected to be relevant to the HCM, and this roadmap ensures that the manual is able to keep up with those technologies.

Organization of this Briefing

The remainder of this briefing is organized as follows:

1. Primer on CV and AV technology, to familiarize the reader with this technology and to establish the background essential to understanding both the types of impacts that these technologies might have on the HCM and the specific research roadmap items being proposed.
2. Summary of the current state of the HCM to reiterate the manual’s role and relevance to transportation planners and analysts, concluding with an assessment of the manual’s current limitations regarding the consideration of CV and AV impacts on its analysis/optimization methods and procedures.
3. Description of a proposed research roadmap to address these limitations.

Primer on Connected and Automated Vehicles

The next wave of vehicle innovation from the perspective of the operator or driver will come in the form of CVs and AVs. This section provides an introduction to both technologies. (*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.)

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

Table 1. Potential CV Applications

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

(Source: Cambridge Systematics, Inc.)

Automated Vehicles are defined as those that use onboard sensing technologies, rather than intervehicle communications, to provide the vehicle and driver with a greater awareness of the surroundings, thereby enabling the automation of one or more driver functions through artificial intelligence, machine learning, machine vision, and computer processing. Intervehicle communications can also be used to achieve such vehicle automation, but when such technologies are used, the more widely used nomenclature refers to these as CVs (see above). These are commonly ranked according to a 0 to 4 scale described by NHTSA. On this scale, Level 0 identifies a technology that does not actively manage any of the vehicle's functions, while Level 4 identifies a technology that handles all driving functions from origin to destination (see figure 2). The term **Autonomous Vehicle** is reserved specifically for Level 4 vehicle automation. More detailed information about Levels 1 to 4 of vehicle automation is provided in the full CV Research Roadmap tech memo.

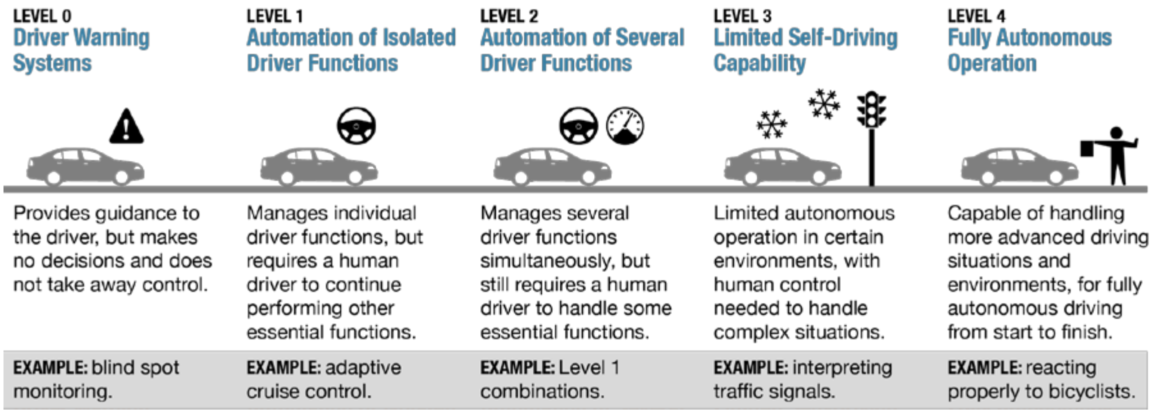

Figure 2. Graphic. NHTSA classification scale for vehicle automation.
(Source: U.S. Department of Transportation, National Highway Safety Administration.)

Benefits

Field tests, simulation studies, and theoretical exercises have been conducted to evaluate the impacts of connected vehicles across several benefit categories. Table 2 summarizes the findings across three benefit categories from several such studies in recent years. Additional impact analyses are expected from other data sources that are anticipated in the future or have only recently been released, including:

- **Research Track 1 of the U.S. DOT CV Safety Pilot Program** (August 2011 to January 2012), which provides survey data from hundreds of drivers at multiple locations in the U.S. on driver acceptance, cost preference, motivation for adoption, and behavioral response to CV technology interfaces and systems.
- **Research Track 3 of the U.S. DOT CV Safety Pilot Program** (2012 to 2013), which provides field data from 3,000 vehicles in Ann Arbor, Michigan, on the effectiveness of CV technology at reducing crashes. (Connected Vehicle Safety Pilot Program (Brochure). U.S. Department of Transportation (USDOT), Research and Innovative Transportation Administration. FHWA JPO-11-031. Accessed 10-5-15. http://www.its.dot.gov/factsheets/pdf/SafetyPilot_final.pdf.)
- **FHWA CV Pilots Deployment Project** (2015 and 2017), which will implement several prototype CV applications to address real-world problems. (Hartman, Katherine. "Connected Vehicles Pilot Deployment Program." *ITS—CV Pilot Deployment Program*. ITS Joint Program Office, USDOT. Accessed 10-5-15. http://www.its.dot.gov/pilots/.)

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

The Importance of Real-World Data

New technologies or innovations often have unforeseen consequences on driver behavior, facility performance, or other areas. For instance, pedestrian countdown timers were intended to inform pedestrians of the remaining time for crossing safely, but were also observed to influence some drivers who would begin to slow down in advance of the actual yellow signal activation, as the countdown approached zero. (Bundy, Brandon. *Modification of driver behavior based on information from pedestrian countdown timers.* Master's Dissertation, Department of Civil, Environmental & Architectural Engineering, University of Kansas. 2008. Accessed 10-5-15.) Similarly unforeseen and unintended outcomes are expected to occur with the deployment of CV and AV applications.

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

Table 2. Summary of Potential Impacts of Connected Vehicle Applications

Category	Extent of Impacts
Capacity and Throughput	• Computer-controlled vehicles could increase in maximum traffic throughput by a factor of 200 percent to 300 percent. (Hayes, Brian. *Leave the Driving to It*. American Scientist, September/October 2011, pages 362 to 366. Accessed 10-5-15.) • In an experiment on I-15 in 1997, researchers estimated V2V technologies could result in a lane capacity of 4,300 vph, compared to 2,000 vph without V2V. (Shladover, Steve. *The GM-PATH Platoon Scenario*. Intellimotion, Volume 6, Number 3, 1997, page 2. Accessed 10-5-15.) • Truck platooning in Europe using the CHAUFFEUR system will provide an estimated 8 percent capacity increase. (Bishop, Richard. *Whatever Happened to Automated Highway Systems?* Traffic Technology International, August/September 2001. Accessed 10-5-15.) • Simulation modeling and field testing by Nissan and California PATH indicate that CACC could provide a lane capacity of 3,970 vph. (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.) • Depending on platooning parameters (e.g., gap spacing), lane capacities with vehicle platooning could reach a theoretical maximum of 8,000 vph.
Emissions and Fuel Consumption	• Wind tunnel tests indicate a 50 percent reduction in drag force for closely spaced platoons, which corresponds to a 20 percent to 25 percent reduction in emissions and fuel consumption. (Shladover, Steve. *The GM-PATH Platoon Scenario.* Intellimotion, Volume 6, Number 3, 1997, page 2. Accessed 10-5-15.) • The CHAUFFEUR truck platooning system will provide up to an estimated 20 percent increase in fuel economy. (Bishop, Richard. *Whatever Happened to Automated Highway Systems?* Traffic Technology International, August/September 2001. Accessed 10-5-15.) • On a high-speed test track, fuel savings of 8 percent to 15 percent were measured

Category	Extent of Impacts
Emissions and Fuel Consumption	in five-vehicle platoons at a vehicle spacing of 5 to 8 meters. (J. Hellaker, C. Grante, and S. Bergqvist. *EARP Topic 1D—Partial Automation for Truck Platooning.* Presentation by the Volvo Group Advanced Technology and Research.) • Platoons of three trucks in Japan were measured to achieve a fuel economy improvement of 8 percent with cooperative cruise control, and a fuel economy improvement of 14 percent and 16 percent with automated driving. (Ibid.) • Platoons of three trucks in Nevada were measured to achieve a fuel economy savings of 4.5 percent to 18.4 percent depending on the truck position, using V2V technology. (X. Lu and S. Shladover. *Original Automated Truck Platooning with DSRC as V2V.* California PATH, UC Berkeley. December 6, 2013.)
Traffic Incidents	• U.S. DOT estimates that CV technologies can reduce, mitigate, or prevent 81 percent of light vehicle crashes by unimpaired drivers. (Read, Richard. *Dallas, Minneapolis, San Francisco Become Part of DOT's "Talking Car" Project*. Motor Authority, May 13, 2011. Accessed 10-5-15.) • A crash analysis of California 2013 collision data found that 78 percent of all crashes could be addressed by V2V technologies, based on their causal factors. (Cambridge Systematics, Inc. and Jim Misener. Interoperability Issues of Vehicle-to-Vehicle Based Safety Systems Project Extension (V2V-I Phase 2): V2V Vehicle Density Analysis. December 10, 2014.)

(Source: Cambridge Systematics, Inc.)

Current State of the Highway Capacity Manual

This section examines the current roles and applications of the HCM, reviews its capabilities, and identifies the existing limitations regarding its ability to account for AV and CV effects. (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.) A basic understanding of the HCM is assumed of the reader, including a familiarity with the manual's general structure/organization (e.g., an understanding that chapters are generally divided by facility type and mode).

Role and Relevance

The HCM is a well-known, widely used, and mature transportation facility analysis tool most frequently used to develop design guidance for new facilities or to evaluate and optimize existing facilities. The HCM uses functions fitted to empirical data to estimate performance characteristics (see figure 3), such as Level of Service (LOS). Procedures for analyzing different facility types are available, including freeway weaving sections, unsignalized intersections, and two-lane highways.

Figure 3. Flowchart. The general principle underlying typical HCM methods.
(Source: Cambridge Systematics, Inc.)

Tools and procedures in the HCM generally fall into one of two categories as shown in figure 4:

1. Performance assessment/evaluation tools (analytical and deterministic tools) are typically used to estimate performance of a single location or facility, over a set of predefined analysis periods. 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.
2. Traffic Signal Optimization Tools are generally used to develop optimized signal timing plans for intersections and corridors, including cycle lengths, splits, and offsets. This is done using deterministic numeric methods and procedures, and is both simpler and faster than simulation. However, it is generally suitable only for simpler situations and smaller networks.

Strengths of the HCM include:

- Its gentle learning curve.
- Its relatively low generalized cost.
- Its ability to support analyses without highly detailed input data.
- Its support for a variety of facility types and characteristics.

Limitations of the HCM include:

- A common analysis assumption of constant traffic demand.
- A general inability to consider interactions between different facilities (e.g., queue spillover effects from one intersection to another).
- Lack of support for facilities and strategies that it was not explicitly designed to accommodate (e.g., two-way left turn lanes, CV applications).

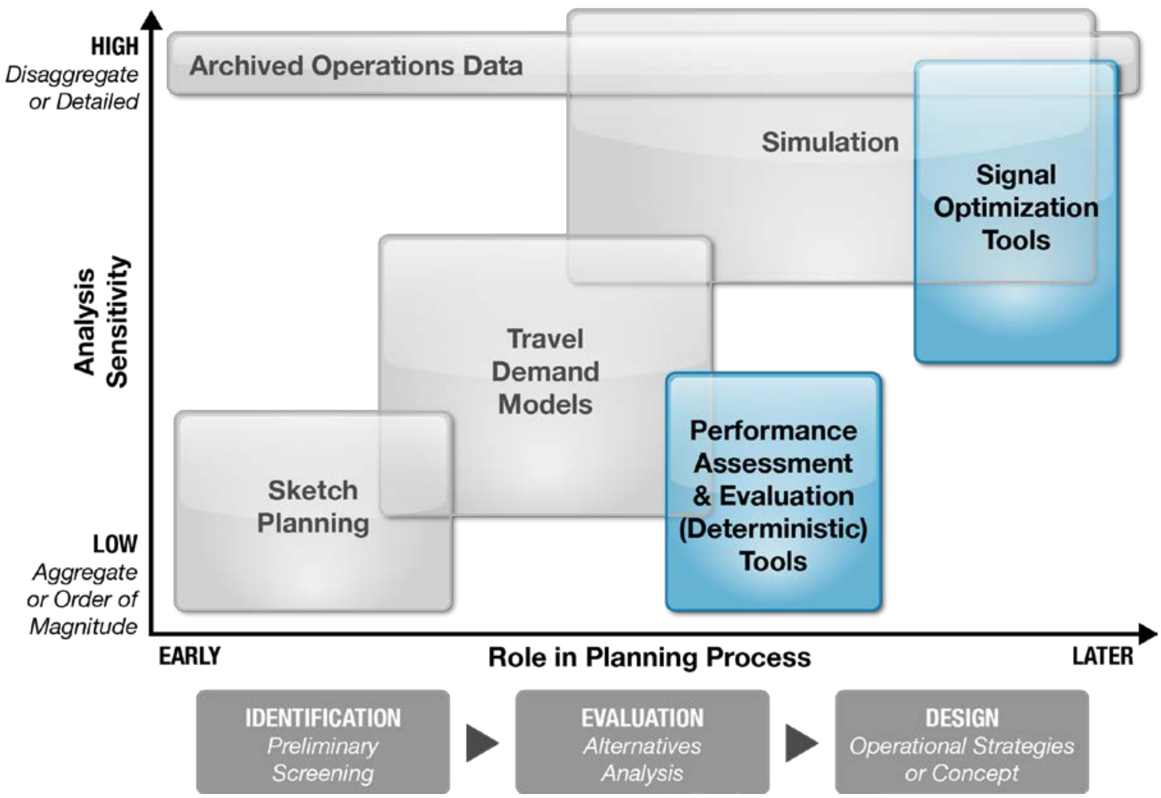

Figure 4. Graph. The role of HCM methods in the transportation planning process.
(Source: Cambridge Systematics, Inc.)

Analysis Capabilities

Table 3 summarizes the capabilities and limitations of the HCM across several analysis dimensions. Figure 4 lists other common planning tools that are available for situations and analyses that the HCM may be unsuitable for, including sketch planning tools, travel demand models, and traffic simulation models. More information about these tools is available in the full CV research roadmap document. (*Connected Vehicles in Transportation Planning, Task 3: Analysis of the Need for New and Enhanced Analysis Tools, Techniques, and Data*, Prepared for U.S. DOT by Cambridge Systematics, June 8, 2015.)

Table 3. Analysis Capabilities and General Limitations of the HCM

Category	HCM suitable for:	Other tools more suitable for:
Scale of Analysis	• Isolated locations. • Segments of a single roadway facility.	• Roadway networks. • Regional analysis.
Usability and Technical Requirements	• Facilities without comprehensive traffic data. • Agencies without access to high-performance computer workstations. • Analysts that are new users of the manual.	• Integration with other software. • Customization for nonnative analyses. • Output of animations and figures.
Facility Types	• Intersections. • Roundabouts (limited support). • Signalized arterials. • Highways and freeways. • Ramp segments. • Auxiliary lanes. • Truck lanes, bus lanes, HOV lanes, and other reserved lanes (limited support). • Toll plazas (limited support).	• Reversible lanes. • Light-rail lines. • Roundabouts (some analysis types). • Truck lanes, bus lanes, HOV lanes, and other reserved lanes (some analysis types). • Toll plazas (some analysis types).
Travel Modes	• Single-occupancy vehicle. • Buses (limited support, represented as passenger-car equivalents). • Trucks (limited support, represented as passenger-car equivalents). • Bicycles (limited support). • Pedestrians (limited support)	• Rail modes. • Motorcycles. • Trucks (some analysis types). • Buses (some analysis types). • Bicycles (some analysis types). • Pedestrians (some analysis types).
Changes in Demand	*Shifts in demand are generally not evaluated directly within HCM methods themselves. Additionally, signal optimization procedures generally assume a constant demand.*	• Route diversion, pretrip, and en route. • Mode shift. • Shift in departure time. • Induced demand.

Category	HCM suitable for:	Other tools more suitable for:
Performance Measures	• Level of service • Speed. • Travel time. • Volume. • V/C ratio. • Density. • Delay (limited support). • Travel-time reliability. • Queue lengths (some facility types).	• Ridership. • Average vehicle occupancy. • Vehicle-miles traveled (some analysis types). • Vehicle-hours traveled (some analysis types). • Number of stops. • Incidents (including duration). • Emissions, fuel consumption, and noise. • Mode split. • Benefit/cost ratio.

(Source: Cambridge Systematics, Inc.)

HCM Limitations Regarding CV and AV Analyses

Although the general limitations of the HCM were discussed in the previous section, it is valuable to further examine the specific gaps that relate to CV analyses. This will provide motivation for the research roadmap presented in the next section. At a high level, three core HCM limitations can be identified:

1. **Capacity-related HCM methods** (including derivative performance measures, such as LOS and V/C Ratio) cannot be used to evaluate projects or facilities that would utilize CV technology, as the impacts of CV strategies are not accounted for in HCM methods. CV applications are expected to improve the capacities of many facilities in different ways, and it will be crucial to look at the degree to which each application impacts the capacities of these facilities. For example, closer following distances will improve freeway link capacities (see figure 5), coordinated weaving maneuvers will improve weaving section capacities, and Intersection Movement Assist applications will change current stop-controlled and signalized intersection capacities (this change may be positive or negative depending on the CV strategy). Initial model formulation and parameter estimation for modeling these impacts can be obtained through theoretical methods, though real-world data from sources such as the CV Pilots Deployment Project will be important for validating and refining those models. Alternatively, the impacts can be modeled directly from empirical data if a sufficiently large amount of data exists for model creation, formulation, estimation, and validation.
2. **Signal timing optimization procedures** may produce suboptimal results if CV strategies are present, as the procedures currently fail to consider the operational/capacity impacts of CV technology (e.g., tighter gap acceptance, closer following distances, reduced reaction times, and other impacts identified and analyzed through #1 above). Although the HCM includes various functions and algorithms that can use custom values for following distance and reaction time, this is expected to be an intractable workaround, as the optimization routines and the functions they use were generally not designed to use parameter values in the ranges that might arise once CV and AV applications become more prevalent (for example, using a reaction time of zero or a headway of fractions of a second). In addition, some impacts on signalization (such as the ability of vehicles to communicate with each other to create gaps for cross traffic, which could eliminate the need for some protected phases) may require changes to the underlying procedures themselves.

3. **Safety benefits of CV and AV technologies** (e.g., curve speed warnings, blind spot warnings, stop sign violation warnings) are not represented in the HCM analysis outcomes. Although the direct safety impacts associated with CV and AV technologies are better captured by other tools, there are still significant indirect capacity-related effects that fall within the scope of the HCM and must be considered as well. These include the impacts of improved safety on travel time reliability, delays that occur when V/C ratios are high, and average speeds that occur when V/C ratios are high. Although the HCM methods may exhibit relatively low sensitivities to such factors, the overall impacts on HCM analysis outcomes may still be highly significant due to the large extent to which CV and AV strategies are expected to reduce the frequency and severity of crashes.

Figure 5. Photo. This truck, designed by Volvo, uses onboard sensors and V2V technology.
(Source: Cambridge Systematics, Inc.)

In addition to these three primary limitations of the HCM in the context of CV applications, additional issues exist that may be expected to limit the reliability and accuracy of HCM analysis results involving CV strategies. These include:

1. **No accounting for the changes to infrastructure** that will become possible (or even necessitated) by the advancement and spread of CV technologies, such as narrower lanes (which may not have the same effect on an automated vehicle that it would affect a human driver).
2. **No existing analysis guidance** regarding the suitability of the HCM for conducting various types of analyses involving CV strategies.
   Limited consideration of penetration/adoption rates and the effect they will have on the realized outcomes associated with CV technologies on various facilities.

Proposed Research Roadmap

This section presents a set of 9 research topics designed to address the limitations identified in the previous section with respect to the handling of CV effects in HCM analysis procedures. These topics are a subset of the 19 described in the full CV research roadmap document, and have been selected for their relevance to the HCM.

This roadmap does not include a discussion of the specific HCM chapters that would be affected by each topic, as it is expected that the outcomes associated with any topic will affect a broad range of chapters depending on the data that are available for various types of transportation facilities and CV strategies. Furthermore, the organization of the HCM is constantly changing to structure its content in the most logical and usable manner possible, and it is not the role of this research roadmap to dictate what contents belong in which chapters of future HCM editions.

Overview

Table 4 lists and briefly describes the nine topics of the proposed HCM research roadmap. Each one may be considered its own potential project or contract, for which additional specifications (e.g., deliverables, tasks, project milestones) would need to be developed in pursuit of the topic's overall objectives. Additional detail for each topic is provided in the following pages. More thorough descriptions of these research topics, including discussions of data needs, potential existing/future data sources, and the ongoing nature of these topics, are available in the full CV Research Roadmap tech memo.

Table 4. Summary of Proposed Research Roadmap Topics Specific to the HCM

Topic	Title	Summary
1	Forecasting penetration and adoption rates	Analysis of user attitudes and perceptions about CV applications, combined with data on the expected availability of supporting technologies from automobile OEMs, to enable forecasts of adoption and penetration rates for each strategy moving forward.
2	Modeling CV capacity impacts	Analysis of modeling methods for the capacity gains and operational outcomes associated with individual CV applications, as functions of market penetration rate, roadway characteristics/configuration (e.g., mixed-flow lanes or dedicated lanes for CV traffic), traffic characteristics, and the design parameters being used by automobile OEMs (e.g., following distances).

Topic	Title	Summary
3	Preparing models for the HCM	Modifying the strategy-specific models of CV-related capacity and operational impacts from topic #2 to make them compatible with current HCM methods, assumptions, inputs, and outputs.
4	Updating signal timing optimization methods	Incorporation of the models from topic #3 into current HCM signal timing optimization procedures, so that they properly account for the capacity/operational impacts associated with various CV applications.
5	Updating performance evaluation methods for capacity impacts	Incorporation of the models from topic #3 into current HCM performance assessment and evaluation tools, so that they properly account for the capacity/operational impacts associated with various CV applications.
6	Modeling CV safety impacts	Analysis of the HCM performance-related outcomes associated with safety improvements afforded by various CV strategies (e.g., improvements in travel time reliability during congested conditions due to reduction in crash occurrence). Development of suitable predictive models for describing those outcomes as functions of penetration rate, prevailing traffic conditions, roadway characteristics, and other reasonable covariates.
7	Updating performance evaluation methods for safety impacts	Incorporating the models of performance-related safety outcomes from CV strategies (see topic #6) into HCM performance assessment and evaluation tools, so that they account for the effects of reduced incident occurrence/severity.
8	Investigating driver acceptance and response to CV applications	Analysis of the range and distribution of driver reactions to various CV technologies, such as acceptance of warnings and route guidance, to more accurately relate penetration/adoption rates to outcomes, and to more reliably model the mode split for CVs.
9	Providing CV analysis guidance	Developing an analysis framework/methodology for accurately capturing the effects/outcomes of CV applications in the HCM and other tools, which would include recommended approaches, best practices, and known limitations, and would promote consistency among analysts. Also, identifying the limitations of the HCM and discussing where it fits in an overall CV analysis toolbox/framework.

(Source: Cambridge Systematics, Inc.)

Figure 6 indicates each topic's timing, expected duration, dependencies, and relevance to the six CV-specific limitations of the HCM identified earlier. More information about the figure 6 roadmap is listed below.

- **Subject to change.** As with any forecast regarding the future driving environment and future availability of technologies, there is an inherent and unavoidable uncertainty with respect to the assumptions about what the future will hold, the outcomes that will be achieved, and the optimal research path to follow as a result. This roadmap has not yet been formally adopted or funded. It should be considered only tentative at this point.
- **Topic start times.** The start time for a given research topic is based on the expected availability of required data and on the timing of other prerequisite research topics that inform it. Unless otherwise noted, all topics are expected to require an additional 6 to 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.

- **Topic durations.** 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.
- **Availability of initial results.** The end dates suggest when initial results might be expected from those topics, but should not be interpreted as the final dates that any work would be performed. It is expected that there will be ongoing work for all of these topics even after their objectives have been initially accomplished, as the topic outcomes will continue to benefit from an infusion of new datasets as they become available over time (for example, data from the FHWA Connected Vehicle Pilots Deployment Project waves in 2015 and 2017, or data from each NHTSA level of AV automation as it is achieved).
- **Topic prioritization.** Each topic is given one of two priority classifications, based on its breadth, relevance to other topics in the roadmap, and impact on C/AV modeling capabilities. *First priority topics* may be considered the higher priority class of topics, and are rated as such either because they are prerequisites for other research topics or because they are very broadly impactful. *Second priority topics*, conversely, may be considered the topics of relatively lower priority in the research roadmap, as they require inputs from other research topics before they can be initiated, or are relatively narrow in scope. Additional details about the prioritization process and interpretation can be found in the full CV Research Roadmap tech memo.

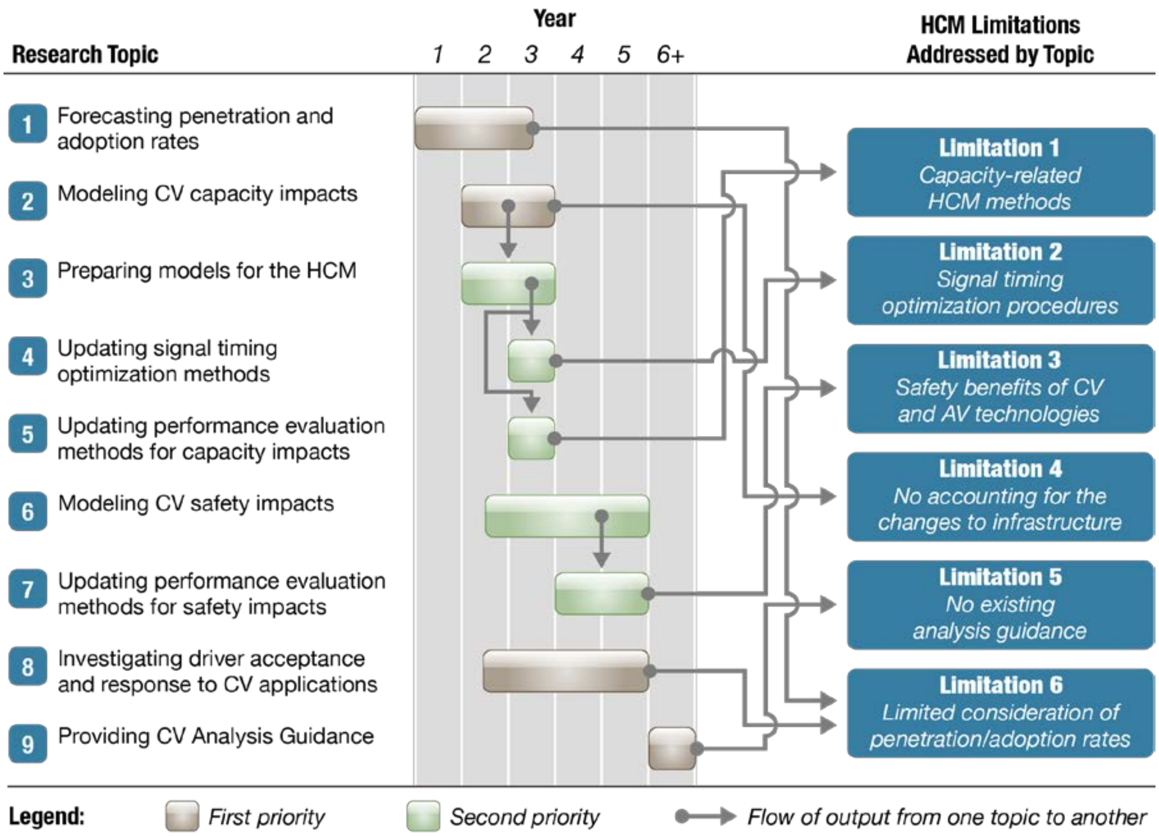

Figure 6. Chart. Research roadmap for addressing CV analysis limitations in the HCM.
(Source: Cambridge Systematics, Inc.)

Details by Topic

To complement the basic descriptions and timing of each research topic given in table 4 and figure 6, three additional types of information are presented by topic in this section:

1. **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.
2. **Potential Lead Organizations.** A listing of potential lead agencies for sponsoring, overseeing, and/or supervising the topic.
3. **Relevance.** An overview of the relevance of the topic in the context of enabling or enhancing C/AV analysis capabilities for the HCM.

Topic 1—Forecasting Penetration/Adoption Rates

- **Resource Needs and Availability:** Data regarding purchasing rates for CV-equipped and nonequipped vehicles will become available in the coming years from automobile OEMs. This topic will also benefit 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. Additional data may also be needed.

- **Potential Lead Organizations:** The Crash Avoidance Metrics Partnership (CAMP), FHWA, and U.S. DOT.
- **Relevance:** Enables more precise forecasting of anticipated benefits associated with different CV strategies by providing more reliable estimates of C/AV penetration rates.

Topic 2—Modeling CV Capacity Impacts

- **Resource Needs and Availability:** Data from large-scale deployments and field tests will be useful for assessing the capacity and operational impacts of CVs on the traffic stream and on various transportation facilities. Data anticipated from FHWA's CV Pilots Deployment Project in 2015 to 2017 thus will be highly relevant. Covariate data and measured outcomes from pilot deployments will be needed for both calibration and validation. The effort to collect and prepare these data may be substantial.
- **Potential Lead Organizations:** National Cooperative Highway Research Program (NCHRP), and the Transportation Research Board (TRB).
- **Relevance:** By exploring and evaluating models for the impacts of CV technology separately for each strategy, this research topic establishes a foundation for later incorporation of CV effects into the HCM.

Topic 3—Preparing Models for the HCM

- **Resource Needs and Availability:** This topic requires the output from topic #2. HCM methods generally seek a balance between precision and simplicity of procedures, such that a method for incorporating a potentially wide range of CV strategies may be challenging.
- **Potential Lead Organizations:** TRB and the HCM subcommittee.
- **Relevance:** This topic takes the models for capacity and performance impacts associated with CV strategies and modifies or adapts them to make them suitable and compatible with existing HCM methods and techniques to the greatest extent possible.

Topic 4—Updating Signal Timing Optimization Methods

- **Resource Needs and Availability:** This topic requires the output from topic #3. Software components of the HCM must be updated as well.
- **Potential Lead Organizations:** TRB and the HCM subcommittee.
- **Relevance:** This research topic focuses on getting the analysis methods and models identified previously for CV strategy capacity and performance impacts integrated into the HCM signal timing optimization procedures.

Topic 5—Performance Evaluation Methods for Capacity Impacts

- **Resource Needs and Availability:** This topic requires the output from topic #3. This topic can be done in parallel with topic #4.
- **Potential Lead Organizations:** TRB and the HCM subcommittee.
- **Relevance:** This research topic focuses on getting the analysis methods and models identified previously for CV strategy capacity and performance impacts integrated into the HCM performance analysis procedures.

Topic 6—Modeling CV Safety Impacts

- **Resource Needs and Availability:** Incidents are rare events; a large portion of this research effort will likely focus on obtaining a sufficiently large sample of crash data and associated covariate data. Such data will potentially be available from the U.S. DOT Connected Vehicle Safety Pilot Program in 2012 to 2013, with additional data anticipated from FHWA's CV Pilots Deployment Project in 2015 to 2017. This topic focuses only on direct safety benefits, such as reductions in incident severity or frequency. Secondary benefits, such as travel-time reliability improvements, are not considered here.
- **Potential Lead Organizations:** TRB, FHWA, U.S. DOT, and CAMP.
- **Relevance:** This research topic focuses on identifying methods for modeling the safety impacts of CV technologies so that those indirect performance impacts can subsequently be incorporated into the HCM analysis tools. This research topic would also explore the relationship between level of benefit and other predictor covariates, such as penetration rate or level of congestion.

Topic 7—Performance Evaluation Methods for Safety Impacts

- **Resource Needs and Availability:** This topic requires the output from topic #6. Software components of the HCM must be updated as well.
- **Potential Lead Organizations:** TRB and the HCM subcommittee.
- **Relevance:** This research topic takes the collision/incident reduction models and integrates them into the HCM tools so that the performance benefits associated with these incident reduction rates can be captured in HCM analyses.

Topic 8—Investigating Driver Response to CV Applications

- **Resource Needs and Availability:** The necessary data for this analysis can be obtained through surveys, driver simulators, field tests, and other localized data gathering. Data on driver acceptance and response to CV systems may also be extracted from existing datasets such as the U.S. DOT Connected Vehicle Safety Pilot Driver Acceptance Clinics. Mode choice models are capable of handling new or hypothetical alternatives.
- **Potential Lead Organizations:** FHWA, NCHRP, TRB, and major metropolitan planning organizations.

- **Relevance:** This research topic 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.

Topic 9—Providing CV Analysis Guidance

- **Resource Needs and Availability:** This topic will require 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 and modeling approaches by strategy and context (e.g., facility type).
- **Potential Lead Organizations:** TRB, FHWA, U.S. DOT.
- **Relevance:** The expected outcome from this research topic is in many ways a CV 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. This topic synthesizes the outcomes and results from all of the other research roadmap topics into a coherent, consistent, and rational analysis framework. It also identifies any new/unresolved research needs and gaps that require additional work and attention.

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