APM APPENDIX 6B

CONSIDERING CONNECTED AND AUTOMATED VEHICLES IN FUTURE-YEAR ROADWAY CAPACITY FORECASTS

Introduction

This appendix provides background on connected and automated vehicles (CAVs) and describes when and how to incorporate CAV adjustments into future-year planning analyses. It is largely based on content from the *Highway Capacity Manual* (HCM) and the Federal Highway Administration (FHWA) pooled fund study *Planning-Level Capacities for CAVs in the Highway Capacity Manual*, led by ODOT with the participation of nine other state DOTs.

The HCM 7th Edition (HCM 7) provides methods for adjusting roadway capacity for the presence of CAVs in the traffic stream on freeways and at signalized intersections and roundabouts. Although no CAVs are currently available commercially, it is expected that CAVs will start to become available within the 20- to 50-year planning horizons of transportation system plans and other long-range transportation studies. A key question that is expected to arise as part of these studies is how likely will it be that an existing roadway can accommodate increased traffic volumes without the need for widening, if a portion of the traffic stream consists of CAVs?

CAVs are defined for the purposes of the HCM as vehicles with an operational cooperative adaptive cruise-control (CACC) system. The combination of connectivity (high-frequency, low-latency intervehicle communication) and automation can allow vehicles equipped with CACC to form platoons and safely travel with shorter headways than human drivers can achieve. These shorter headways, in turn, create the potential for more vehicles to use a roadway lane per hour than is possible at present. At high percentages of CAVs in the traffic stream (typically, 60 to 80 percent or higher), significant increases in roadway capacities potentially can occur.

This appendix includes the following sections:

- Concepts, Definitions, and Limitations
- Guidance on Estimating the CAV Percentage
- Guidance on Adjusting Capacity for CAV Presence
- Guidance on Scenario Development
- Illustrative Examples

More information can be found in the Final Report for the pooled fund study, available on the APM website under Supplemental Materials, and in the supplemental chapters listed below that are a part of HCM Volume 4, available online at https://hcmvolume4.org/.

- **Chapter 26** Freeway & Highway Segments: Supplemental
- **Chapter 31** Signalized Intersections: Supplemental
- **Chapter 33** Roundabouts: Supplemental

Purpose of this Appendix

This appendix is intended to support longer-range planning analyses that include one or more future scenarios where CAVs are assumed to be commercially available and present in the traffic stream. As of 2022, no vehicles meeting the HCM definition of a CAV were commercially available. Therefore, no capacity adjustment for CAVs should be made in analyses involving a near-term future, such as traffic impact analyses. CAV technology is still in development and will continue to evolve once it becomes commercially available. As a result, the future reality will undoubtedly be different than the future that is forecasted using this appendix's capacity adjustments. Consequently, the results of analyses applying this appendix should be interpreted as an indication of what *could* happen, rather than being taken as the final word as to what *will* happen. As discussed later in the appendix, it is recommended that CAV analyses employ more than one scenario that test different assumptions about CAV availability and capacity effects, to help gauge the likelihood that CAVs will meaningfully affect future roadway operations.

The research that developed this appendix's CAV capacity adjustments found that substantial improvements in capacity start to occur when the percentage of CAVs in the traffic stream reaches 60 to 80 percent. CAV-related capacity improvements occur due to CAVs' ability to form platoons of five to ten closely spaced vehicles. At lower CAV percentages, most CAV platoons will be short due to the many human-driven vehicles still in the traffic stream, and the potential capacity benefit is therefore much lower. For safety reasons, CAVs will need to operate with longer gaps when driving behind human-driven vehicles.

As discussed in more detail later in this appendix, it will likely be decades in the future before sufficient CAVs are in the traffic stream on most roadways to have a substantial effect on capacity. Even if CAVs became commercially available tomorrow, the adoption of previous automotive technology such as airbags and antilock brakes indicates that the new technology will likely initially only be available as an option on higher-end vehicles and will take many years to become standard equipment on all vehicles. In addition, once a particular technology becomes standard, it still takes well over a decade for the U.S. automotive fleet to turn over. As a result, the effects of CAVs on roadway operations within a 20-year planning horizon are likely to be limited. Nevertheless, this information is provided (1) to allow analysts to answer questions from decision-makers, advisory committees, the public, and other stakeholders about the potential effects of CAVs; and (2) because the CAV percentage might be higher in certain situations, such as on a freeway lane reserved for CAVs.

Concepts, Definitions, and Limitations

What is a CAV?

As described in the HCM, "CAVs integrate two separate types of technology, communications and automation. The combination of these technologies is required to achieve roadway capacity increases." CAVs are distinct from connected vehicles (CVs) and automated vehicles (AVs). The HCM defines CVs, AVs, and CAVs as follows:

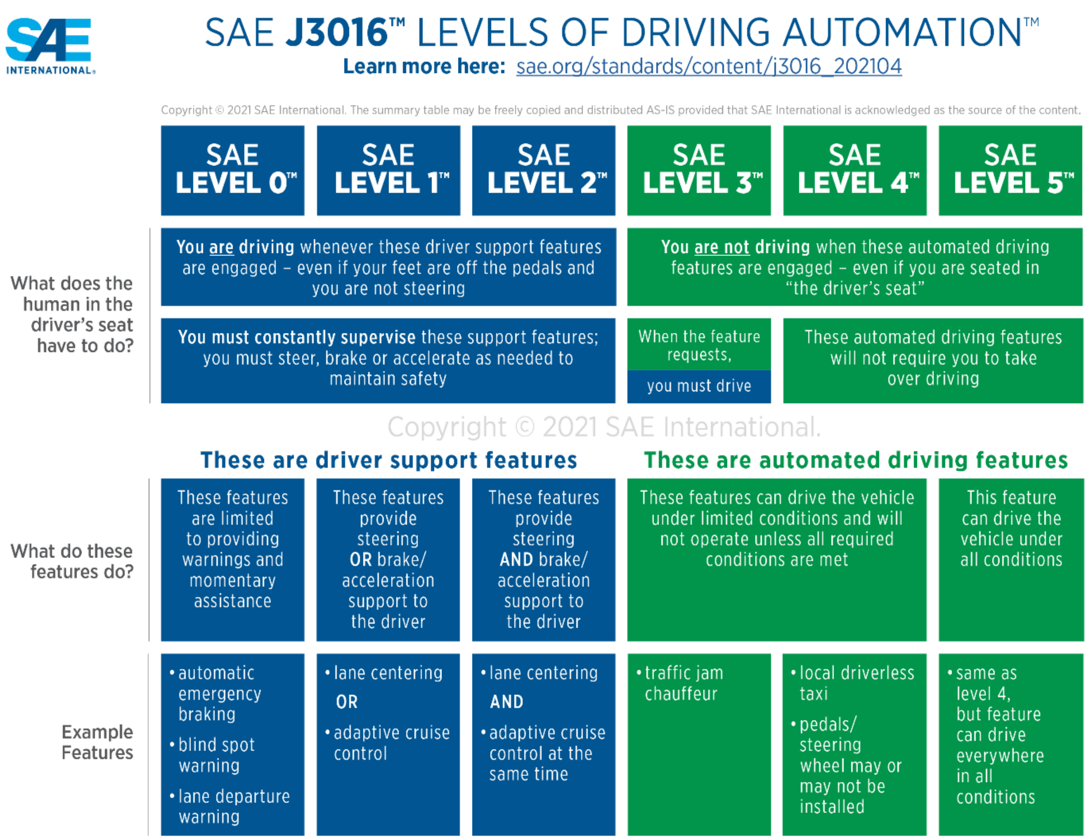
- **Connected vehicles** transmit data about their status to their surroundings (e.g., roadside infrastructure, other road users). They also receive information about their surroundings (e.g., traffic conditions, weather conditions, presence of potential conflicting vehicles, traffic signal timing) that motorists can use to adjust their driving behavior in response to conditions present at a given time and location. This exchange of information offers potential safety, fuel economy, and environmental benefits. However, it is not clear how connectivity affects car-following and driver behavior and subsequently roadway capacity.
- **Automated vehicles** take over all or a portion of the driving task. Depending on the level of automation, a human may still need to take over under certain conditions. In the absence of connectivity, the information available to automated vehicles is limited to that which can be gathered by on-board sensors, which is typically constrained by a sensor's line of sight and the rate at which the sensor takes measurements (e.g., 10 times per second). As a result, for both safety and passenger comfort reasons, current adaptive cruise control systems offer minimum time gaps that are similar to, or longer than, the gaps used by human drivers, and thus may decrease roadway capacity when in widespread use.[1]
- **Connected and automated vehicles** communicate with each other and with roadside infrastructure. The connectivity element provides automated driving systems with more complete information about a vehicle's surroundings and enables cooperative vehicle maneuvers that improve roadway operations. The vehicle's enhanced detection capabilities, as well as redundancy in detection, enable an automated driving system to operate more efficiently and more safely than with only an on-board system.[2] In particular, the CACC feature enabled by vehicle-to-vehicle communication allows CAVs to safely operate in platoons at shorter headways than possible by either human-driven vehicles or automated vehicles using adaptive cruise control only.

[1] Jones, S. *Cooperative Adaptive Cruise Control: Human Factors Analysis*. Report FHWA-HRT-13-045. Federal Highway Administration, Washington, D.C., Oct. 2013.
[2] Krechmer, D., K. Blizzard, M.G. Cheung, R. Campbell, V. Alexiadis, J. Hyde, J. Osborne, M. Jensen, S. Row, A. Tudela, E. Flanigan, and J. Bitner. *Connected Vehicle Impacts on Transportation Planning*. Primer and Final Report. Report FHWA-JPO-16-420. Federal Highway Administration, Washington, D.C., June 2016.

The Society of Automotive Engineers (SAE) defines six levels of automation, shown in Exhibit 6B-1 and listed below:

- **Level 0: No Automation.** The human driver is responsible for controlling all aspects of the dynamic driving tasks even with enhanced warning and intervention systems.
- **Level 1: Driver Assistance:** Automation assists the human driver with either steering or braking/accelerating (lateral or longitudinal).
- **Level 2: Partial Automation.** Automation assists the human driver with both steering and braking/accelerating simultaneously (lateral and longitudinal).
- **Level 3: Conditional Automation.** The automated driving system can take full responsibility for driving tasks on certain parts of a trip within specific operational design domains. The human driver is expected to re-engage when the vehicle can no longer carry out driving duties. The driver shifts safety-critical functions to the vehicle under certain traffic and environmental conditions.
- **Level 4: High Automation.** The vehicle can take full responsibility for driving tasks within specified operational design domains and will not require the driver to re-engage within those domains.
- **Level 5: Full Automation.** The vehicle can drive an entire trip on any road in any weather condition.

Exhibit 6B-1 SAE Levels of Automation



Source: SAE

The CAVs modeled in the pooled fund study that developed this appendix's capacity adjustments used level 4 and 5 automation. As of 2022, no vehicles are available commercially with these levels of automation. As described below, the CAVs were modeled using CACC logic developed for the FHWA that was interfaced with a commercial simulation model.

Potential CAV Effects on Roadway Operations

There is much uncertainty around CAVs and the effects they will have on roadway operations and capacity. The modeling conducted as part of the pooled fund study showed that capacity increases with increasing CAV percentage on freeways and at signalized and roundabout intersections. These capacity increases are primarily due to the potential for CAVs to form platoons of closely spaced vehicles.

A variety of research identifies potential CAV effects beyond roadway capacity and operations. A report by the Victoria Transport Policy Institute (VTPI)[3] summarizes potential CAV benefits (e.g., fewer crashes due to driver error, mobility for non-drivers, support for vehicle sharing) and costs or problems (e.g., crashes due to system failures, communications infrastructure costs, security and privacy concerns). In particular, the potential costs and problems represent issues beyond the challenge of building a self-driving car that will need to be addressed before the potential of CAVs can be realized.

Limitations of the HCM CAV Capacity Adjustment Factors

Trucks: The pooled fund study did not model freeway operation with connected and automated trucks and more research is needed in this area, particularly with respect to the effects of closely spaced truck platoons on automobile lane-changing, on-ramp merging, and freeway operations in mountainous terrain.

Pedestrian and Bicycle Interactions: The pooled fund study did not model the interactions of CAVs, pedestrians, and bicyclists at signalized intersections and roundabouts. At signalized intersections, pedestrians and bicyclists do not conflict with exclusive through and protected left-turn movements and therefore do not affect those movements' saturation flow rates. Pedestrians and bicyclists do conflict with permitted signalized right- and left-turn movements, and the HCM method reduces those movements' capacity in proportion to the time the conflict zone (crosswalk and parallel bicycle through movement) is blocked. Only exclusive lanes were modeled as part of the pooled fund study; shared lanes, such as through–right lanes, that could be affected by pedestrians and bicyclists were not modeled. At roundabouts, the pedestrian crosswalk is located in advance of the roundabout entry and therefore does not directly affect the capacity of the approach lane(s) at the circulatory roadway. The HCM applies a passenger car equivalency to bicyclists traveling in a roundabout's circulatory roadway. Based on the above, in general, the HCM's capacity adjustments for the effects of pedestrians and bicyclists on human-driven vehicles are also applicable to CAVs.

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[3] Litman, Todd. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.* Victoria Transport Policy Institute, Victoria, B.C. Updated January 25, 2023.

Stop-controlled and alternative intersections: The pooled fund study modeled two-way stop-controlled (TWSC) intersections, but the results were not conclusive as to the operational effects of CAVs. The pooled fund study did not model all-way stop-controlled intersections or alternative intersection geometries.

Other technologies: The pooled fund study did not consider other technologies, such as vehicle-to-infrastructure (V2I) communication, and is limited by the uncertainties around how CAV technology will evolve.

Assumptions Built into the HCM's CAV Capacity Adjustments

The HCM's capacity adjustments for CAVs were developed from simulations uncalibrated to field observations. Historically, HCM methods have been based on "empirical observations of actual vehicles using actual roadway facilities, simulation calibrated to field-observed conditions, or both." However, because at present there are no CAVs in the traffic stream to observe, a different approach is required.

The pooled fund study used an "agent-based" (i.e., fully customizable vehicle and driver behavior) simulation modeling framework in which CAV and non-CAV behavior could be modeled differently. In particular, CAVs were modeled using CACC logic developed for the FHWA. A commercial simulation model modeled the behavior of human-driven vehicles and provided locations and trajectories of all vehicles to the CACC model at 0.1-second intervals, comparable to the update rate expected in the future for intervehicle communications. Based on this information, the CACC model determined how the CAVs would behave in the next time step and returned that information to the commercial simulation model.

The model was first calibrated to match the HCM's value of capacity for the situation being modeled. Then, by varying the proportion of CAVs and overall traffic volumes, the researchers observed how the CAV proportion affected roadway throughput (i.e., the maximum pre-breakdown flow rate, used to represent capacity) and saturation flow rate. Capacity adjustment factors (CAFs) were developed by dividing the average observed throughput for a given situation by the HCM capacity value for the same situation.

Key assumptions made in the modeling relate to:

1. Intervehicle gap
2. System reliability
3. Traffic stream composition

Each of these assumptions is discussed below. Full details of the modeling are available in the pooled fund study's final report, as discussed in the introduction to this appendix.

Intervehicle Gap

The modeling assumed an intervehicle gap based on the following assumptions:

- **CAV capability.** The modeled CAVs had vehicle-to-vehicle communication abilities and a working CACC system. CAVs acting as platoon leaders reverted to adaptive cruise control (i.e., relying on on-board sensors only).
- **Human-driven vehicle capability.** The operation of human-driven vehicles was calibrated for three scenarios for freeways: 2,400 passenger cars per hour per lane (pc/h/ln, matching the HCM's base capacity for basic freeway segments with a 70 mph free-flow speed), 2,100 pc/h/ln, and 1,800 pc/h/ln. The latter two scenarios represent freeway segments with some combination of lower base free-flow speeds, narrow lanes, limited or no lateral clearance, high ramp density, and unfamiliar drivers. For signalized intersections, the model was calibrated to the HCM's base saturation flow rate of 1,900 pc/h/ln for through movements. For roundabouts, the model was calibrated to the HCM capacity curve for the condition being modeled (e.g., single- or double-lane approach).
- **Platooning behavior.** CAVs formed platoons in the model. A CAV became the leader of a platoon when the vehicle in front of it was either a non-CAV or a CAV that was the last vehicle in a platoon that had reached its maximum allowed length. Otherwise, a CAV that followed another CAV joined the preceding CAV's platoon. One-vehicle platoons were possible, and relatively common when the proportion of CAVs in the traffic stream was low. A CAV's status could change from leader to follower and back, depending on lane-changing and merging activity.
- **Intraplatoon gaps.** For freeways and signalized intersections, several different intervehicle gaps within platoons were tested, and a distribution of gaps having an average intervehicle gap of 0.71 seconds (s) was used to develop the CAV capacity adjustments. For roundabouts, a fixed intervehicle gap of 0.7 s was used.
- **Interplatoon gaps.** A CAV that was the leader of a platoon operated in adaptive cruise control mode, with a gap to the next vehicle of 2.0 s on freeways and 1.5 s on arterials.
- **Maximum platoon size.** The maximum platoon size was 10 passenger cars on freeways and 8 passenger cars on arterials, constrained by the need to accommodate lane changes, merges at freeway ramps, and the need to maintain reliable communication between the platoon leader and the vehicles at the rear of the platoon.

The HCM methodology does not provide an option to adjust these assumptions. A variety of factors will affect the intervehicle gap that CAVs ultimately operate with, including legal or regulatory requirements, decisions by vehicle manufacturers, consumer preferences, the need to accommodate lane-changing and merging, and differences in vehicle performance. For example, vehicle manufacturers could design for longer intraplatoon gaps out of liability concerns or to increase passenger comfort by reducing the amount of acceleration and deceleration required to maintain a minimum safe gap.

System Reliability

The pooled fund study's modeling assumed that "all necessary communication elements are in place and working with a high degree of reliability." This assumption is necessary for CAVs to operate with short intervehicle gaps and thereby achieve capacity improvements.

Traffic Stream Composition

The modeling varied the percentage of CAVs in the traffic stream in 20% increments from 0% to 100% CAVs. The HCM methodology requires an analyst to specify the proportion of CAVs in the traffic stream. If the proportion falls between one of these 20% increments, the freeway CAF, roundabout capacity model adjustment factors, and signalized intersection saturation flow rates can be interpolated.

Uncertainties around CAVs

There are a number of uncertainties around the development, deployment, adoption, and operation of CAVs. Some of the key questions include:

- How soon will CAVs become commercially available?
- How will CAVs operate in urban environments, particularly around pedestrians and bicyclists?
- How will traffic volumes and travel patterns change with the adoption of CAVs?
- What regulations will exist for CAVs, including how closely they can follow another vehicle and which areas they are or are not permitted?
- How much will CAVs cost and how will this influence the rate of adoption?
- What safety issues or perceptions will influence CAV adoption?
- What level of risks will manufactures tolerate and what Original Equipment Manufacturer (OEM) safety margins will be set?
- Will the communication technology needed for CAVs to reach their full potential be standardized? When and where will the technology be in place and how well will it be maintained?
- How quickly will vehicle fleets turn over and how will CAV adoption vary by vehicle type (e.g., truck, automobile) and area (e.g., urban, rural)?
- How will CAVs perform in inclement weather, work zones, or during other traffic disruptions?

Due to these uncertainties, the HCM recommends that CAV adjustments be applied to the "evaluation of *"what if"* scenarios, rather than being taken as the final word on what *will* happen once CAVs become widespread." It suggests the analyst consider:

- *What if the minimum headway permitted by technology, regulation, or policy, or the average headway produced by different vehicles' user settings, is longer than the modeling assumed?* In this case, the capacity increase would be less than predicted.
- *How reliable will the necessary communications and automation technology be?* To the extent that individual CAV-capable vehicles must be driven by a human at any given time due to equipment malfunction, the proportion of operating CAVs in the traffic stream will be less than the proportion of CAV-capable vehicles. (Alternatively, the demand will be lower, in the situation where only vehicles with functioning systems are allowed on the facility.)
- *How quickly will CAV technology become available and adopted, and how will CAVs affect travel demand?* The assumptions made related to these questions will determine the assumed volume and proportion of CAVs in the traffic stream, along with the assumed capacity adjustment.

Glossary

The HCM defines the following CAV-related terms:

Adaptive cruise control (ACC)—A driver assistance system that automatically adjusts a vehicle's speed to maintain a set following distance from the vehicle in front, relying on data from on-board sensors (e.g., cameras, radar, lidar). ACC systems produce time gaps to preceding vehicles similar to, or longer than, those used by human drivers.

Automated vehicle (AV)—A vehicle equipped with an automated driving system capable of performing some or all driving functions without requiring intervention by a human in the vehicle. Fully automated vehicles perform all driving functions without any intervention from a human in the vehicle. Automated vehicles do not have to be connected and can use on-board sensors to detect their surroundings. Highly automated vehicles might not have a steering wheel or brake pedal in the passenger cabin.

Capacity—The maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions.

Capacity adjustment factor (CAF)—An adjustment to base capacity to reflect the effects of severe weather, incidents, and work zones, the presence of CAVs, or other factors.

Connected vehicle (CV)—A vehicle capable of communicating vehicle status (e.g., location, speed, direction, brake status) to other vehicles and to transportation management centers. CVs also receive information on infrastructure (e.g., queues ahead, weather, recommended speed) from roadside units and also receive status information (e.g., emerging braking application) from other vehicles. CVs display information about infrastructure and nearby CV status for use by the driver; the driver is in charge of taking appropriate action in response to the information or warnings and remains "in-the-loop" for the driving function.

Connected and automated vehicle (CAV)—A vehicle that combines self-driving and connectivity features, allowing safe operation in platoons at shorter headways than possible by either human-driven vehicles or automated vehicles using adaptive cruise control only. CAVs are capable of driving without human intervention for specific parts of a trip (e.g., only on freeways) or all of a trip. For HCM purposes, a CAV is a vehicle with an operating CACC system.

Cooperative adaptive cruise control (CACC)—An ACC system that also integrates information communicated from preceding vehicles, roadside infrastructure, or both to allow faster reactions to changes in conditions and safe operation at shorter headways than possible with either human-driven vehicles or ACC systems relying solely on on-board sensors.

Market penetration rate—The percentage of the traffic stream composed of CAVs. For HCM purposes, it is the percentage of the vehicle fleet on a specific roadway with an operating CACC system, which may be larger or smaller than the overall fleet composition.

Guidance on Estimating the CAV Percentage

The primary input into the HCM methodology for developing capacity adjustments for CAVs is the percentage of CAVs in the traffic stream. This value may depend both on the broader state and national fleet composition, as well as location-specific factors such as urban vs. rural areas or Interstate vs. non-Interstate highways.

Early predictions on when CAVs will become available and be adopted have proven to be overly optimistic. Several companies have recently moved away from automation to focus on nearer-term service applications, suggesting the deployment of CAVs may be further away than previously thought. Current predictions vary widely, given the number of potential factors that could affect market adoption, including the rate of technological development, political intervention, public perception and preferences, CAV costs, and initial use cases (e.g., automated truck freight movement, automated ridesharing vehicles). The pooled fund study's literature review noted the following:

- Some experts believe it will be decades and not years before a vehicle can drive itself at any speed on any road in any weather.[4]

[4] Litman, Todd. *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.* Victoria Transport Policy Institute, Victoria, B.C. Updated November 6, 2022.

- AV adoption widespread enough to have a profound impact on the transportation system is likely to be far off.[5]
- In order to see market saturation of highly automated vehicles, the technology needs perfecting. Once technology is perfected, it is predicted that it will take another 13 years for 50% of cars and 27 years for 90% of cars to operate at highly automated levels.[6]

It is important to keep in mind that most advancements in automotive technology are currently being driven by safety, comfort, and convenience, and not capacity. The HCM's capacity adjustments assume a high level of communication and automation technologies that enable vehicles to travel at shorter headways. When viewing research on market penetration rates, it is therefore important to consider what level of automation and connectivity is assumed in a given study and to distinguish marketing hype from actual vehicle capabilities. The CAVs assumed by the HCM's method correspond to SAE automation levels 4 and 5, which were not commercially available as of 2022.

Exhibit 6B-2 summarizes available research on CAV adoption.

Exhibit 6B-2 CAV Adoption Research Percentages

Decade	VTPI (2023)[1]	Iowa Study (2017)[2]	SAFE Study (2018)[3]	S&P Financial Services (2018)[4]
2020s	0%	0–10%	<10%	0–20%
2030s	1–4%	10–50%	15–70%	5–50%
2040s	10–30%	20–80%	50–90%	
2050s	30–50%	40–100%	100%	
2060s	50–80%	65–100%		
2070s	?			

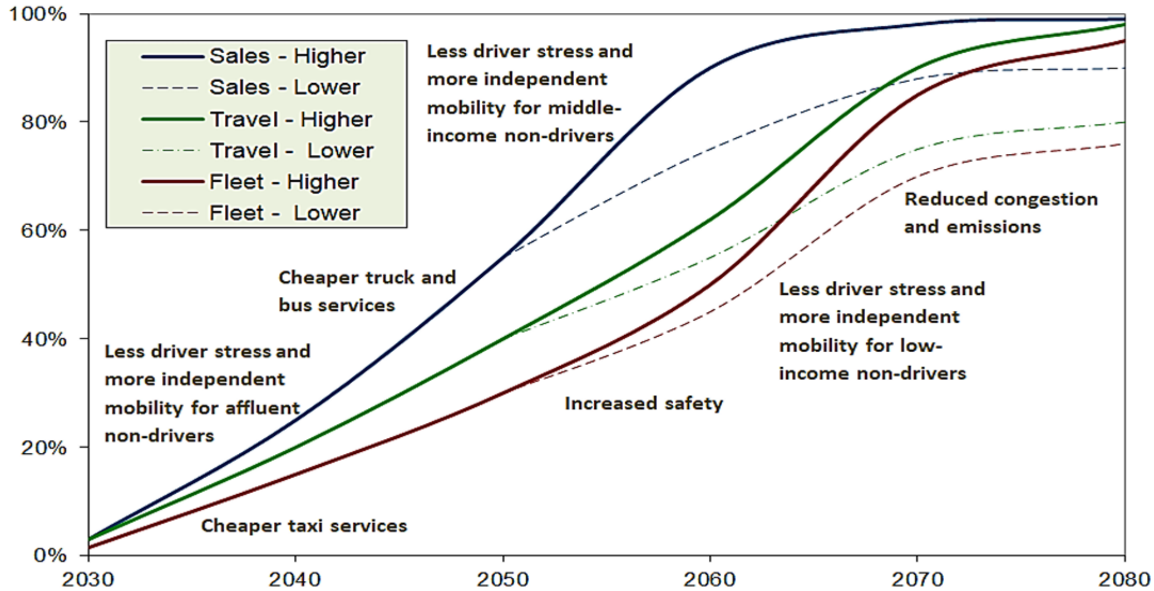
Notes:

1. VTPI considers estimates from several researchers along with its own estimates. The estimates shown are for AV percentage of travel. Further projections for vehicles sales and fleet are provided in Exhibit 6B-8.
2. Iowa DOT Interstate 80 Planning Study projections reflect the AV adoption rate at automation level 3 or above. They are based on industry-leading research and reflect a range of conservative to aggressive market adoption. Further details are provided in Exhibit 6B-4.
3. Securing America's Future Energy (SAFE) study. Rates reflects AV percentage of travel and reflect a fleet deployment scenario and personal ownership scenario, shown in Exhibit 6B-5.
4. Reflects AV share of total light vehicle sales and a range of low to high disruption, shown in Exhibit 6B-6.

[5] Forsgren, K., Shah, D., & Lum, D. *The Road Ahead for Autonomous Vehicles*. Standard & Poor's (S&P) Financial Services LLC. 2018.

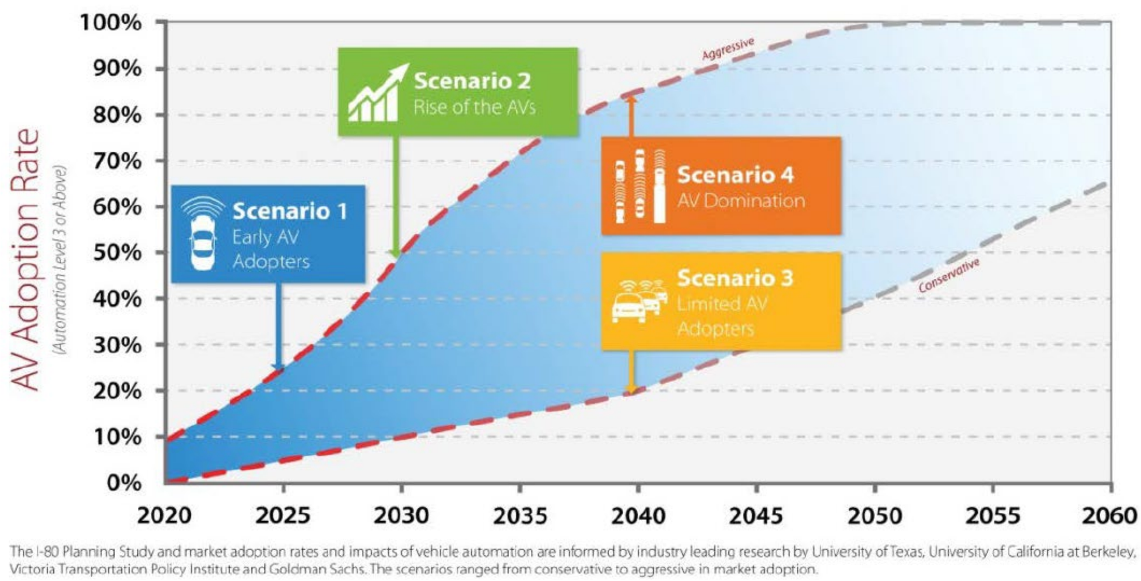
[6] Straight, B. *Autonomous vehicle timeline: Perhaps your kids will ride in one*. Freight Waves. 2018.

Exhibit 6B-3 VTPI Autonomous Vehicle Sales, Fleet, and Travel Projections



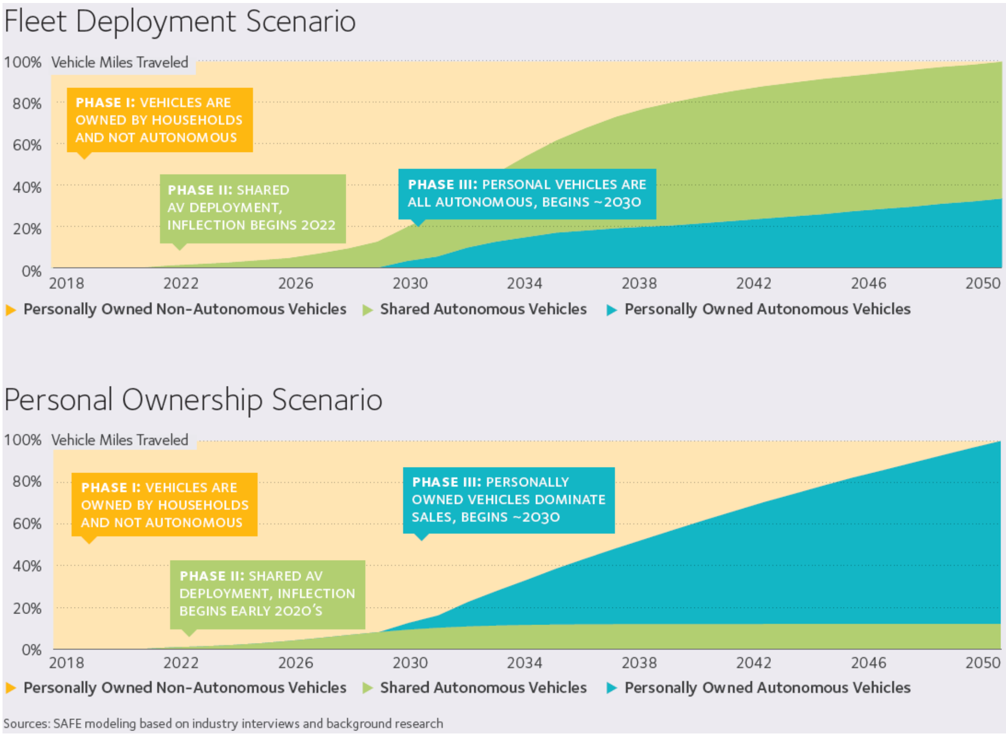
Source: VTPI, *Autonomous Vehicle Implementation Predictions*. Updated January 25, 2023.

Exhibit 6B-4 Iowa Study AV Adoption Rate



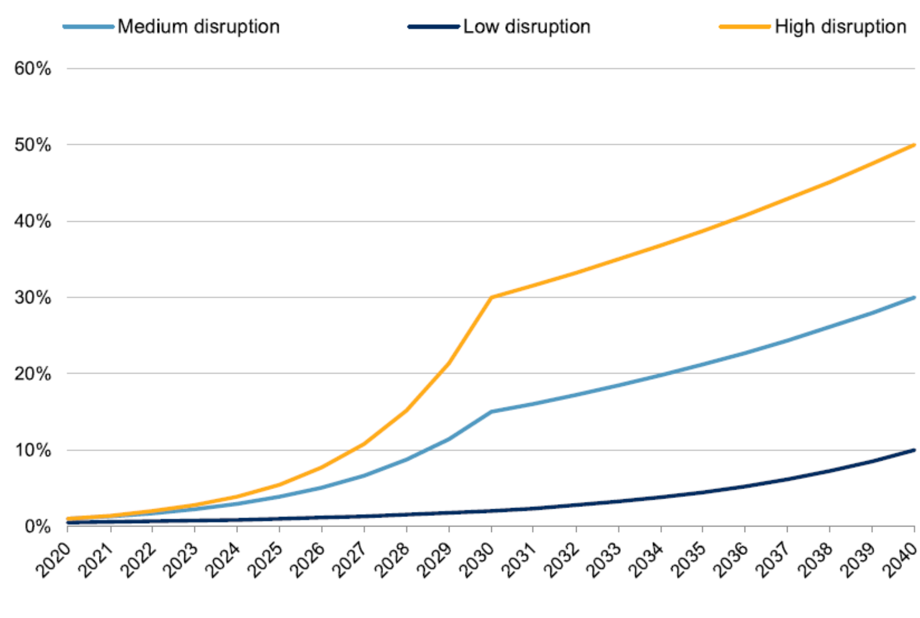
Source: Iowa DOT, *Interstate 80 Planning Study (PEL)*. June 2017.

Exhibit 6B-5 SAFE Study Fleet Depolyment and Personal Ownership Scenarios



Source: SAFE, *America's Workforce and the Self-Driving Future*. June 2018.

Exhibit 6B-6 S&P Financial Services AV Share of Total Light Vehicle Sales



Source: S&P Global Ratings.

Source: Forsgren, K., Shah, D., & Lum, D. *The Road Ahead for Autonomous Vehicles*. S&P Financial Services LLC. 2018.

Potential Differences by Fleet Type

Some research predicts that commercial trucks will be the first production vehicles on the road with more advanced levels of automation, such as platooning. The move towards autonomous trucking may be driven by both technology and financial incentives. Some companies are exploring a transfer hub model, where trucks would operate in an autonomous mode on highways and then switch to human-driven on local roads close to their destination. Research indicates that there is a significant case for the business value of autonomous trucks, noting "decreased labor costs, enhanced driving times and range, improved fuel efficiency, and… better safety performance."[7] The current HCM methodologies do not provide the option to vary CAV market penetration by fleet type, and note that future research is needed to assess the effect of automated and connected trucks on traffic streams.

Given that the first production CAVs to be available are expected to be significantly more expensive than non-automated vehicles, due to the additional sensors, communications equipment, and computing power required, private CAV ownership may be limited in early years until the price of components falls to more affordable levels. Instead, an initial use case that may develop is automated ride-hailing vehicles. This use case would allow ride-hailing companies to recoup the vehicle cost by keeping it in service for much of the day, while allowing households to experience some of the benefits of CAVs without the significant up-front investment in an automated vehicle. Other examples of potential CAV applications include transit and on-demand delivery services. These applications could also have implications for changing household travel patterns and behaviors.

Potential Differences by Facility Type

Some highway types may experience higher CAV percentages than others, depending on the initial CAV use cases that develop. For example, major truck freight routes (e.g., Interstate highways, US 97) may experience higher CAV percentages if the trucking industry is an early adopter of automation, especially if a transfer hub model is pursued that focuses on the more-controlled highway environment for automation. Major commute routes to urban areas may experience higher CAV percentages if commuters purchase CAVs to support a less-stressful, more productive, and/or longer commute.

It is also conceivable that CAV-only lanes could be developed in the future to improve facility safety, promote the adoption of CAVs, and/or provide smoother operations for CAVs and their occupants. In this case, the CAV-only lane would have 100% CAVs, while the general-purpose lanes would only have those CAVs entering or exiting the facility. Note that the pooled fund study found that converting a general purpose lane to CAV-only will generally not increase freeway throughput relative to keeping the entire facility a mix of CAVs and non-CAVs, but that converting a managed lane to CAV-only

[7] Zarif, R. et al. *Autonomous Trucks lead the way.* Deloitte. February 17, 2021.

does have the potential to increase throughput once CAV volumes on the facility approach the vehicle volume using the managed lane.[8]

Potential Differences by Area Type

It is likely that in the early years of deployment, CAVs will be more prevalent in urban areas than in rural areas, given the greater number of potential early use cases (e.g., commuting, ride-hailing, freight distribution) existing in urban areas. In addition, the potential market for private CAVs, and thus the presence of dealerships with staff with the necessary skills to service CAVs, is likely to be most concentrated in urban areas. However, it is conceivable that a rural CAV owner could have a CAV drive itself to a dealership in an urban area to receive regularly scheduled maintenance. Recently, autonomous vehicle testing has started to focus on rural roads. University of Iowa's *Automated Driving Systems (ADS) for Rural America* is focused on the testing and use of automated driving technologies on rural roadways, with the goals of representing rural roadways in AV research and broadening mobility. Texas A&M Engineering Experiment Station is also studying CAVs in rural applications as part of its AVA: Automated Vehicles for All program, including rural roads in Texas.

Recommendations for Estimating the CAV Percentage

Given that CAV technology is still being developed and will continue to evolve for some time, and given the unknowns related to CAV adoption once CAVs are commercially available, any specific guidance regarding CAV percentage will quickly become dated. It is recommended that:

- Analysts review the most recent projections on CAV deployment from various researchers when starting the study,
- Consider local conditions that might suggest a higher or lower percentage of CAVs than a national average, and
- Test multiple CAV scenarios to determine whether the assumed CAV percentage makes a difference in the analysis conclusions.

Guidance on estimating the CAV percentage for applications in Oregon is provided in Appendix 6C. It is expected that Appendix 6C will be updated over time as new research becomes available.

[8] Schroeder, B. et al. 2022. *Capacity Adjustment Factors for Connected and Automated Vehicles in the* Highway Capacity Manual: *Phase 1 and 2 Final Report.* Appendix A, Freeway Scenario 3. Oregon Department of Transportation, Salem.

Guidance on Adjusting Capacity for CAV Presence

As of 2022, no vehicles were available commercially that met the definition of a CAV for the purposes of an HCM analysis (i.e., a vehicle with an operating cooperative adaptive cruise control system that is capable of communicating with other vehicles and driving without human intervention in any situation). The capacity adjustment process presented in this section is intended for use only in longer-range planning analyses.

Because CAVs are not yet commercially available, capacity adjustments for CAVs should not be made in near-term analyses such as traffic impact studies.

This section provides guidance for adjusting the future capacity of freeways, signalized intersections, and roundabouts to account for the presence of CAVs in the traffic stream. All future-year analyses involve some degree of uncertainty, but this is particularly the case with CAV analyses. As described above, CAV technology is only partially developed at present, it is not fully known how the technology will operate once it becomes available, and it is not known when or how quickly CAVs will become available. As a consequence:

- **CAV analyses should only be conducted as part of broad-brush and screening analyses** investigating the potential sufficiency of a roadway to accommodate forecasted future volumes. Section 11.2 in Chapter 11 defines broad-brush and screening analysis. Exhibit 6B-7 lists types of planning studies where CAV analyses might be or are not applicable.
- **CAV analyses should not be conducted for horizon years prior to 2040.** CAVs may become commercially available considerably earlier. However, they are expected to form a small enough portion of the overall traffic stream prior to 2040 that they would not significantly influence roadway capacity or planning study recommendations, particularly considering all the other uncertainties in future-year analyses (e.g., traffic volume forecasts, travel demand patterns). Therefore, near-term final design decisions should not rely on CAV analyses. CAV analyses are optional for horizon years of 2040 or later.
- **CAV analyses are recommended to incorporate more than one scenario** to test the effects of different assumptions (e.g., percent CAVs in the traffic stream, CAV capacity benefit) on the analysis conclusions. Guidance on scenario analysis is provided in the next section.

Exhibit 6B-7 Applicability of CAV Analyses to Common Transportation and Planning and Engineering Applications

Application	CAV Analysis Applicable?
Regional Transportation Plan	◐
Transportation System Plan	◐
Corridor Plan	◐
Refinement Plan[1]	○
Project Development[1]	○
Traffic Impact Study	○

Notes: ○ = not applicable, ◐ = possibly applicable, ● = likely applicable.
[1] CAV analysis may be applicable if the analysis year is 2040 or later

See Appendix 6C for additional guidance on the applicability of CAV analyses and contact TPAU for specific questions or direction.

Capacity Adjustments for Freeways

Screening Analysis

Section 11.3 in Chapter 11 presents four-step processes for estimating the capacity of basic freeway, merge–diverge, and weaving sections. To estimate a section's capacity with CAVs in the traffic stream, do the following:

- First, determine the section's adjusted capacity without CAVs, using the equation provided in Step 4 of the process for a basic freeway, merge–diverge, or weaving section, as appropriate, and applying a default value of 1.00 for CAF_{CAV}.

- Next, determine the value of CAF_{CAV}:
  - For basic freeway sections, use Exhibit 6B-8, applying the assumed proportion of CAVs in the traffic stream and the adjusted segment capacity without CAVs, and interpolating in the table as needed.
  - For merge–diverge sections, use Exhibit 6B-9, applying the assumed proportion of CAVs in the traffic stream and interpolating in the table as needed.
  - For weaving sections, use Exhibit 6B-10, applying the assumed proportion of CAVs in the traffic stream and volume ratio (weaving demand flow rate divided by total demand flow rate), and interpolating in the table as needed.

- Finally, determine the section's capacity with CAVs by multiplying the capacity without CAVs by the value of CAF_{CAV} determined in the previous step.

Exhibit 6B-8 Capacity Adjustment Factors for Basic Freeway Sections based on Adjusted Segment Capacity without CAVs

Proportion of CAV's in Traffic Stream	2,400 pc/h/ln	2,100 pc/h/ln	1,800 pc/h/ln
0	1.00	1.00	1.00
20	1.02	1.02	1.15
40	1.07	1.10	1.27
60	1.13	1.25	1.40
80	1.22	1.37	1.60
100	1.33	1.52	1.78

Source: HCM 7, Exhibit 26-15.
Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and adjusted segment capacities.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to the given adjusted segment capacity.

Exhibit 6B-9 Capacity Adjustment Factors for Merge–Diverge Sections

Proportion of CAVs in Traffic Stream	CAF_{CAV}
0	1.00
20	1.02
40	1.07
60	1.16
80	1.33
100	1.45

Source: HCM 7, Exhibit 26-16.
Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and adjusted segment capacities.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,200 pc/h/ln.

Exhibit 6B-10 Capacity Adjustment Factors for Weaving Sections based on Volume Ratio

Proportion of CAVs in Traffic Stream	0.2	0.3	0.4
0	1.00	1.00	1.00
20	1.03	1.04	1.05
40	1.08	1.08	1.09
60	1.15	1.15	1.13
80	1.23	1.22	1.20
100	1.37	1.37	1.34

Source: HCM 7, Exhibit 26-17.
Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and volume ratios.
The volume ratio is the weaving demand flow rate divided by the total demand flow rate in the segment.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,200 pc/h/ln.

Broad Brush Analysis

Exhibit 11-11 in Chapter 11 presents generalized design-hour, peak-direction freeway capacities for various combinations of urban and rural area types; level, rolling, and mountainous terrain; and posted automobile speed limits ranging from 50 to 70 mph. An equation following the exhibit can be used to adjust the exhibit's values to better reflect local conditions; this equation can also be used to account for the effects of CAVs on future capacity. Use Exhibit 6B-9 for merge–diverge sections to determine a CAF_{CAV} value to use with this equation, based on the assumed proportion of CAVs in the traffic stream. Interpolate in the table as needed.

Capacity Adjustments for Roundabouts

The capacity model for entry lanes to a roundabout consists of exponential curves whose intercepts and slopes have been fitted to field data for single-lane approaches and, separately, the left and right lanes of two-lane approaches. To account for the presence of CAVs in the traffic stream, the HCM applies CAV adjustment factors f_A and f_B to the intercept and slope parameters, respectively. The f_A adjustment increases the intercept, resulting in a higher starting entry capacity, while the f_B adjustment reduces the slope, causing the entry capacity to decrease more slowly as conflicting circulatory traffic volume increases.

The capacity equation in Step 5 of the roundabout automobile methodology in Chapter 12 is modified as follows to account for CAVs:

$$C = f_A A e^{(-f_B B \times V_c)}$$

where:

C = roundabout entry lane capacity (pc/h)
A = intercept parameter, from Exhibit 6B-11
V_c = circulating (conflicting) flow (pc/h)
B = slope parameter, from Exhibit 6B-11
f_A = CAV adjustment factor for the intercept parameter, from Exhibit 6B-12
f_B = CAV adjustment factor for the slope parameter, from Exhibit 6B-12

Exhibit 6B-11 Roundabout Entry Lane Capacity Model Parameters

Entry Lane Type	*A*	*B*
One-lane entry conflicted by one circulating lane	1,380	0.00102
Two-lane entry conflicted by one circulating lane (both entry lanes)	1,420	0.00091
One-lane entry conflicted by two circulating lanes	1,420	0.00085
Two-lane entry conflicting by two circulating lanes (right entry lane)	1,420	0.00085
Two-lane entry conflicting by two circulating lanes (left entry lane)	1,350	0.00092

Source: HCM 7, Exhibit 33-12

Exhibit 6B-12 Capacity Adjustment Factors for CAVs for Roundabouts

Proportion of CAVs in Traffic Stream	1-Lane Entry				2-Lane Entry					
	1 Circulating Lane		2 Circulating Lanes[a]		1 Circulating Lane, Both Lanes[a]		2 Circulating Lanes, Left Lane		2 Circulating Lanes, Right Lane	
	f_A	f_B	f_A	f_B	f_A	f_B	f_A	f_B	f_A	f_B
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	1.05	0.99	1.03	0.99	1.05	0.99	1.03	0.99	1.05	0.96
40	1.12	0.97	1.08	0.96	1.12	0.97	1.08	0.96	1.12	0.93
60	1.22	0.94	1.18	0.92	1.22	0.94	1.18	0.92	1.20	0.87
80	1.29	0.90	1.28	0.89	1.29	0.90	1.28	0.89	1.27	0.84
100	1.35	0.85	1.38	0.85	1.35	0.85	1.38	0.85	1.34	0.80

Notes: [a] These cases were not specifically analyzed in the research and thus are suggested approximations.
CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions.
Assumptions: Human-driven vehicles operate with average gaps calibrated to the entry lane capacity given by HCM Chapter 22.

Capacity Adjustments for Signalized Intersections

Through Movements

The presence of CAVs in a through movement traffic stream can be accounted for by using an adjusted base saturation flow rate value from Exhibit 6B-13 to replace the standard base saturation flow rate. As discussed in Chapter 3, ODOT uses a base saturation flow rate of 1,900 pc/h/ln for signalized intersections in the Portland, Salem, and Eugene metropolitan areas (with some exceptions) and 1,750 pc/h/ln elsewhere. The table column used to select the adjusted saturation flow rate should match the base saturation flow rate that would otherwise be used. The adjusted base saturation flow rate can then be used with the normal saturation flow adjustment factors for heavy vehicle presence, parking activity, etc. The research conducted as part of the pooled fund study did not study the effect of lane width and CAVs and therefore the HCM suggests that the adjustment for lane width should not be applied when CAVs are present.

Exhibit 6B-13 CAV-Adjusted Base Saturation Flow Rates for Through Movements at Signalized Intersections

Proportion of CAVs in Traffic Stream	**Base = 1,900** pc/h/ln	**Base = 1,750** pc/h/ln
0	1,900	1,750
20	2,000	1,870
40	2,150	2,040
60	2,250	2,150
80	2,550	2,500
100	2,900	2,900

Source: Adapted from HCM 7, Exhibit 31-64.
Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Assumes no interaction with non-motorized road users, no adverse weather impacts, and a facility without driveways or access points impacting saturation flow rates.
Interpolate for other CAV proportions.

Note that the column for a base saturation flow rate of 1,750 pc/h/ln is an extension of the HCM method. For freeways, the pooled fund study found that the facility throughput was the same at 100% CAVs regardless of the starting capacity (i.e., capacities reduced due to lower design speeds). The same principle has been applied in Exhibit 6B-13 when estimating the CAV-adjusted saturation flow rate from a starting point of 1,750 pc/h/ln.

Protected Left-Turn Movements

The presence of CAVs in a protected left-turn traffic stream (including the protected portion of protected–permitted left-turn operation) can be accounted for by applying a saturation flow rate adjustment factor $f_{CAV,prot}$ from Exhibit 6B-14 to the base saturation flow rate of 1,750 or 1,900 pc/h/ln. This factor is applied in addition to the usual adjustments for heavy vehicle presence, area type, etc. As with through movements, the adjustment for lane width should not be applied in a CAV analysis.

Exhibit 6B-14 Saturation Flow Rate CAV Adjustment for Protected Left-Turn Movements at Signalized Intersections

Proportion of CAVs in Traffic Stream	Saturation Flow Rate Adjustment for Protected Left Turns, $f_{CAV,prot}$
0	1.00
20	1.01
40	1.07
60	1.11
80	1.21
100	1.56

Source: HCM 7, Exhibit 31-65.

Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s, CAV interplatoon gap = 1.5 s, maximum CAV platoon size = 8 pc, human-driven vehicles operate with through movement saturation flow rates calibrated to 1,900, assumes no interaction with non-motorized road users, no adverse weather impacts, and a facility without driveways or access points impacting saturation flow rates.
Interpolate for other CAV proportions.

Permitted Left-Turn Movements

The presence of CAVs in a permitted left-turn traffic stream (including the permitted portion of protected–permitted left-turn operation) can be accounted for by applying a saturation flow rate adjustment factor $f_{CAV,perm}$ from Exhibit 6B-15 to the base saturation flow rate of 1,750 or 1,900 pc/h/ln. The adjustment factor to be used depends on both the opposing through volume per lane and the proportion of CAVs in the traffic stream. The CAV adjustment factor is applied in addition to the usual adjustments for heavy vehicle presence, area type, etc. As with through movements, the adjustment for lane width should not be applied in a CAV analysis.

Exhibit 6B-15 Saturation Flow Rate CAV Adjustment for Permitted Left-Turn Movements at Signalized Intersections

Proportion of CAVs in Traffic Stream	Saturation Flow Rate Adjustment for Permitted Left Turns $f_{CAV,perm}$ by Opposing Through Volume Per Lane (pc/h/ln)			
	300	450	600	750
0	1.00	1.00	1.00	1.00
20	1.12	1.04	1.03	1.07
40	1.20	1.16	1.12	1.18
60	1.29	1.22	1.26	1.36
80	1.43	1.43	1.57	1.60
100	1.76	1.72	1.66	1.90

Source: HCM 7, Exhibit 31-66.

Notes: CAV = connected and automated vehicle, defined as a vehicle with an operating cooperative adaptive cruise control system.

Assumptions: Average intervehicle gap within CAV platoons = 0.71 s, CAV interplatoon gap = 1.5 s, maximum CAV platoon size = 8 pc, human-driven vehicles operate with through movement saturation flow rates calibrated to 1,900, assumes no interaction with non-motorized road users, no adverse weather impacts, and a facility without driveways or access points impacting saturation flow rates.

Interpolate for other CAV proportions.

Right-Turn Movements

No research has been performed to date on the effects of CAVs on the capacity of right-turn movements. Therefore, no saturation flow adjustment for CAVs should be made for these movements.

Guidance on Scenario Development

If an analysis meets the requirements outlined above and CAVs are going to be considered, it is recommended that the analyst develop a range of scenarios in order to understand how CAVs could impact operations. These scenarios can be used to create bookends to describe the range of future operations. For example, the analysis could forecast a freeway's future volume-to-capacity ratio assuming CAV proportions of 0%, 40%, and 80%. This type of analysis can help demonstrate how significantly (or insignificantly) CAVs may affect roadway operations. In some cases, the analysis may lead to the conclusion that with a higher proportion of CAVs in the traffic stream, fewer lanes are needed on a freeway or at an intersection, while in other cases the analysis' conclusions may not change.

Illustrative Examples

The following examples are intended to demonstrate instances when CAVs may be considered. They are not intended to be prescriptive, but instead to illustrate potential applications of the capacity adjustments described in this appendix. Appendix A of the pooled fund study Phase 1 and 2 final report provides additional examples.

To be able to apply CAV capacity adjustments, the analyst needs to assume one or more values of the percentage of CAVs in the traffic stream that could possibly occur in the forecast year. The examples in this section assume that the analyst has reviewed the "Guidance on Estimating the CAV Percentage" section and has selected low and high estimates of the CAV percentage based on the latest information available at the time of the analysis, considering both the forecast year and site-specific conditions. The CAV percentages used in these examples are illustrative only and *should not* be taken as recommendations for the percentages that should be assumed in an actual analysis.

Example 6B-1 Freeway Analysis (Screening Method)

This example is a variation of Example Problem 11-2 in the APM that has been adjusted to account for the potential presence of CAVs.

- First, determine the section's adjusted capacity without CAVs, using the equation provided in Step 4 of the process for a basic freeway and applying a default value of 1.00 for CAF_{CAV}.

  Step 1. Gather Input Data. The freeway segment being analyzed is located in an urban area with mountainous terrain, with a FFS of 55 mph. There are three lanes in each direction. The AADT is 160,000 with K = 8.2 and D = 52; the volume includes 4.1% heavy vehicles. The driver population is familiar with the facility.

  The AADT must be converted into a peak-hour volume by multiplying by the decimal version of the facility's *K*- and *D*-factors, resulting in a (rounded) volume of 6,820 veh/h.

  Step 2. Adjust Volumes. The peak-15-minute demand flow rate is determined by dividing the peak hour volume by the peak hour factor. The PHF is unknown; therefore, the default value of 0.94 for freeways is used (see Appendix 11C or HCM 7). The resulting demand flow rate is 6,820 / 0.94 = 7,255 veh/h.

  Step 3. Determine the Capacity Adjustment Factor. Because this section has a population of drivers familiar with the facility, CAF_{pop} = 1.00. To begin with, assume a default value of 1.00 for CAF_{CAV}.

  Step 4. Determine Section Capacity. Because the section is located in mountainous terrain, a truck equivalency of 5 is used. The capacity of the basic freeway section is then:

$$c = \frac{\left(2{,}200 + 10 \times (\min(70, FFS) - 50)\right)}{1 + (E_T - 1)(\%HV/100)} \times CAF_{pop} \times CAF_{CAV}$$

$$= \frac{\left(2{,}200 + 10 \times (\min(70{,}55) - 50)\right)}{1 + (5 - 1)(4.1/100)} \times 1.00 \times 1.00 = 1{,}933 \text{ pc/h/ln}$$

- Next, determine the value of CAF_{CAV}:
  - For basic freeway sections, use Exhibit 6B-8, applying the assumed proportion of CAVs in the traffic stream and the adjusted segment capacity without CAVs, and interpolating in the table as needed.

Based on the most recent information available to the analyst, the U.S. fleet is expected to consist of 10–30% CAVs in the analysis year of 2045. Because this freeway serves as a commute route in an urban area, the higher value of 30% is selected for the baseline scenario. A lower rate of 10% is selected for an alternative scenario in which CAV adoption takes longer.

The CAF_{CAV} is interpolated based on a segment capacity of 1,933 pc/h/ln, using the portion of Exhibit 6B-8 shown below.

Proportion of CAVs in Traffic Stream	Adjusted Segment Capacity without CAVs 2,100 pc/h/ln	Adjusted Segment Capacity without CAVs 1,800 pc/h/ln
0	1.00	1.00
20	1.02	1.15
40	1.10	1.27

CAF for 10% proportion of CAVs in traffic stream:

$$CAF(2{,}100\ \mathrm{pc/h/ln}) = 1.00 + (1.02 - 1.00)\frac{(10-0)}{(20-0)} = 1.010$$

$$CAF(1{,}800\ \mathrm{pc/h/ln}) = 1.00 + (1.15 - 1.00)\frac{(10-0)}{(20-0)} = 1.075$$

The resulting CAFs are then interpolated for adjusted segment capacity as follows:

$$CAF(1{,}933\ \mathrm{pc/h/ln}) = 1.075 + (1.010 - 1.075)\frac{(1{,}933 - 1{,}800)}{(2{,}100 - 1{,}800)} = 1.0462$$

CAF for 30% proportion of CAVs in traffic stream:

$$CAF(2{,}100\ \mathrm{pc/h/ln}) = 1.02 + (1.10 - 1.02)\frac{(30-20)}{(40-20)} = 1.060$$

$$CAF(1{,}800\ \mathrm{pc/h/ln}) = 1.15 + (1.27 - 1.15)\frac{(30-20)}{(40-20)} = 1.210$$

The resulting CAFs are then interpolated for adjusted segment capacity as follows:

$$CAF(1{,}933\ \mathrm{pc/h/ln}) = 1.210 + (1.060 - 1.210)\frac{(1{,}933 - 1{,}800)}{(2{,}100 - 1{,}800)} = 1.1435$$

- Finally, determine the section's capacity with CAVs by multiplying the capacity without CAVs by the value of CAF_{CAV} determined in the previous step.

  The section's per-lane capacity is multiplied by the number of lanes and the interpolated CAF to give its capacity with 10% CAVs in the traffic stream:

  $$1{,}933 \times 3 \times 1.0462 = 6{,}067 \text{ pc/h}$$

  and with 30% CAVs in the traffic stream:

  $$1{,}933 \times 3 \times 1.1435 = 6{,}631 \text{ pc/h}$$

  The *v/c* ratio for each scenario is determined by dividing the volume of 7,255 by the capacity:

Proportion of CAVs in Traffic Stream	Capacity	v/c Ratio
0	5,799 pc/h	1.25
10	6,067 pc/h	1.20
30	6,631 pc/h	1.09

  As shown, the freeway is forecast to be over capacity whether the proportion of CAVs in the traffic stream is 0%, 10%, or 30%.

Example 6B-2 Freeway Capacity Analysis (Broad-Brush Method)

This example is a variation of Example Problem 11-10 in the APM that has been adjusted to account for the potential presence of CAVs.

A six-lane urban freeway (three lanes in each direction) is located in rolling terrain and has a 50-mph speed limit. The projected 2060 AADT is 121,400, the *K*-factor is 7.7, the *D*-factor is 54, the PHF is 0.92, and the heavy-vehicle percentage is 9.1. Determine the capacity and v/c ratio under these conditions, considering the influence of CAVs.

The design-hour volume *V* is:

$$V = AADT \times \frac{K}{100} \times \frac{D}{100} = 121{,}400 \times \frac{7.7}{100} \times \frac{54}{100} = 5{,}050 \text{ veh/h}$$

The capacity obtained from Exhibit 11-11, which assumes 5% heavy vehicles, a PHF of 0.94, and two travel lanes, is 3,655 veh/h. An adjusted local capacity can be determined as follows by substituting the local heavy-vehicle percentage, PHF, and number of lanes, while keeping the table values for all other inputs that are unknown or unchanged:

$$c_{adj} = c_{table} \times \frac{PHF_{local}}{PHF_{table}} \times \frac{1 + (E_T - 1)(\%HV_{table}/100)}{1 + (E_T - 1)(\%HV_{local}/100)} \times \frac{N_{local}}{2} \times CAF_{pop} \times CAF_{CAV}$$

$$c_{adj} = 3{,}655 \times \frac{0.92}{0.94} \times \frac{1 + (3 - 1)(5/100)}{1 + (3 - 1)(9.1/100)} \times \frac{3}{2} \times 1.00 \times 1.00 = 4{,}994 \text{ pc/h}$$

This capacity can also be adjusted to account for the effects of CAVs on future capacity by applying a CAF_{CAV}.

Based on the most recent information available to the analyst, the U.S. fleet is expected to consist of 40–60% CAVs in the analysis year of 2060.

The CAF_{CAV} is based on a segment capacity of 1,665 pc/h/ln, using the portion of Exhibit 6B-8 shown below.

Proportion of CAVs in Traffic Stream	Adjusted Segment Capacity without CAVs 1,800 pc/h/ln
40	1.27
60	1.40

Because the segment capacity is lower than what is provided in the HCM, the values for 1,800 pc/h/ln are used. The CAF values in the HCM are higher for lower segment capacities, so using the values for 1,800 pc/h/ln is conservative.

The section's per-lane capacity is multiplied by the number of lanes and the CAF to give its capacity with 40% CAVs in the traffic stream:

$$1{,}665 \times 3 \times 1.27 = 6{,}344 \text{ pc/h}$$

and with 60% CAVs in the traffic stream:

$$1{,}665 \times 3 \times 1.40 = 6{,}993 \text{ pc/h}$$

The *v/c* ratio for each scenario is determined by dividing the volume of 5,050 by the capacity:

Proportion of CAVs in Traffic Stream	Capacity	v/c ratio
0	4,994 pc/h	1.01
40	6,344 pc/h	0.80
60	6,993 pc/h	0.72

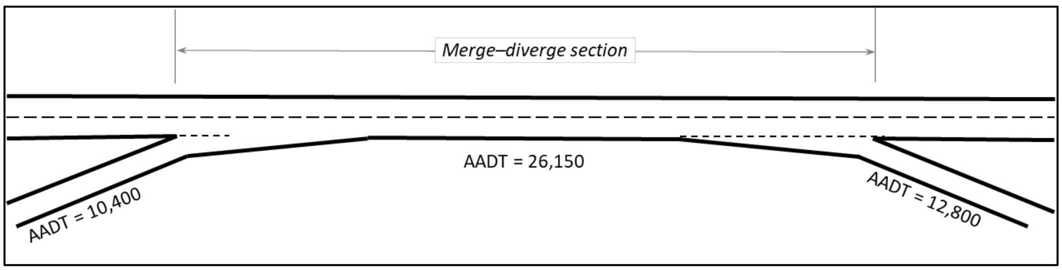
As shown, the freeway is forecast to be over capacity without considering CAVs, but well under capacity with 40% to 60% CAVs in the traffic stream.

Example 6B-3 Merge–Diverge Section Analysis (Screening Method)

This example is a variation of Example Problem 11-5 in the APM that has been adjusted to account for the potential presence of CAVs.

- First, determine the section's adjusted capacity without CAVs, using the equation provided in Step 4 of the process for a merge-diverge section and applying a default value of 1.00 for CAF_{CAV}.

  Step 1. Gather Input Data. The merge–diverge section has the lane configuration and 2045 directional AADTs shown below:



  This section of freeway is level and has 16.8% heavy vehicles, a *K*-factor of 9.3, and a FFS of 60 mph. The ramps have *K*-factors of 10.0. The on-ramp has 10.2% heavy vehicles, while the off-ramp has 3.5% heavy vehicles. No ramp metering is in use and drivers are familiar with the facility.

  The directional AADTs must be converted into peak-hour volumes by multiplying by the decimal version of the facility's *K*-factor. This results in a (rounded) freeway merge–diverge section volume of 2,430 veh/h, an on-ramp volume of 1,040 veh/h, and an off-ramp volume of 1,280 veh/h.

  Step 2. Adjust Volumes. The peak-15-minute demand flow rates are determined by dividing the peak hour volumes by the PHF. The PHF is unknown; therefore, the freeway default value of 0.95 is used. For the freeway ramp section, this is 2,430 / 0.95 = 2,558 veh/h. Similarly, the on-ramp flow rate is 1,095 veh/h and the off-ramp flow rate is 1,347 veh/h.

  Step 3. Determine Capacity Adjustment Factors. The merge–diverge section capacity adjustment factor CAF_{ramp} is 0.95. Because the driver population consists of familiar drivers, CAF_{pop} = 1.00. There is no ramp metering; therefore, CAF_{meter} = 1.00. To begin with, assume a default value of 1.00 for CAF_{CAV}.

Step 4. Determine the Section Capacity and v/c Ratio. The section capacity is calculated as:

$$c = \frac{\left(2{,}200 + 10 \times (\min(70, FFS) - 50)\right)}{1 + (E_T - 1)(\%HV/100)} \times CAF_{ramp} \times CAF_{pop} \times CAF_{meter} \times CAF_{CAV}$$

$$c = \frac{\left(2{,}200 + 10 \times (\min(70{,}60) - 50)\right)}{1 + (2 - 1)\left(\frac{16.8}{100}\right)} \times 0.95 \times 1.00 \times 1.00 \times 1.00 = 1{,}871 \text{ veh/h/ln}$$

- Next, determine the value of CAF_{CAV}:
  - For merge–diverge sections, use Exhibit 6B-9, applying the assumed proportion of CAVs in the traffic stream and interpolating in the table as needed.

Based on the most recent information available to the analyst, the U.S. fleet is expected to consist of 10–30% CAVs in the analysis year of 2045. Because this freeway serves as a commute route in an urban area, the higher value of 30% is selected for the baseline scenario. A lower rate of 10% is selected for an alternative scenario in which CAV adoption takes longer.

The CAF_{CAV} is interpolated using the portion of Exhibit 6B-9 shown below.

Proportion of CAVs in Traffic Stream	CAF_{CAV}
0	1.00
20	1.02
40	1.07

CAF for 10% proportion of CAVs in traffic stream:

$$CAF = 1.00 + (1.02 - 1.00)\frac{(10 - 0)}{(20 - 0)} = 1.010$$

CAF for 30% proportion of CAVs in traffic stream:

$$CAF = 1.02 + (1.07 - 1.02)\frac{(30 - 20)}{(40 - 20)} = 1.045$$

- Finally, determine the section's capacity with CAVs by multiplying the capacity without CAVs by the value of CAF_{CAV} determined in the previous step.

The section's per-lane capacity is multiplied by the number of lanes and the interpolated CAF to give its capacity with 10% CAVs in the traffic stream:

$$1{,}871 \times 2 \times 1.010 = 3{,}779 \text{ pc/h}$$

and with 30% CAVs in the traffic stream:

$$1{,}871 \times 2 \times 1.045 = 3{,}910 \text{ pc/h}$$

The *v/c* ratio for each scenario is determined by dividing the volume of 2,558 by the capacity:

Proportion of CAVs in Traffic Stream	Capacity	v/c ratio
0	3,741 pc/h	0.68
10	3,779 pc/h	0.68
30	3,910 pc/h	0.65

As shown, the freeway is forecast to operate under capacity whether the proportion of CAVs in the traffic stream is 0%, 10%, or 30%.

A methodology for adjusting the on-ramp and off-ramp capacity due to the presence of CAVs is not yet available, so the on-ramp *v/c* ratio is 1,095 / 2,000 = 0.55, while the off-ramp *v/c* ratio is 1,347 / 2,000 = 0.67.

Example 6B-4 Roundabout Analysis (Screening Method)

This example utilizes the traffic volumes from Example Problem 13-3 in the APM, also used in Example 6B-5. This example assumes a roundabout analysis is being conducted for a 2060 planning scenario using Vistro to evaluate future options.

The projected 2060 volumes and potential lane configurations were coded in Vistro, with a default peak hour factor of 0.92 and a default of 2% heavy vehicles assumed. The volume tab from Vistro is shown below.

Volumes

Number	1											
Intersection	**New Intersection**											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration												
Turning Movement	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	*27*	*299*	*27*	*27*	*326*	*27*	*217*	*978*	*109*	*136*	*1087*	*27*
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Base Volume Adjustment Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Final Base Volume [veh/h]	*25*	*275*	*25*	*25*	*300*	*25*	*200*	*900*	*100*	*125*	*1000*	*25*
Heavy Vehicles Percentage [%]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Proportion of CAVs [%]	0.00											
Growth Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
TIA Demand												
In-Process Volume [veh/h]	0	0	0	0	0	0	0	0	0	0	0	0
Future Background Volume [veh/h]	*25*	*275*	*25*	*25*	*300*	*25*	*200*	*900*	*100*	*125*	*1000*	*25*
Site-Generated Trips [veh/h]	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Diverted Trips [veh/h]	0	0	0	0	0	0	0	0	0	0	0	0
Pass-by Trips [veh/h]	0	0	0	0	0	0	0	0	0	0	0	0
Existing Site Adjustment Volume [veh/h]	0	0	0	0	0	0	0	0	0	0	0	0
Net new site trips [veh/h]	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Other Volume [veh/h]	0	0	0	0	0	0	0	0	0	0	0	0
Future Total Volume [veh/h]	*25*	*275*	*25*	*25*	*300*	*25*	*200*	*900*	*100*	*125*	*1000*	*25*
Total Hourly Volume [veh/h]	*25*	*275*	*25*	*25*	*300*	*25*	*200*	*900*	*100*	*125*	*1000*	*25*
Peak Hour Factor	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200	0.9200
Other Adjustment Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Total 15-Minute Volume [veh/h]	*7*	*75*	*7*	*7*	*82*	*7*	*54*	*245*	*27*	*34*	*272*	*7*
Total Analysis Volume [veh/h]	*27*	*299*	*27*	*27*	*326*	*27*	*217*	*978*	*109*	*136*	*1087*	*27*
Pedestrian Volume [ped/h]	0			0			0			0		

With these inputs, Vistro projects the v/c ratios shown below.

Traffic Control ✓ ☐ Automatic Optimization

	↑			↓			→			←		
Number	1											
Intersection	New Intersection											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration												
Turning Movement	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	27	299	27	27	326	27	217	978	109	136	1087	27

Intersection Settings

Lanes

	Northbound	Southbound	Eastbound		Westbound	
Overwrite Calculated Critical Headway	☐	☐	☐	☐	☐	☐
User-Defined Critical Headway [s]	4.00	4.00	4.00	4.00	4.00	4.00
Overwrite Calculated Follow-Up Time	☐	☐	☐	☐	☐	☐
User-Defined Follow-Up Time [s]	3.00	3.00	3.00	3.00	3.00	3.00
A (intercept)	1380.00	1380.00	1420.00	1420.00	1420.00	1420.00
B (coefficient)	0.00102	0.00102	0.00091	0.00091	0.00091	0.00091
HV Adjustment Factor	0.98	0.98	0.98	0.98	0.98	0.98
Entry Flow Rate [veh/h]	361	388	626	705	600	676
Capacity of Entry and Bypass Lanes [ve	388	376	902	902	858	858
Pedestrian Impedance	1.00	1.00	1.00	1.00	1.00	1.00
Capacity per Entry Lane [veh/h]	380	369	885	885	842	842
X, volume / capacity	0.93	1.03	0.69	0.78	0.70	0.79

Movement, Approach, & Intersection Results

	Northbound	Southbound	Eastbound		Westbound	
Average Lane Delay [s/veh]	63.41	89.45	16.19	20.86	17.06	22.09
Lane LOS	F	F	C	C	C	C
95th-Percentile Queue Length [veh]	9.97	12.68	5.79	8.05	5.87	8.15
95th-Percentile Queue Length [ft]	249.29	316.88	144.70	201.28	146.66	203.86
Approach Delay [s/veh]	63.41	89.45	18.67		19.73	
Approach LOS	F	F	C		C	
Intersection Delay [s/veh]	32.06					
Intersection LOS	D					

As shown, the southbound approach is projected to be over-capacity (1.03) and the northbound approach is approaching capacity (0.93).

Based on the most recent information available to the analyst, the U.S. fleet is expected to consist of 40–60% CAVs in the analysis year of 2060. The percentage of CAVs was adjusted in Vistro to model operations with 40% CAVs and with 60% CAVs.

With 40% CAVs:

Volumes

Enter text to search...

	↑			↓			→			←		
Number	1											
Intersection	**New Intersection**											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration	+			+			┤├			┤├		
Turning Movement	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	*27*	*299*	*27*	*27*	*326*	*27*	*217*	*978*	*109*	*136*	*1087*	*27*
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Base Volume Adjustment Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Final Base Volume [veh/h]	*25*	*275*	*25*	*25*	*300*	*25*	*200*	*900*	*100*	*125*	*1000*	*25*
Heavy Vehicles Percentage [%]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Proportion of CAVs [%]	40.00											
Growth Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Traffic Control

Automatic Optimization

Enter text to search...

	↑			↓			→			←		
Number	1											
Intersection	**New Intersection**											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration	+			+			┤├			┤├		
Turning Movement	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*	*Left*	*Thru*	*Right*
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	*27*	*299*	*27*	*27*	*326*	*27*	*217*	*978*	*109*	*136*	*1087*	*27*

Intersection Settings						
Lanes						
Overwrite Calculated Critical Headway	☐	☐	☐	☐	☐	☐
User-Defined Critical Headway [s]	4.00	4.00	4.00	4.00	4.00	4.00
Overwrite Calculated Follow-Up Time	☐	☐	☐	☐	☐	☐
User-Defined Follow-Up Time [s]	3.00	3.00	3.00	3.00	3.00	3.00
A (intercept)	*1545.60*	*1545.60*	*1590.40*	*1590.40*	*1590.40*	*1590.40*
B (coefficient)	*0.00099*	*0.00099*	*0.00088*	*0.00088*	*0.00088*	*0.00088*
HV Adjustment Factor	*0.98*	*0.98*	*0.98*	*0.98*	*0.98*	*0.98*
Entry Flow Rate [veh/h]	*361*	*388*	*626*	*705*	*600*	*676*
Capacity of Entry and Bypass Lanes [ve	*451*	*438*	*1024*	*1024*	*976*	*976*
Pedestrian Impedance	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Capacity per Entry Lane [veh/h]	*442*	*430*	*1004*	*1004*	*957*	*957*
X, volume / capacity	*0.80*	*0.89*	*0.61*	*0.69*	*0.61*	*0.69*
Movement, Approach, & Intersection Results						
Average Lane Delay [s/veh]	*37.54*	*50.33*	*12.09*	*14.55*	*12.64*	*15.25*
Lane LOS	*E*	*F*	*B*	*B*	*B*	*C*
95th-Percentile Queue Length [veh]	*7.24*	*9.25*	*4.32*	*5.78*	*4.37*	*5.84*
95th-Percentile Queue Length [ft]	*180.88*	*231.32*	*108.00*	*144.38*	*109.15*	*145.94*
Approach Delay [s/veh]	37.54	50.33	13.39		14.02	
Approach LOS	**E**	**F**	**B**		**B**	
Intersection Delay [s/veh]	*20.50*					
Intersection LOS	*C*					

With 60% CAVs:

Volumes

	↑			↓			→			←		
Number	1											
Intersection	New Intersection											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration												
Turning Movement	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	27	299	27	27	326	27	217	978	109	136	1087	27
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Base Volume Adjustment Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Final Base Volume [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Heavy Vehicles Percentage [%]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Proportion of CAVs [%]	60.00											
Growth Factor	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Traffic Control ☐ Automatic Optimization

	↑			↓			→			←		
Number	1											
Intersection	New Intersection											
Notes												
Control Type	Roundabout											
Analysis Method	HCM 7th Edition											
Name												
Show Name	☐			☐			☐			☐		
Approach	Northbound			Southbound			Eastbound			Westbound		
Lane Configuration												
Turning Movement	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
Base Volume Input [veh/h]	25	275	25	25	300	25	200	900	100	125	1000	25
Total Analysis Volume [veh/h]	27	299	27	27	326	27	217	978	109	136	1087	27

Intersection Settings

Lanes

	Northbound	Southbound	Eastbound	Eastbound	Westbound	Westbound
Overwrite Calculated Critical Headway	☐	☐	☐	☐	☐	☐
User-Defined Critical Headway [s]	4.00	4.00	4.00	4.00	4.00	4.00
Overwrite Calculated Follow-Up Time	☐	☐	☐	☐	☐	☐
User-Defined Follow-Up Time [s]	3.00	3.00	3.00	3.00	3.00	3.00
A (intercept)	1683.60	1683.60	1732.40	1732.40	1732.40	1732.40
B (coefficient)	0.00096	0.00096	0.00086	0.00086	0.00086	0.00086
HV Adjustment Factor	0.98	0.98	0.98	0.98	0.98	0.98
Entry Flow Rate [veh/h]	361	388	626	705	600	676
Capacity of Entry and Bypass Lanes [ve	510	496	1131	1131	1079	1079
Pedestrian Impedance	1.00	1.00	1.00	1.00	1.00	1.00
Capacity per Entry Lane [veh/h]	500	487	1109	1109	1058	1058
X, volume / capacity	0.71	0.78	0.55	0.62	0.56	0.63

Movement, Approach, & Intersection Results

	Northbound	Southbound	Eastbound	Eastbound	Westbound	Westbound
Average Lane Delay [s/veh]	26.26	33.04	9.95	11.58	10.35	12.06
Lane LOS	D	D	A	B	B	B
95th-Percentile Queue Length [veh]	5.55	7.02	3.51	4.57	3.54	4.60
95th-Percentile Queue Length [ft]	138.64	175.61	87.76	114.18	88.42	115.06
Approach Delay [s/veh]	26.26	33.04	10.81		11.26	
Approach LOS	D	D	B		B	
Intersection Delay [s/veh]	15.21					
Intersection LOS	C					

The v/c ratio by lane for each scenario are compared below. As shown, assuming 40% to 60% of CAVs in the traffic stream results in all lanes operating below 0.90.

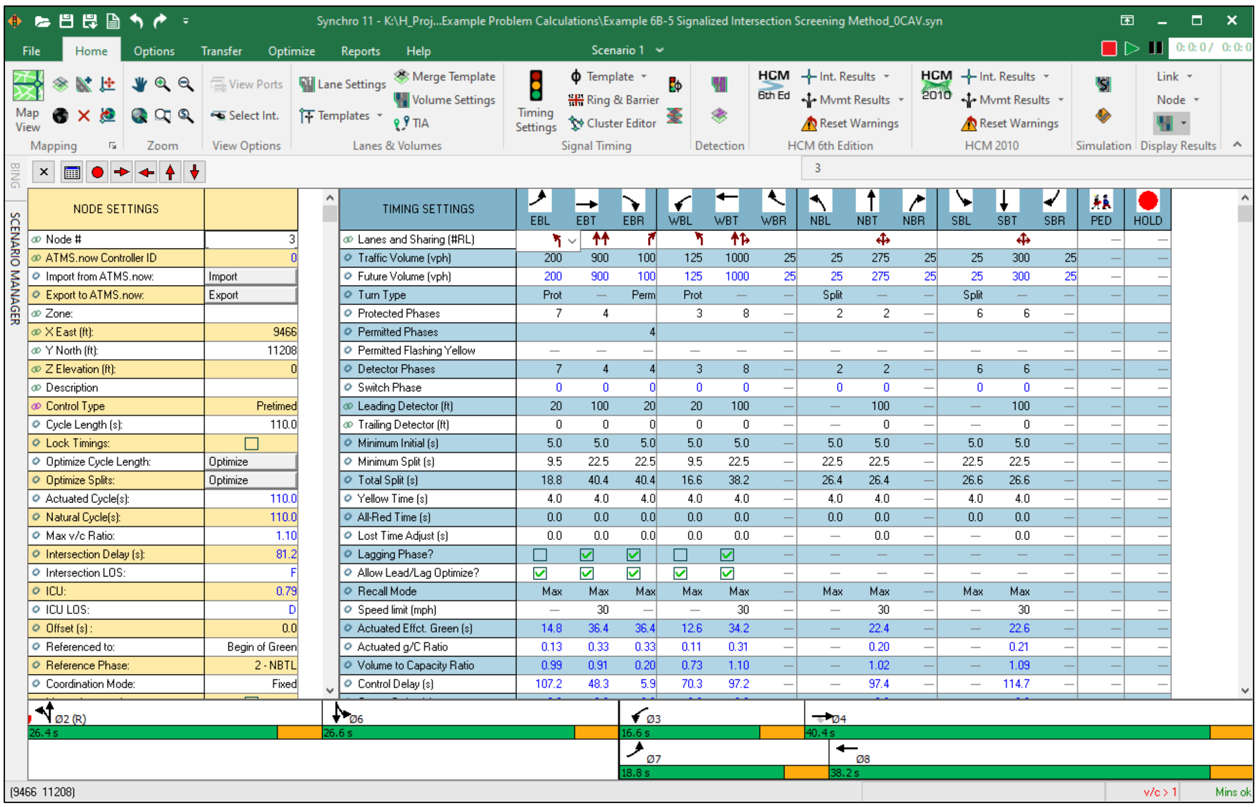
Lane Group	0% CAV’s	40% CAV’s	60% CAV’s
NB entry	0.93	0.80	0.71
SB entry	1.03	0.89	0.78
EB left lane	0.69	0.61	0.55
EB right lane	0.78	0.69	0.62
WB left lane	0.70	0.61	0.56
WB right lane	0.79	0.69	0.63

If the analyst wanted to know what proportion of CAVs in the traffic stream would be needed for all approaches to operate under capacity (<1.0), the assumed CAV proportion could be adjusted incrementally until the v/c ratio of the southbound approach reached 0.99 or less. In this case, a CAV proportion of 12% or greater is needed. While this analysis method is not precise enough to conclude that at exactly 12% CAVs, all roundabout entry lanes will operate under capacity, this exercise may give the analyst more confidence that the roundabout will operate under capacity in 2060 even if CAVs are implemented more slowly than projected.

Example 6B-5 Calculating Critical Intersection v/c Ratio in Synchro (Screening Method)

This example is a variation of Example Problem 13-3 in the APM that has been adjusted to account for the potential presence of CAVs, assuming the intersection analysis is for a year 2060 planning scenario.

The projected 2060 volumes and existing lane configurations at an intersection were coded in Synchro and the signal timing optimized in Synchro. It was assumed that the signalized intersection has protected left turn signal phasing on the east and west approaches and split phasing on the north and south approaches. See the Synchro signal timing settings window below.



In the Synchro HCM 2000 report, the critical movements are those identified with a 'c' as shown below:

HCM Signalized Intersection Capacity Analysis
3: 11/19/2022

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Ideal Flow (vphpl)	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750
Total Lost time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Util. Factor	1.00	0.95	1.00	1.00	0.95			1.00			1.00	
Frt	1.00	1.00	0.85	1.00	1.00			0.99			0.99	
Flt Protected	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (prot)	1630	3260	1458	1630	3248			1692			1693	
Flt Permitted	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (perm)	1630	3260	1458	1630	3248			1692			1693	
Peak-hour factor, PHF	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Adj. Flow (vph)	217	978	109	136	1087	27	27	299	27	27	326	27
RTOR Reduction (vph)	0	0	73	0	1	0	0	2	0	0	2	0
Lane Group Flow (vph)	217	978	36	136	1113	0	0	351	0	0	378	0
Turn Type	Prot	NA	Perm	Prot	NA		Split	NA		Split	NA	
Protected Phases	7	4		3	8		2	2		6	6	
Permitted Phases			4									
Actuated Green, G (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Effective Green, g (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Actuated g/C Ratio	0.13	0.33	0.33	0.11	0.31			0.20			0.21	
Clearance Time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Grp Cap (vph)	219	1078	482	186	1009			344			347	
v/s Ratio Prot	c0.13	0.30		0.08	c0.34			c0.21			c0.22	
v/s Ratio Perm			0.02									
v/c Ratio	0.99	0.91	0.07	0.73	1.10			1.02			1.09	
Uniform Delay, d1	47.5	35.2	25.2	47.1	37.9			43.8			43.7	
Progression Factor	1.00	1.00	1.00	1.00	1.00			1.00			1.00	
Incremental Delay, d2	58.5	12.6	0.3	22.2	60.8			53.5			74.0	
Delay (s)	106.1	47.7	25.5	69.3	98.7			97.3			117.7	
Level of Service	F	D	C	E	F			F			F	
Approach Delay (s)		55.6			95.5			97.3			117.7	
Approach LOS		E			F			F			F	

Intersection Summary			
HCM 2000 Control Delay	82.4	HCM 2000 Level of Service	F
HCM 2000 Volume to Capacity ratio	1.05		
Actuated Cycle Length (s)	110.0	Sum of lost time (s)	16.0
Intersection Capacity Utilization	78.9%	ICU Level of Service	D
Analysis Period (min)	15		
c Critical Lane Group			

Scenario 1 11:35 am 11/18/2022 Baseline

Synchro 11 Report
Page 1

Critical movements

After identifying the critical movements, adjusted flow rates and saturated flow rate values for each can be pulled from the Synchro HCM6 report as shown below.

HCM 6th Signalized Intersection Summary
3: 05/30/2023

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Initial Q (Qb), veh	0	0	0	0	0	0	0	0	0	0	0	0
Ped-Bike Adj(A_pbT)	1.00		1.00	1.00		1.00	1.00		1.00	1.00		1.00
Parking Bus, Adj	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Work Zone On Approach		No			No			No			No	
Adj Sat Flow, veh/h/ln	1723	1723	1723	1723	1723	1723	1723	1723	1723	1723	1723	1723
Adj Flow Rate, veh/h	217	978	109	136	1087	27	27	299	27	27	326	27
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Percent Heavy Veh, %	2	2	2	2	2	2	2	2	2	2	2	2
Cap, veh/h	221	1083	483	188	1015	25	26	292	26	25	299	25
Arrive On Green	0.13	0.33	0.33	0.11	0.31	0.31	0.20	0.20	0.20	0.21	0.21	0.21
Sat Flow, veh/h	1641	3273	1460	1641	3264	81	129	1434	129	120	1454	120
Grp Volume(v), veh/h	217	978	109	136	545	569	353	0	0	380	0	0
Grp Sat Flow(s),veh/h/ln	1641	1637	1460	1641	1637	1708	1693	0	0	1695	0	0
Q Serve(g_s), s	14.5	31.4	5.9	8.8	34.2	34.2	22.4	0.0	0.0	22.6	0.0	0.0
Cycle Q Clear(g_c), s	14.5	31.4	5.9	8.8	34.2	34.2	22.4	0.0	0.0	22.6	0.0	0.0
Prop In Lane	1.00		1.00	1.00		0.05	0.08		0.08	0.07		0.07
Lane Grp Cap(c), veh/h	221	1083	483	188	509	531	345	0	0	348	0	0
V/C Ratio(X)	0.98	0.90	0.23	0.72	1.07	1.07	1.02	0.00	0.00	1.09	0.00	0.00
Avail Cap(c_a), veh/h	221	1083	483	188	509	531	345	0	0	348	0	0
HCM Platoon Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Upstream Filter(I)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00
Uniform Delay (d), s/veh	47.5	35.1	26.6	47.0	37.9	37.9	43.8	0.0	0.0	43.7	0.0	0.0
Incr Delay (d2), s/veh	56.4	12.1	1.1	21.4	60.3	59.6	54.7	0.0	0.0	74.9	0.0	0.0
Initial Q Delay(d3),s/veh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
%ile BackOfQ(50%),veh/ln	9.3	14.1	2.2	4.7	21.9	22.8	14.5	0.0	0.0	16.6	0.0	0.0
Unsig. Movement Delay, s/veh												
LnGrp Delay(d),s/veh	103.8	47.2	27.7	68.4	98.2	97.5	98.5	0.0	0.0	118.6	0.0	0.0
LnGrp LOS	F	D	C	E	F	F	F	A	A	F	A	A
Approach Vol, veh/h		1304			1250			353			380	
Approach Delay, s/veh		55.0			94.6			98.5			118.6	
Approach LOS		E			F			F			F	

Timer - Assigned Phs		2	3	4		6	7	8				
Phs Duration (G+Y+Rc), s		26.4	16.6	40.4		26.6	18.8	38.2				
Change Period (Y+Rc), s		4.0	4.0	4.0		4.0	4.0	4.0				
Max Green Setting (Gmax), s		22.4	12.6	36.4		22.6	14.8	34.2				
Max Q Clear Time (g_c+I1), s		24.4	10.8	33.4		24.6	16.5	36.2				
Green Ext Time (p_c), s		0.0	0.1	1.9		0.0	0.0	0.0				

Intersection Summary			
HCM 6th Ctrl Delay			82.1
HCM 6th LOS			F

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Critical movements

Adjusted flow rate

Saturated flow rate

Note: Example Problem 13-3 in the APM that Example Problem 6B-5 is based off uses Synchro 9 and HCM 2010 to identify adjusted and saturated flow rates. HCM6 combined HCM 2010's separate saturation flow adjustments for grade and heavy vehicles into a single adjustment, resulting in a slightly different saturation flow rate.

Based on the most recent information available to the analyst, the U.S. fleet is expected to consist of 40–60% CAVs in the analysis year of 2060. The base saturation flow rates for the exclusive through movements, protected left turns, and permitted left turns can be adjusted to account for the presence of CAVs. Saturation flow rates for lane groups with shared movements are not unadjusted as CAV effects on shared movements and exclusive right-turn have not yet been addressed by research.

Exhibit 6B-13 provides CAV-adjusted flow rates for through movements at signalized intersections. For movements with a base saturated flow rate of 1,750 pc/h/ln, the adjusted base saturation flow rate is 2,040 with 40% CAVs and 2,150 with 60% CAVs.

Exhibit 6B-14 provides saturation flow rate adjustment factors for protected left-turn movements at signalized intersections. The adjustment factor is 1.07 with 40% CAVs (resulting in an ideal saturated flow of 1,873) and 1.11 with 60% CAVs (resulting in an ideal saturated flow of 1,943).

The adjusted saturated flow rates were input in Synchro and the resulting output sheets are shown below:

With 40% CAVs:

HCM Signalized Intersection Capacity Analysis
3: 04/05/2023

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Ideal Flow (vphpl)	1873	2040	1750	1873	1750	1750	1750	1750	1750	1750	1750	1750
Total Lost time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Util. Factor	1.00	0.95	1.00	1.00	0.95			1.00			1.00	
Frt	1.00	1.00	0.85	1.00	1.00			0.99			0.99	
Flt Protected	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (prot)	1744	3800	1458	1744	3248			1692			1693	
Flt Permitted	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (perm)	1744	3800	1458	1744	3248			1692			1693	
Peak-hour factor, PHF	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Adj. Flow (vph)	217	978	109	136	1087	27	27	299	27	27	326	27
RTOR Reduction (vph)	0	0	73	0	1	0	0	2	0	0	2	0
Lane Group Flow (vph)	217	978	36	136	1113	0	0	351	0	0	378	0
Turn Type	Prot	NA	Perm	Prot	NA		Split	NA		Split	NA	
Protected Phases	7	4		3	8		2	2		6	6	
Permitted Phases			4									
Actuated Green, G (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Effective Green, g (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Actuated g/C Ratio	0.13	0.33	0.33	0.11	0.31			0.20			0.21	
Clearance Time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Grp Cap (vph)	234	1257	482	199	1009			344			347	
v/s Ratio Prot	c0.12	0.26		0.08	c0.34			c0.21			c0.22	

Adjusted base saturation flow rate

Critical movements

HCM 6th Signalized Intersection Summary
3: 05/30/2023

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Initial Q (Qb), veh	0	0	0	0	0	0	0	0	0	0	0	0
Ped-Bike Adj(A_pbT)	1.00		1.00	1.00		1.00	1.00		1.00	1.00		1.00
Parking Bus, Adj	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Work Zone On Approach		No			No			No			No	
Adj Sat Flow, veh/h/ln	1844	2008	1723	1844	1723	1723	1723	1723	1723	1723	1723	1723
Adj Flow Rate, veh/h	217	978	109	136	1087	27	27	299	27	27	326	27
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Percent Heavy Veh, %	2	2	2	2	2	2	2	2	2	2	2	2
Cap, veh/h	236	1263	483	201	1015	25	26	292	26	25	299	25
Arrive On Green	0.13	0.33	0.33	0.11	0.31	0.31	0.20	0.20	0.20	0.21	0.21	0.21
Sat Flow, veh/h	1756	3816	1460	1756	3264	81	129	1434	129	120	1454	120

Saturated flow rate

With 60% CAVs:

HCM Signalized Intersection Capacity Analysis
3:	04/05/2023

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (vph)	200	900	100	125	1000	25	25	275	25	25	300	25
Ideal Flow (vphpl)	1943	2150	1750	1943	1750	1750	1750	1750	1750	1750	1750	1750
Total Lost time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Util. Factor	1.00	0.95	1.00	1.00	0.95			1.00			1.00	
Frt	1.00	1.00	0.85	1.00	1.00			0.99			0.99	
Flt Protected	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (prot)	1810	4005	1458	1810	3248			1692			1693	
Flt Permitted	0.95	1.00	1.00	0.95	1.00			1.00			1.00	
Satd. Flow (perm)	1810	4005	1458	1810	3248			1692			1693	
Peak-hour factor, PHF	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Adj. Flow (vph)	217	978	109	136	1087	27	27	299	27	27	326	27
RTOR Reduction (vph)	0	0	73	0	1	0	0	2	0	0	2	0
Lane Group Flow (vph)	217	978	36	136	1113	0	0	351	0	0	378	0
Turn Type	Prot	NA	Perm	Prot	NA		Split	NA		Split	NA	
Protected Phases	7	4		3	8		2	2		6	6	
Permitted Phases			4									
Actuated Green, G (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Effective Green, g (s)	14.8	36.4	36.4	12.6	34.2			22.4			22.6	
Actuated g/C Ratio	0.13	0.33	0.33	0.11	0.31			0.20			0.21	
Clearance Time (s)	4.0	4.0	4.0	4.0	4.0			4.0			4.0	
Lane Grp Cap (vph)	243	1325	482	207	1009			344			347	
v/s Ratio Prot	c0.12	0.24		0.08	c0.34			c0.21			c0.22	

Adjusted base saturation flow rate

Critical movements

HCM 6th Signalized Intersection Summary
3:	05/30/2023

Movement	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lane Configurations												
Traffic Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Future Volume (veh/h)	200	900	100	125	1000	25	25	275	25	25	300	25
Initial Q (Qb), veh	0	0	0	0	0	0	0	0	0	0	0	0
Ped-Bike Adj(A_pbT)	1.00		1.00	1.00		1.00	1.00		1.00	1.00		1.00
Parking Bus, Adj	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Work Zone On Approach		No			No			No			No	
Adj Sat Flow, veh/h/ln	1913	2116	1723	1913	1723	1723	1723	1723	1723	1723	1723	1723
Adj Flow Rate, veh/h	217	978	109	136	1087	27	27	299	27	27	326	27
Peak Hour Factor	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Percent Heavy Veh, %	2	2	2	2	2	2	2	2	2	2	2	2
Cap, veh/h	245	1331	483	209	1015	25	26	292	26	25	299	25
Arrive On Green	0.13	0.33	0.33	0.11	0.31	0.31	0.20	0.20	0.20	0.21	0.21	0.21
Sat Flow, veh/h	1822	4021	1460	1822	3264	81	129	1434	129	120	1454	120

Saturated flow rate

As shown, the critical movements have not changed with the assumed CAV presence.

Flow ratios for the critical movement lane groups are calculated by dividing the adjusted flow rate by the saturated flow rate and summed, as shown below.

Lane Group	0% CAV's	40% CAV's	60% CAV's
EBL	217/1,641 = 0.13	217/1,756 = 0.12	217/1,822 = 0.12
WBT/R	1,087/3,264 = 0.33	1,087/3,264 = 0.33	1,087/3,264 = 0.33
NB	299/1,434 = 0.21	299/1,434 = 0.21	299/1,434 = 0.21
SB	326/1,454 = 0.22	326/1,454 = 0.22	326/1,454 = 0.22
Sum	.13+.33+.21+.22=0.89	.12+.33+.21+.22=0.88	.12+.33+.21+.22=0.88

Cycle length = 110 sec
Lost time per phase = 4 sec
Total Lost time = 16 sec

The critical intersection v/c ratio is then calculated using the HCM equation:

For 0% CAVs:

Xc = Sum of critical flow ratios * C/(C-L) = 0.89 * 110/(110-16) = 1.04

For 40% and 60% CAVs:

Xc = Sum of critical flow ratios * C/(C-L) = 0.88 * 110/(110-16) = 1.03

As shown, having 40–60% CAVs in the traffic stream has a relatively small impact on the intersection's overall operations, due in part to the use of shared through and turning movement lanes. The CAV adjustment factors currently available only apply to protected left turns, permitted left turns, and exclusive through movements. The capacity benefits gained by the platooning of CAVs is likely to be more pronounced in exclusive lanes, given the slowing required for turning movements. The analyst could conclude from this exercise that the presence of CAVs is unlikely to significantly affect the traffic signal's operations in the forecast year.