Assessment of Capacity Changes Due to Automated Vehicles on Interstate Corridors

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16. Abstract:

This study was designed to assess capacity changes due to the introduction of connected vehicles (CVs) and automated vehicles (AVs) on Virginia freeway corridors. Overall, three vehicle types, including legacy vehicles (LVs); vehicles equipped with adaptive cruise control (ACC) (AVs); and vehicles equipped with cooperative adaptive cruise control (CACC) (connected automated vehicles [CAVs]), were considered in mixed traffic scenarios. Each scenario included light-duty passenger vehicles and heavy vehicles (HVs) with AV and CAV capabilities to determine their overall effect on capacity.

The team developed an AV and CAV driving behavior model and evaluated it on a test network. According to the testing results, the 100% AV and 100% CAV scenarios increased road capacity by 28% and 92% over the 100% LV scenario, respectively, on a basic freeway segment with intermediate vehicle behavior. Moreover, in the case of the HV scenario, AVs and CAVs showed a substantial capacity increase. Simulations were also conducted on models of I-95 in Virginia, where AVs and CAVs improved capacity compared to LVs. However, in some scenarios during congested conditions, AVs performed worse than LVs with reduced speeds and increased travel times because of the frequent stop-and-go conditions because of short headways. This issue was mitigated with the implementation of CAVs because of their ability to communicate and increase string stability. Under uncongested conditions, AVs and CAVs improved throughput and reduced delays as compared to LVs but caused a small decrease in speeds and an increase in travel times. Additional simulations were performed on models of I-81 to test the effects of extended grades and high percentages of HVs, where AVs and CAVs were found to have a high potential of improving operations when compared to LVs. The presence of steep grades negatively affected the performance of all types of vehicles, especially HVs, when compared to flat terrain. CAVs with their communication capabilities, particularly at high market penetrations, were capable of achieving capacity increases over AV and LV scenarios in the selected I-81 segment.

AVs and CAVs proved capable of improving highway operations. Even in the presence of high percentages of HVs and steep grades, vehicles equipped with AV and CAV technologies provided better performance than LVs. Ultimately, AVs and CAVs need full market penetration to operate at their maximum potential. However, these technologies, even in mixed traffic, could still offer operational benefits at lower penetrations.

The Virginia Department of Transportation's (VDOT) Traffic Engineering Division should stay updated on developments in AVs to ensure that VDOT simulation models reflect the existing and anticipated vehicle fleet. They should consider using the capacities described in this report as guidance when calibrating models of CVs and AVs in simulations of freeway corridors. Because capacity estimates depend on AV and CAV market penetration, VDOT and the Virginia Transportation Research Council should investigate methods to estimate the prevalence, capabilities, and rate of usage of CV and AV driving technologies on Virginia roads.

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FINAL REPORT

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ABSTRACT

This study was designed to assess capacity changes due to the introduction of connected vehicles (CVs) and automated vehicles (AVs) on Virginia freeway corridors. Overall, three vehicle types, including legacy vehicles (LVs); vehicles equipped with adaptive cruise control (ACC) (AVs); and vehicles equipped with cooperative adaptive cruise control (CACC) (connected automated vehicles [CAVs]), were considered in mixed traffic scenarios. Each scenario included light-duty passenger vehicles and heavy vehicles (HVs) with AV and CAV capabilities to determine their overall effect on capacity.

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INTRODUCTION

In *Calendar Year 2018-2021 Virginia Department of Transportation (VDOT) Business Plan* (VDOT, 2017), one of the stated agency goals was to "Ensure Efficient Highway Operations." One of the most challenging issues in meeting that goal is congestion on interstate corridors. VDOT has been very proactive in the use of technology to make Virginia's interstates more efficient and reliable for the traveling public. Recent technology implementations by VDOT include variable corridor pricing, advanced traveler information, and research on connected vehicles (CVs) and automated vehicles (AVs). Much of the ongoing research on CVs and AVs has focused on the safety considerations in the deployment of these vehicles, and there is a need to understand the operational impacts on areas where there is currently congestion in Virginia. The introduction of connectivity and communication in transportation infrastructure and vehicles is expected to increase roadway capacity as vehicles can comfortably and safely travel at short headways. Many new vehicles have technology and safety features that employ adaptive cruise control (ACC) and lane-keeping assistance. Future AVs are likely to employ these technologies along with connectivity to allow for increased capacity.

Traditional capacity estimation tools and traffic simulation software rely on models of human driving behavior and have not been calibrated to model the complexities of the transition to computer-driven CVs and AVs, especially not a future where CVs and AVs are the only types of vehicles on Virginia interstates. New models are needed that capture the behavior of AVs and CAVs in traffic to improve the accuracy of capacity estimation tools and simulation software.

In order to gain insights on the capacity impacts of AVs, simulation is needed as cooperative adaptive cruise control (CACC) is not widely available and there is no way to determine which drivers in the field are using ACC features at a given moment. Simulation will allow for the ability to understand the impacts of automation of the driving process, with vehicles adjusting to shorter following distances, thus potentially increasing capacity and reducing variability in speeds and vehicle behavior. The adjustments to capacity may change operations and mitigate the need for the expansion of roadways and other transportation demand management programs. This study had the goal of providing guidance on the impact of CVs and AVs on capacity and to help VDOT understand what levels of market penetration (MP) of AVs will necessitate changes to design guidelines and planning practices.

PURPOSE AND SCOPE

The purpose of the study was to (1) investigate potential legal implications of AVs on Virginia freeways; (2) quantify the change in interstate capacity due to varying levels of penetration of automated technologies; (3) gain an understanding of the effect of automated driving on interstate speed and throughput; and (4) assess the impacts for future VDOT planning and operations of interstates.

The scope of the study was limited to interstate highways. The effects of technology in both rural and urban settings were examined. The research question examined was: “What is the effect of the implementation of AV and CAV technologies on interstate capacity in Virginia, including consideration of MP of the technology and roadway characteristics?” This research question led to the answering of the following operational policy question: “What actions should VDOT take to prepare for AVs because of changes in highway capacity?” To answer these questions, the research team investigated capacity changes using PTV VISSIM traffic simulation software (hereinafter “VISSIM”).

A comprehensive experimental design implemented on three test geometries was the basis for the investigation detailed in this report. The results from each of the three scenarios illustrated different components of capacity to provide decision makers with the information needed to make informed decisions on future transportation infrastructure investments.

Assumptions

The terms *automated vehicles, autonomous vehicles,* and *connected automated vehicles* are sometimes used interchangeably in the literature, but they describe different aspects of operation and communication. For this study, pertinent terms were defined as follows:

- Legacy vehicles (LVs) are vehicles that do not have ACC or lane-keeping assistance. These vehicles require humans to sense the environment around the vehicle and execute the driving task without vehicle assistance.

- Automated vehicles (AVs) automate some or all elements of the driving process. Technologies that are currently automating the driving process but have not entirely replaced the driver include basic systems such as cruise control and traction control, more advanced systems such as ACC and lane-keeping assistance, and combinations of these systems. For the purposes of this study, AVs refer to vehicles with ACC or some other automated control of throttle that can respond to changing traffic conditions.

- Autonomous vehicles are fully self-driving vehicles where there is no input from the driver in the driving task. These vehicles are a subset of AVs, which include vehicles that automate only an individual driving task such as lane-keeping. Some autonomous vehicles employ a safety driver that can disengage the autonomous mode. These vehicles do not connect to other vehicles or infrastructure. Fully autonomous vehicle technology is still in development, although industry leaders have been active in the research and testing of autonomous vehicles.

- A connected vehicle (CV) or connected automated vehicle (CAV) is a vehicle that is capable of communicating with other vehicles or roadside infrastructure using wireless technology. CVs that are not automated rely on the driver to conduct the driving task, where the CAV does not require human interaction for some or all tasks.

In this study, the LV was assumed to be a vehicle without connectivity or advanced automation technology, such as ACC and lane-keeping. AVs are considered to be completely automated vehicles without connectivity. For CAVs, the assumption for automation is the same as for AVs with connectivity to the roadside and other vehicles.

Study Limitations

Although this study was a comprehensive simulation study of the potential outcomes that could occur due to the implementation of AVs on Virginia interstates, several issues cannot be simulated easily:

- *Non-recurring congestion*. The introduction of AVs promises to reduce the number of crashes significantly and mitigate some of the effects of weather-related non-recurring congestion. Even in areas of recurring congestion, such as I-66 in Northern Virginia, non-recurring congestion due to crashes and police activity extends the length of congestion and reduces the capacity of the roadway during lane blockages or rubbernecking. Benefits tied to the reduction in non-recurring congestion were not explicitly examined in this study.

- *Narrowing of lanes due to the precise latitudinal positioning of the vehicle.* There may be opportunities to narrow lane widths under high AV penetrations, potentially allowing the creation of additional lanes within the existing right of way. If the travel lanes are narrowed, then lane changing might be more limited by the lane configurations; however, with limited right of way for most urban interstates, this might be a significant development. This study does not consider lane-narrowing, which may be possible with automated driving systems.

- *Exclusive lanes*. This study looked only at mixed AV and LV flow in shared lanes and did not explicitly examine exclusive AV managed lanes adjacent to mixed lanes. The results from the basic network at 100% AV and 100% CAV provide insight on how managed lanes would operate and the amount of capacity expected from those lanes —restricting certain lanes to AVs could also change the capacity of corridor level simulations for the mixed flow case. More information on dedicated lanes for AVs can be found in *National Highway Cooperative Research Program (NCHRP) Report 891* (Booz Allen Hamilton, WSP, and New Jersey Institute of Technology, 2018).

- *Vehicle ownership rates*. Several prominent automobile original equipment manufacturers (OEMs) have been exploring business models of shared AV fleets instead of private vehicle ownership. A fleet or on-demand rental model could encourage more car sharing, which could decrease demand to levels below the available capacity in many parts of Virginia. Alternative vehicle use and ownership models were not explored in this study.

- *Trip pricing.* Governments, insurers, or AV fleet operators may tax or charge per vehicle-trip based on the anticipated congestion of the travel route at the time of the trip. This dynamic pricing may have the effect of disincentivizing peak hour trips and encouraging trip time spreading, which may reduce peak-period demand but increase off-peak demand. This was not examined in this study.

- *Assumptions for vehicle movement.* The assumptions for the vehicle movement algorithms are detailed in this report; however, algorithms for vehicle movement in specialty situations, such as weaving areas, were not implemented in the simulation.

However, merging and diverging behavior was accounted for at interchanges and during platooning maneuvers.

- *Limitations of simulation.* Simulation is limited by the modeling of driver behavior for LVs and the algorithms implemented for AVs and CAVs. Current efforts by automobile OEMs have been investigating the use of machine learning and artificial intelligence techniques for the movement of vehicles. The algorithms implemented for this study were derived from a state-of-the-art literature review.

LITERATURE REVIEW

Before the methodology of this study is discussed, the current legal and regulatory environment for the behavior of automated vehicles operating on freeways in Virginia needs to be reviewed. Likewise, past attempts to assess the impacts of CVs and AVs on capacity need to be reviewed to assist in the development of the methodology used in this study.

Legal and Regulatory Review

The purpose of this analysis was to ascertain possible bounds on permissible behavior for AVs both currently and in the near future as they might affect capacity modeling. Five aspects were considered: following distances, lateral movements, lane restrictions, platooning, and dedicating lanes for AVs. This analysis was not performed by an attorney and does not represent any official legal interpretation by the Commonwealth of Virginia or any of its agencies. The Office of the Attorney General has not yet issued any interpretations of many of these issues. The list of legal and regulatory issues identified in this study is neither comprehensive nor exhaustive. When case law is cited, it is based on the analysis of other cited legal scholarship and may be from non-Virginia courts; these decisions may have persuasive but not binding authority on cases in Virginia courts.

Following Distance Standards

The vehicle behavior with the most significant impact on freeway capacity is the distance or time headway at which a vehicle follows the vehicle directly ahead. The spacing between vehicles can be expressed in units of distance or time. Spacing can be converted between distance and time using Equation 1:

$$d = vt \qquad (Eq. 1)$$

In this equation, d is the distance (feet or meters), t is the time (seconds), and v is the speed of the vehicle (feet per second or meters per second).

In addition, there are two standard definitions of vehicle spacing: gap and headway. *Gap* refers to the separation between the rear of the lead vehicle and the front of the following vehicle. *Headway* refers to the separation between the front of the lead vehicle and the front of the following vehicle.

The gap can be converted to headway using Equations 2 and 3:

$$d_{headway} = d_{gap} + x_l \qquad (Eq. 2)$$

$$t_{headway} = t_{gap} + \frac{x_l}{v} \qquad (Eq. 3)$$

where

$d_{headway}$ is the distance headway (feet or meters)
d_{gap} is the distance gap (feet or meters)
$t_{headway}$ is the time headway (seconds)
t_{gap} is the time gap (seconds)
x_l is the length of the lead vehicle (feet or meters)
v is the vehicle speed (feet per second or meters per second).

Driver's Education Training

Many state departments of motor vehicles (DMVs), in their driving training courses, recommend headways of 2 to 4 seconds (Le Vine et al., 2017). The Virginia DMV (2018) recommends a varying headway of between 2 and 4 seconds depending on the speed of the vehicle, as shown in Table 1.

These headways are directly related to capacity: 2-second headways yield 1,800 veh/ln/hr; 3-second headways yield 1,200 veh/ln/hr; and 4-second headways yield 900 veh/ln/hr. Observed and theoretical capacities are higher than those suggested by the Virginia DMV following distances. The *Highway Capacity Manual* (HCM) assumes a theoretical maximum capacity of a freeway under ideal conditions of 2,250 to 2,400 passenger cars per hour per lane depending on free-flow speed (Transportation Research Board, 2016). These equate to headways of 1.5 to 1.6 seconds.

AVs may also follow at shorter than recommended time headways. The ACC feature in a 2017 Audi Q7 can be set to the following time gap of 1 second (Audi AG, 2016), and Virginia recently hosted a truck platoon demonstration with gaps of 0.6 seconds at speeds of 55 mph (Reiskin, 2017). In research demonstrations, AVs have driven with gaps as short as 13 ft and 0.18 seconds when using vehicle-to-vehicle communications (Tsugawa, 2013).

Table 1. Recommended Time Headways in Dry Conditions

Recommended Headway	Vehicle Speed
2 seconds	Under 35 mph
3 seconds	35-45 mph
4 seconds	46-70 mph

Source: Virginia Department of Motor Vehicles (2018).

Statutory Guidance

The *Virginia Driver's Manual* is an informational tool. Therefore, these recommendations do not supersede "the Code of Virginia, Virginia Administrative Code, or any other statute" (Virginia DMV, 2018). The Code of Virginia is less specific than DMV guidance regarding following distance. Va. Code § 46.2-816 states: "The driver of a motor vehicle shall not follow another vehicle, trailer, or semitrailer more closely than is reasonable and prudent, having due regard to the speed of both vehicles and the traffic on, and conditions of, the highway at the time." Violation of this restriction can constitute negligence per se (Smith, 2013), and the overall effect of this law on capacity depends on the interpretation of the qualitative terms "reasonable and prudent."

Assured Clear Distance Ahead (ACDA) Doctrine

One attempt to define a reasonable following distance is the ACDA doctrine. This refers to a common law manifestation of defensive driving concepts where a vehicle operator is responsible for maintaining a sufficient gap so that the vehicle can be stopped for an object within his or her path. Pearson (2005) defines ACDA as requiring a driver to "regulate his speed so that he can stop within the range of his vision." Most jurisdictions follow this standard, presuming negligence on the part of the following driver in a rear-end collision regardless of whether the leading vehicle was moving or stopped (Buchwalter et al., 1963).

An exception to the ACDA doctrine is the Sudden Emergency doctrine, which excuses a driver from negligence in a collision with a vehicle, person, or object that moves unexpectedly into the lane, either laterally or vertically, e.g., a falling tree branch. Buchwalter et al. (1963) provides an example: "A motorist driving at a reasonable speed and obeying the rules of the road is generally not liable for injuries to a child who darts in front of the vehicle so suddenly that the motorist cannot avoid injuring the child, as where a child darts out from behind other vehicles that were stopped in traffic, directly into the path of the vehicle, and there is no evidence that [the] driver was driving too fast." A vehicle abruptly changing lanes into the path of another vehicle may also qualify under the Sudden Emergency doctrine (Decker v. Wofford, 1960), whereas physical features of the roadway may not (Coppola v. Jameson, 1972).

Human drivers routinely violate the ACDA standard. In low-light conditions, drivers adhering to ACDA would be limited to speeds of 20 mph to avoid striking a "dark-clad pedestrian" (Leibowitz et al., 1998). Le Vine et al. (2017) note that ACDA generally requires drivers to avoid striking both the vehicle ahead and stationary objects. Avoiding only the vehicle ahead is referred to as the "weak" interpretation and allows closer following distances. Also avoiding stationary objects is referred to as the "strong" interpretation, as it requires that a driver maintain sufficient space to stop not only for the vehicle ahead but also for debris that may appear within the driver's range of vision only after the leading vehicle has passed over it. For example, in the case in which a tractor-trailer may drive over a moderately sized box with which a smaller following car might collide; the driver of the following vehicle would need to maintain a following distance adequate to come to a complete stop. Disregarding reaction time, a vehicle traveling at 55 mph and capable of decelerating at a rate of 16.4 ft/s^2 (Le Vine et al., 2017) must maintain a time gap of 2.46 seconds to the leading vehicle to avoid striking run-over debris, a distance greater than the minimum settings on some ACC systems (Audi AG, 2016), as well as following distances observed in the field.

Le Vine et al. (2017) calculate minimum allowable headway as shown in Equation 4:

$$H_{min} = t_{lag\ f} + \frac{v}{2a_f} - \frac{x_{veh} - \frac{v^2}{2a_l}}{v} \qquad (Eq. 4)$$

where

H_{min} is the minimum allowable time headway (seconds)
$t_{lag\ f}$ is the reaction time of following vehicle f, set as 0.4 seconds unless otherwise noted
a_f is the maximum deceleration of following vehicle f (ft/s^2)
a_l is the assumed maximum deceleration of leading vehicle l (ft/s^2)
v is the free-flow speed (feet per second)
x_{veh} is the length (units of distance) of leading vehicle l, set to 19 ft unless otherwise noted.

The derivation of the minimum headway equation can be found in Appendix B of Le Vine et al. (2016).

Based on a vehicle's braking ability, the applied interpretation of ACDA, assumptions regarding the leading vehicle's braking ability, and vehicle speeds, there are several ways that adherence to ACDA may impact minimum following headways and freeway capacity. Le Vine et al. (2017) identifies 11 scenarios, shown in Table 2.

In many scenarios, the following vehicle is expected to brake at 16.4 ft/s^2, which represents both the upper limit of ACC braking standards and the lower limit of forward collision mitigation system standards. The leading vehicle is expected to brake at various, often higher rates of deceleration, forcing the following vehicle to leave adequate spacing. Headways varied from 0.6 seconds for following vehicles assumed to be capable of braking at the same rate as the lead vehicle, to 29.2 seconds for the following vehicle that can decelerate no faster than is permitted on high-speed rail. In most scenarios, however, time headways at 75 mph range from 0.9 to 2.6 seconds.

Table 2. Automated Vehicle-Following Scenarios With Different ACDA Interpretations and Assumptions

Name	a_l (ft/s^2)	a_f (ft/s^2)	Min. Allowable Headway (s) 55 mph	65 mph	75 mph	Notes
Baseline Weak	28.3	16.4	1.7	1.8	2.0	Must stop for vehicle ahead only
Baseline Strong	Inf	28.3	2.1	2.3	2.5	Must also stop for debris
Scenario 1	21.3	16.4	1.2	1.3	1.3	Wet pavement
Scenario 2	41.6	16.4	2.1	2.4	2.6	Assumes lead vehicle is high performance
Scenario 3	N/A	a_l	0.6	0.6	0.6	Assumes can brake at same rate as lead vehicle
Scenario 4	41.6	28.3	1.1	1.1	1.2	Following vehicle can brake at maximum rate
Scenario 5	30.38	26.21	0.8	0.8	0.9	a_l and a_f brake at 99.9th and 0.1th percentile of typical passenger car hard brake, respectively
Scenario 6	28.3	1.8	21.6	25.4	29.2	a_f same as high-speed rail
Scenario 7	28.3	26.0	0.8	0.7	0.7	a_f set so that local maximum capacity attained at v = 75 mph
Scenario 8	28.3	16.4	1.3	1.4	1.6	Instant reaction time using CV technologies (0.4 s all other scenarios)
Scenario 9	28.3	16.4	1.7	1.8	2.0	25% longer lead vehicle length

Source: Le Vine et al. (2017).
ACDA = Assured Clear Distance Ahead; a_l = leading vehicle; a_f = following vehicle; Inf = infinite; N/A = not applicable; CV = connected vehicle.

Human drivers have been observed to violate ACDA requirements routinely. Video of vehicles on a California freeway was collected and analyzed as part of the Next Generation Simulation (NGSIM) study (Federal Highway Administration, 2007). Assuming that following vehicles could brake at maximum rates with negligible reaction time, drivers violated ACDA 0.2% of the time (Le Vine et al., 2017). Under more realistic assumptions of reaction times between 0.5 and 1.75 seconds, vehicles were observed to violate ACDA requirements between 1.5% and 49% of the time (Le Vine et al., 2017).

Industry Standards

ACC systems on production vehicles generally adhere to ISO 15622 standard (International Organization for Standardization, 2010). Under this standard, vehicles are limited to the following time gap of 0.8 seconds or higher. At least one available time gap setting should be within the range of 1.5 to 2.2 seconds. When the ACC system is initiated and has not retained the previous time gap setting selected by the driver, then the time gap must be set to a "predefined default value equal of 1.5 s or greater" (International Organization for Standardization, 2010).

Summary of Standards

Table 3 lists several of the time headways discussed in this section. All represent vehicles with various levels of automation except the DMV headway. All but one of the Le Vine et al. (2017) settings (Scenario 8) represent unconnected vehicles that cannot communicate wirelessly with the lead vehicle but instead must rely on their sensors to detect closing speed.

Table 3. Examples of Car-Following Headways

Citation	Headway at 65 mph (s)	Notes[a]
Le Vine et al. 2017	0.6-2.6	Requires adherence to Assured Clear Distance Ahead doctrine. See citation and Table 10 for parameters and assumptions.
International Organization for Standardization 2010	1.0	Minimum allowable headway for the ACC system.
	1.7	Minimum default headway for the ACC system.
	2.4	Maximum default headway for the ACC system.
Audi AG 2016	1.2	Minimum headway setting for 2017 Audi Q7's ACC system.
	2	Recommended headway setting for 2017 Audi Q7's ACC.
Virginia Department of Motor Vehicles 2018	4	Recommended headway, not specified in the Code of Virginia.

ACC = adaptive cruise control.
[a] Time gaps have been converted to headways by adding 0.2 seconds, i.e., the time required for a vehicle to travel 19 ft (the length of a vehicle) at 65 mph.

Legal Definition of Driver

A 2018 NCHRP legal audit of state motor vehicle codes for AVs noted that following distance laws in most states, including Virginia (§ 46.2-816), refer to the "driver" of a motor vehicle. If the term "driver" is interpreted as referring only to a natural person, then following distance restrictions may not apply to AVs:

> Following distance requirements generally apply to the "driver" of a vehicle. But recall that the term "driver" is ambiguous and can thus have a range of meanings, which includes the possibility that trucks with an ADS properly engaged have no "driver" and hence are not bound by any following distance requirement at all (National Academies of Sciences, Engineering, and Medicine, 2018).

The authors of the study recommend that policymakers consider the possibility that their existing vehicle codes might be interpreted to regulate only "drivers" who are human, exempting highly automated vehicles (where automated driving systems are effectively the "drivers") from most regulation.

Lateral Movement Statutes

The Virginia DMV recommends—but does not require—driving in the middle of the lane, especially when driving through work zones (Virginia DMV, 2018). In addition, several statutes address lane selection on freeways. Table 4 is a non-comprehensive list of statutes with potential relevancy for AV operations on freeways.

The Virginia statutes listed in Table 4 may affect capacity models in several ways. Section 46.2-842.1 of the Code of Virginia requires drivers traveling "to the left and abreast of another motor vehicle on a divided highway" to move to the right as soon as they can safely do so when signaled either by "audible or light signal" by an overtaking driver.

Table 4. Sample of Virginia Statutes Regarding Lane Selection Relevant to Automated Vehicles on Freeways

Code of Virginia	Relevant Language
§ 46.2-838. Passing when overtaking a vehicle.	The driver of any vehicle overtaking another vehicle proceeding in the same direction shall pass at least two feet to the left of the overtaken vehicle and shall not again drive to the right side of the highway until safely clear of such overtaken vehicle, except as otherwise provided in this article.
§ 46.2-804. Special regulations applicable on highways laned for traffic; penalty.	Any vehicle proceeding at less than the normal speed of traffic at the time and place and under the conditions existing shall be driven in the lane nearest the right edge or right curb of the highway when such lane is available for travel except when overtaking and passing another vehicle or in preparation for a left turn or where right lanes are reserved for slow-moving traffic as permitted in this section;
§ 46.2-842.1. Drivers to give way to certain overtaking vehicles on divided highways.	It shall be unlawful to fail to give way to overtaking traffic when driving a motor vehicle to the left and abreast of another motor vehicle on a divided highway. On audible or light signal, the driver of the overtaken vehicle shall move to the right to allow the overtaking vehicle to pass as soon as the overtaken vehicle can safely do so. A violation of this section shall not be construed as negligence per se in any civil action.
§ 46.2-921.1. Drivers to yield right-of-way or reduce speed when approaching stationary emergency vehicles or public utility vehicles on highways; penalties.	The driver of any motor vehicle, upon approaching a stationary vehicle that is displaying a flashing, blinking, or alternating blue, red, or amber light or lights as provided in § 46.2-1022, 46.2-1023, or 46.2-1024, subdivision A 1 or 2 of § 46.2-1025, or subsection B of § 46.2-1026 shall (i) on a highway having at least four lanes, at least two of which are intended for traffic proceeding as the approaching vehicle, proceed with caution and, if reasonable, with due regard for safety and traffic conditions, yield the right-of-way by making a lane change into a lane not adjacent to the stationary vehicle or (ii) if changing lanes would be unreasonable or unsafe, proceed with due caution and maintain a safe speed for highway conditions. The provisions of this section shall not apply in highway work zones as defined in § 46.2-878.1.

Modelers using microscopic simulation may wish to incorporate this behavior into lane-changing models, especially if AV developers choose to implement audible or light signals when a driver is overtaking in order to leverage this statute.

Capacity may decrease if AV drivers strictly adhere to § 46.2-921.1. Often referred to as the "move over law," this statute requires drivers encountering stationary vehicles with activated blue, red, or amber lights "on a highway having at least four lanes, at least two of which are intended for traffic proceeding as the approaching vehicle" to move into the lane not adjacent to the stationary vehicle. If changing lanes is "unreasonable or unsafe," the driver should "proceed with due caution and maintain a safe speed for highway conditions." This may decrease capacity as vehicles switch lanes. This may also decrease capacity if AV developers determine that the "safe speed for highway conditions" is significantly lower than free-flow speed.

Platooning Statutes

For this section, *platoons* refer to two or more vehicles that operate on roadways in a close formation with automated driving technologies on some, but not necessarily all, vehicles. To achieve small headways of 1 second or less—and the resulting reductions in wind resistance and fuel usage—wireless connectivity among the vehicles is often used. Early deployments of platooning in the United States are expected to involve the trucking industry, as it enables long-distance shipment of goods with lower fuel costs, improved safety, and fewer paid drivers. Platoons do not require high levels of automation, as the lead vehicle in the platoon may be driven by a human who is responsible for slowing for traffic and avoiding incidents. The remaining vehicles may merely follow the vehicle ahead, provided they can safely move to the shoulder in the event of a hardware or software failure.

Virginia uses the reasonable and prudent standard for regulating following distances (§ 46.2-816):

> The driver of a motor vehicle shall not follow another vehicle, trailer, or semitrailer more closely than is reasonable and prudent, having due regard to the speed of both vehicles and the traffic on, and conditions of, the highway at the time.

According to a recent NCHRP report auditing state laws on vehicle automation, states such as Virginia that use only the reasonable and prudent standard may not need to modify their legislation to permit closely spaced platoons:

> However, in states that currently apply Approach #1, the due care or "reasonable and prudent"-type standard that allows for safe distances between vehicles to vary based "the speed of such vehicles and the traffic upon and the condition of the highway" would arguably allow for safe distances to vary based on the [connected and automated driving system] features that enable truck platooning (National Academies of Sciences, Engineering, and Medicine, 2018).

Scribner (2018), in a report from the Competitive Enterprise Institute, concurs with the finding in the NCHRP report but recommends adding language to § 46.2-816 explicitly exempting CV and AV applications.

A recent audit of state motor vehicle law found that although state DMVs and departments of transportation generally treat platoons as groups of individual trucks, there are other terms in state statutes that might be interpreted to cover platoons:

> To take one example, in the UVC and many of the state codes in our sample, there is a repeated reference to a "combination of vehicles," a term that is rarely defined. While there appears to be a strong consensus that the term does not cover platoons, the law itself is somewhat ambiguous on this point (National Academies of Sciences, Engineering, and Medicine, 2018).

In Virginia, the term "combination of vehicles" appears in 29 statutes but is not defined. [These statutes include § 46.2-1117.1. Commercial delivery of towaway trailers; § 46.2-697.

Fees for vehicles not designed or used for transportation of passengers; § 46.2-1110. Height of vehicles; damage to overhead obstruction; penalty; § 46.2-1104. Reduction of limits by Commissioner of Highways and local authorities; penalties; § 46.2-644.01. Lien of keeper of garage, § 46.2-1112. Length of vehicles, generally; special permits; vehicle combinations, etc., operating on certain highways; penalty; § 46.2-613.1. Civil penalty for violation of license, registration, and tax requirements and vehicle size limitations; § 3.2-5812. Capacity of scales not to be exceeded; determining gross or tare weight of vehicle or combination of vehicles; § 46.2-701. Combinations of tractor trucks and semitrailers; five-year registration of certain trailer fleets; § 46.2-1116. Vehicles having more than one trailer, etc., attached thereto; exceptions; § 46.2-1117.1. Commercial delivery of towaway trailers; § 46.2-113. Violations of this title; penalties; § 46.2-1083. Rear fenders, flaps, or guards required for certain motor vehicles; § 46.2-1127. Weight limits for vehicles using interstate highways; § 46.2-1018. Marker lights on vehicles or loads exceeding thirty-five feet; § 46.2-872. Maximum speed limits for vehicles operating under special permits; § 46.2-100. Definitions; § 46.2-341.4. Definitions; § 46.2-2000. Definitions; § 46.2-341.16. Vehicle classifications, restrictions, and endorsements; § 46.2-704. Prohibited operations; checking on weights; penalties; § 46.2-1138.2. Town ordinances concerning weight limits on certain roads; § 46.2-1067. Within what distances brakes should stop vehicle; § 46.2-1138.1. City ordinances fixing weight limits on certain roads; § 46.2-657. When registration by nonresident not required; § 46.2-843. Limitations on overtaking and passing; § 46.2-870. Maximum speed limits generally; § 46.2-1231.1. Immunity from liability for certain towing; § 46.2-1068. Emergency or parking brakes.] The authors of the legal audit recommend that policymakers consider providing guidance or introducing new legislation to provide a clearer definition of truck platoons. If platoons were classified under the term "combination of vehicles," the authors argued, truck platoons would probably violate most length and weight restrictions (National Academies of Sciences, Engineering, and Medicine, 2018). In Virginia, vehicle lengths are covered under § 46.2-1112, which in most circumstances limits combinations of vehicles to 65 ft. Gross weight for a combination of vehicles on interstate highways is generally limited to 80,000 lb (84,000 lb with a fee) under § 46.2-1127, § 46.2-1126, and § 46.2-1128.

Past Studies of CV and AV Capacity

AV Capacity on a Basic Freeway Segment

The HCM defines a basic freeway segment as "outside the influence area of any merge, diverge, or weaving segments and of any signalized intersections" (Transportation Research Board, 2016). The basic freeway segment does not include interactions with merging, diverging, or weaving sections, and the capacity evaluation is dependent on free-flow speed, where a 75 mph free-flow speed correlates to an estimated base capacity of 2,400 pc/hr/ln. The capacity analysis is used to determine the number of lanes necessary to achieve a target level of service in design and to identify what conditions lead to capacity exceedance (Teodorović and Janić, 2017). In a basic freeway segment, AV longitudinal assistance is anticipated to have an impact through the platooning of vehicles, where short following distances and uniform maneuvering can improve traffic flow operations and throughput.

Simulation Studies

Huang et al. (2000) used simulation to evaluate the impact of AVs on a highway. In this study, AVs were able to select maneuvering movements from eight alternatives. Based on a simulation with mixed LVs and AVs, the introduction of AVs at more than 70% increased the capacity from 2,000 veh/hr/ln to approximately 5,000 veh/hr/ln. In addition, the study suggested possible AV operational parameters such as average speed, maximum deceleration, desired headway, and a decision tree for AV behavior. The assumptions in this study used much higher speeds than allowed on roadways in Virginia.

Kesting et al. (2008) focused on investigating control strategies for an ACC system capable of adapting to various traffic situations. The authors' contributions focused on investigating the response of an ACC system to various traffic conditions when the driver specifies a time headway and initial velocity. The authors simulated an on-ramp bottleneck and considered traffic conditions in that bottleneck that included upstream (before), within (congested), and downstream (after).

Talebpour and Mahmassani (2016) also simulated LVs, CVs, and AVs with different car-following models to investigate the impact on traffic flow stability and throughput. The authors concluded that CVs and AVs improve string stability of traffic flow and AVs prevent shock wave formation and propagation better than CVs. Moreover, in the simulation, the throughput at 90% AV (0% CV) was 2,500 veh/hr/ln whereas the same MP of CV 90% (0% AV) was 2,200 veh/hr/ln.

Delis et al. (2015) investigated a car-following model to evaluate traffic flow dynamics for ACC-compatible vehicles. The critical component of the model is that the relaxation time in the ACC system is related only to the direct leading vehicle. The results demonstrated benefits in ACC-capable vehicles in terms of flow and capacity.

VanderWerf et al. (2001, 2002) provided a mathematical model for ACC vehicle simulation purposes. The study provides operational parameters for ACC vehicles in which a headway time gap of 1.4 seconds was observed. The acceleration and deceleration parameters were set at 2 m/s^2 and -3 m/s^2, respectively, and the vehicles' desired speed was set at 29 m/s (65 mph). A highway capacity of 2,200 veh/hr/ln was found for ACC-compatible vehicles at 100% penetration.

Field Studies

The effect of AVs on basic freeway segments was investigated as early as 1996 by researchers in the Automated Highway System Program (Raza and Ioannou, 1996). Kanaris et al. (1997) completed a spacing and capacity evaluation for an automated highway system by considering fully autonomous vehicle operation and levels of infrastructure-supported vehicle automation. The study provided a base case consideration of operational parameters that adapted to present-day analysis with present-day vehicle operations. In addition, the vehicle throughput mathematical models can be referenced for capacity estimation when a sensitivity analysis of operational parameters is performed.

Shladover et al. (2012) evaluated ACC capacity by using field data collected from drivers in an ACC vehicle to estimate time headway spacing. In this study, 31.1% of the sampled drivers selected 2.2 seconds of headway spacing, 18.5% of the drivers selected 1.6 seconds, and 50.4% of the drivers were comfortable selecting 1.1 seconds. The authors found little capacity effect due to the consideration of ACC vehicles with capacity ranges of 2,030 to 2,100 veh/hr/ln with full ACC MP. The results provided in this study give a reference to actual collected data from drivers in terms of their spacing comfort when using ACC technology.

CAVs on a Basic Freeway Segment

Simulation Studies

The connectivity of AVs provides the ability to coordinate the movement of vehicles on the roadway. CACC is the most critical technology for enabling CAVs. The vehicle-to-vehicle (V2V) communication capabilities of CAVs can minimize following distances in environments where CACC vehicles are present in high penetrations and coordinate acceleration and braking actuation in platoons of vehicles to ensure smooth traffic flow. Smooth traffic flow is not possible with LVs or AVs because there is no coordination between vehicles in either of those two types of vehicles.

In the previously discussed studies of ACC capacity evaluation by VanderWerf et al. (2001, 2002), the authors also examined capacity estimates of vehicles with CACC capabilities. Although many of the operational parameters of the CACC vehicles were the same as with ACC, the desired headway gap was reduced to 0.5 seconds. In platoons of CACC vehicles, the change in the following distance resulted in capacity observations of up to 4,550 veh/hr/ln with 100% CACC MP.

van Arem et al. (2006) modeled CACC using the MICroscopic model for Simulation of Intelligent Cruise control (MIXIC), a car-following model, and evaluated CACC based on the number of shock waves, average speed, and capacity. The simulation was conducted on a highway at a bottleneck segment with and without a CACC exclusive lane. The results showed that high CACC MP leads to a few shock waves and high average speed. In addition, the authors concluded that 60% and 80% CACC MP significantly increase the highest maximum traffic volume after the bottleneck.

Zhao and Sun (2013) evaluated capacity considering ACC vehicles in a platooned environment for a basic freeway segment. The authors' main contribution focused on discussing the implementation of the Intelligent Driver Model (IDM) (a car-following model) in VISSIM to implement AV behavior. The authors estimated the maximum capacity of nearly 3,000 veh/hr under 100% CACC MP and 10 vehicle platoons.

Ntousakis et al. (2015) simulated ACC vehicles by using the AIMSUM simulation software with the Gipps car-following model and IDM. In the simulation, the authors used the Gipps model for AVs and IDM for LVs because IDM can reflect LV stop-and-go waves, contrary to the Gipps model, which was not able to show the waves. The results showed that high ACC MP rates result in high capacity, with a capacity of approximately 3,600 veh/hr/ln at 100% of CACC penetration time gaps set between 0.8 and 1.1 seconds.

Melson et al. (2018) investigated CACC characteristics from a planning perspective using MIXIC and the Link Transmission Model for dynamic network assignment. Capacity improvements due to the introduction of CACC might cause significant congestion because of the Braess paradox; the modification of a road network to improve traffic conditions may worsen its actual traffic condition. Both MIXIC and the Link Transmission Model showed that CACC performs better than LVs. Also, MIXIC showed that the capacity of CACC is 4,500 veh/hr/ln whereas the capacity of LVs is 2,300 veh/hr/ln.

Shelton et al. (2016) simulated the traffic impacts of CAVs in an urban setting. The researchers used a multi-resolution model that combines three types of modeling: macroscopic, mesoscopic, and microscopic. From the microscopic simulation parameter validation step, CAVs mimic the LVs and CACC vehicles with a capacity of 2,424 veh/hr/ln and 3,952 veh/hr/ln, with each at 100% penetration.

Field Studies

Shladover et al. (2012) evaluated ACC capacity by using field data collected from actual drivers in a CACC vehicle to estimate time headway spacing. From the authors' observations, 12% of drivers chose a time space setting of 1.1 seconds, 7% chose 0.9 seconds, 24% chose 0.7 seconds, and 57% chose 0.6 seconds. The authors found a significant capacity effect due to the consideration of CACC vehicles with a capacity as high as 4,000 veh/hr/ln under assumptions of 100% CACC MP. Su et al. (2016) compared ACC field data to the IDM using ACC-equipped vehicles. The study showed the biggest root mean square error for distance gap, with speed differential being much more accurate.

An ACC and CACC study was conducted by Milanés and Shladover (2014). Four Infinity M56s equipped with ACC were modified with communication equipment to have CACC functionality. The research team found that ACC has an overshooting problem resulting in the following vehicle's acceleration being higher than that of the leading vehicle and that CACC could eliminate the problem. The team suggested a new car-following model that could replace

IDM, as the model has an undershooting problem as well as a time gap error. The proposed ACC/CACC model uses a gap error that is calculated by comparing the location of the subject vehicle and preceding vehicle, desired time gap setting, and speed of the subject vehicle.

CAV Platoons

Platooning is defined as several vehicles traveling close together in a single lane. The communication link in CAVs allows for scenarios where platoons perform coordinated maneuvers, uniform braking, and intelligent decision-making strategies to minimize driver delay and increase highway capacity. Significant capacity impacts on a highway setting can be attributed to the effectiveness of forming and maintaining platoons at close distances.

Work by Fernandes and Nunes (2015) focused on developing CAV platooning algorithms to maintain highway capacity during transitions. Their research identified four algorithms as possible transition scenarios: platoon new leader's positioning algorithm, platoon vehicles' positioning algorithm, platoon joining maneuvers management algorithm, and extra spacing for secure maneuvering improvement algorithm. The work considers merging and diverging scenarios and capacity estimates with the use of the Simulation for Urban Mobility traffic simulator.

Songchitruksa et al. (2016) simulated CAV behavior by using VISSIM. They defined the CACC platoon formation rules as follows:

- First, two CACC-equipped vehicles are in the same lane with 100 m spacing.

- Second, the following CACC vehicle should follow for 10 seconds to join a platoon.

- Third, the following vehicles in a platoon have the desired time gap from a multinomial distribution that has four levels (0.6, 0.7, 0.9, and 1.1 second).

The study suggested that platoon dissipation conditions commence when one of the following occurs:

- a wireless signal from the wireless reception model drops
- the vehicle is the 11th vehicle in a platoon (maximum 10 vehicle platoon)
- a non-CACC vehicle cuts into the platoon.

The results showed that the CACC platoon system increased freeway throughput. Benefits were greatest when the freeway had high volumes and high CACC penetration rates and CACC vehicles traveled in the left lane.

Different platooning scenarios have been studied in conjunction with CAVs. Kesting et al. (2008) considered platooning in the evaluation of highway capacity and provided unique combinations of possible scenarios and operational parameters of 10 and 20 vehicle platoons. Carbaugh et al. (1998) considered platooning evaluations, where vehicles followed between 1 and 2 m. The focus of Fishelson et al. (2013) was on evaluating platooning safety in a CAV environment; platoon sizes of 3, 5, 6, 9, 11, 13, 15, 17, 19, and 21 vehicles were considered. VanderWerf et al. (2001) considered ACC and CACC platoons in their evaluation of capacity with a platoon size of 20 vehicles. Last, Zhao and Sun (2013) evaluated platooning scenarios with CACC vehicles with 6 vehicles in a platoon.

Heavy Vehicles (HVs)

Little CAV research has focused on HVs, but the impact of heavy CAVs could be significant on many corridors, such as the I-81 corridor in Virginia. Raza and Ioannou (1996) stated that evaluation of the impact of CAVs on commercial HVs on traffic congestion and economic growth was necessary. Raza and Ioannou stated two reasons why commercial HVs are likely to be early adopters of AV technology. First, the average truck travels 6 times as much and consumes 27 times more fuel than an average passenger car. Second, the average cost of a commercial HV is 5 times higher than that of an average passenger vehicle, making the additional cost of automation technologies a smaller proportion of total vehicle cost. Automated highway systems (Raza and Ioannou, 1996) provide operational parameter considerations for trucks and HVs (Kanaris et al., 1997; Kanellakopoulos and Tomizuka, 1997). Kesting et al. (2008) provided additional HV operational parameters and vehicle considerations. The authors restricted the truck's performance, such as the desired speed, safe time gap, and maximum acceleration, in IDM to replicate the truck's behavior. This research was conducted in the 1990s and constituted the fundamental formulations for the next generation of AVs.

Table 5 summarizes the operational parameters found in the literature of most value to the study methodology. Appendix A provides a synthesis of the studies in this section. These details provide useful information not included in this section due to the emphasis on AV operational parameters. The gaps in the research that were seen were robust studies of penetration rates of the different technologies and studies of the effects of these technologies in actual corridors where there are interactions caused by weaving segments and bottlenecks.

Table 5. Summary of Findings for Operational Parameters for LVs, AVs, and CAVs

Source	Operational Parameters (LV | ACC | CACC)	Capacity (veh/hr/ln)		
		LV	AV	CAV
Ioannou et al. 1996	Avg. speed (ft/s): (N/A | 88 | 88) Comfortable acceleration (ft/s^2): (N/A | 4.83 | 4.83) Comfortable deceleration (ft/s^2): (N/A | 3.22 | 3.22) Desired headway (s): (N/A | 0.416 | 0.72)		3,850	5,810
Huang et al. 2000	Avg. speed (ft/s): (82.02 | 82.02 | N/A) Max. deceleration (ft/s^2): (15 | 15 | N/A) Desired headway: (N/A | 1 s + 10 m | N/A)	2,000	4,750	
VanderWerf et al. 2001	Desired headway (s): (N/A | 1.4 | 0.5)	2,050	2,200	4,550
VanderWerf et al. 2002	Avg. speed (ft/s): (95.14 | 95.14 | 95.14) Comfortable acceleration (ft/s^2): (9.65 | 9.65 | 9.65) Comfortable deceleration (ft/s^2): (9.65 | 9.65 | 9.65) Desired headway (s): (1.1 | 1.4 | 0.5)	2,099	2,142	4,259
VanderWerf et al. 2001	Traffic mix: 20% LV, 20% ACC, 60% CACC			2,100-2,900
Freckleton et al. 2013	Vehicle length (ft): (16.4 | N/A | 16.4) Avg. speed (ft/s): (110 | N/A | 110) Max. acceleration (ft/s^2): (8.2 | N/A | 8.2) Max. deceleration (ft/s^2): (8.2 | N/A | 8.2) Intra-platoon spacing (ft): (3.28 | N/A | 3.28) Inter-platoon spacing (ft): (98.43 | N/A | 98.43)	2,257		8,601
Shladover et al. 2012	Vehicle length (ft): (15.42 | 15.42 | 15.42) Avg. speed (ft/s): (95.33 | 95.33 | 95.33) Comfortable acceleration (ft/s^2): (6.56 | 6.56 | 6.56) Comfortable deceleration (ft/s^2): (6.56 | 6.56 | 6.56) Desired headway (s): (1.48-1.8 | 1.1-2.2 | 0.6-1.1)	2,018	2,030-2,100	3,970
Fernandes 2015	Vehicle length (ft): (N/A | N/A | 9.84) Avg. speed (ft/s): (N/A | N/A | 50.03)			7,200
Shelton et al. 2016	Avg. speed (ft/s): (85.07-105.6 | N/A | 85.07-105.6)	2,424		3,952
Melson et al. 2018	Vehicle length (ft): (14.6 | N/A | 14.6) Avg. speed (ft/s): (73.33 | N/A | 73.33) Desired headway (s): (N/A | N/A | 0.6) Desired spacing (ft): (6.5 | N/A | N/A)	2,300		4,500

LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; ACC = adaptive cruise control; CACC = cooperative adaptive cruise control; N/A = not applicable.

METHODS

Four tasks were performed to achieve the study objectives:

1. custom simulation development
2. simulation scenario development
3. simulation plan development
4. analysis of test networks.

Custom Simulation Development

This section describes the development of the custom simulation for CVs and AVs. This simulation tool was designed in order to be able to simulate the interaction of LVs, AVs, and CAVs.

Simulation Software

VISSIM was used to assess the selected Virginia highway corridors. The research team used VISSIM 10 with its dynamic link library (DLL) (compiled by C++) to model car-following, lane changing, and communication. Many studies have used VISSIM's external driving behavior model to simulate AVs and CAVs (Melson et al., 2018; Songchitruksa et al., 2016; Zhao and Sun, 2013). At the time of this study, PTV had not released the VISSIM CAV model; however, the research team consulted with PTV in the development of the models for this study.

Two external driving modules have been widely used in VISSIM: the COM interface and the external driving behavior model (Drivingbehavior.dll). The COM interface can access all data inside VISSIM and can control some aspects of the simulation, such as vehicle insertion, but it cannot explicitly control lateral movement. On the other hand, the external driving behavior model receives the current state of the vehicle and its surroundings from VISSIM, and the DLL computes the acceleration/deceleration of the vehicle as well as the lateral movement behavior. Then, the external driving behavior model passes these values back to VISSIM to be used in the current time step. In this study, the research team used the COM interface to run multiple simulations and export results and used the external driving behavior model for car-following, lane changing, CACC maneuvering, and forming a platoon. The following subsections detail the development of the car-following algorithms inserted into VISSIM through the use of an external DLL.

Car-Following Models for LVs, AVs, and CAVs

The research team reviewed six car-following models used widely in microscopic traffic simulation. The Gipps car-following model has been used in many studies; however, some noted that near the end of the bottleneck (Spyropoulou, 2007), the Gipps model shows the unrealistic behavior named the "pinch effect." The pinch effect is a congested state that consists of a stationary downstream front at the on-ramp bottleneck; homogeneous, lightly congested traffic near a ramp; and velocity oscillations ("small jams") farther upstream (Treiber et al., 2010). IDM (Kesting et al., 2010) also has been used widely in microscopic traffic simulation in recent studies investigating AVs. This model is a collision-free and complete model, as is the Gipps model. The Milanés and Shladover (2014) model was derived from data obtained from the tests of four production vehicles in California. MIXIC has also been used widely for simulating ACC and CACC (Milanés and Shladover, 2014). After a review of the car-following models, MIXIC was chosen as the model to be implemented for this study. Table 6 summarizes the advantages and disadvantages of each car-following model.

Table 6. Advantages and Disadvantages of Each Car-Following Model

Model	Advantages	Disadvantages
Gipps	• Collision-free • Complete model	• Shows unrealistic behavior in a specific condition
IDM/ Modified IDM	• Collision-free • Complete model • Many modified versions exist	• Need to compile for VISSIM
Milanés and Shladover	• Verified by actual test drive data	• Tested in specific condition (highway setting)
MIXIC	• Collision-free • Complete model • Straightforward	• Need to compile for VISSIM
Wiedemann	• VISSIM's default model	• Not widely used for AVs and CAVs

IDM = Intelligent Driver Model; MIXIC = MICroscopic model for Simulation of Intelligent Cruise control; AV = automated vehicle; CAV = connected automated vehicle.

Selected Car-Following Model (MIXIC)

The research team determined that a modified MIXIC was the most appropriate model because it was developed for intelligent vehicles and the model has been used in CAV research similar to this study (Federal Highway Administration, 2015). Because the model is relatively simple, it is easy to understand the vehicle's current condition and movement within the simulation. Modifications to the model were made for the parameters of the vehicles tested in this study.

MIXIC was developed in 1995 by van Arem et al. (1995) to investigate the impact of ACC on traffic flow. The model assumes that the driver tries to match the speed of the preceding vehicle. At the same time, the driver attempts to keep the space gap at the desired value. The model was revised in 2006 by the authors to incorporate CACC characteristics (van Arem et al., 2006). Equations 5 and 6 represent the vehicle acceleration under MIXIC:

$$a_{ref} = \dot{x_n}(t + \Delta t) = min\left(a_n^{ref_v}, a_n^{ref_d}\right) \qquad (Eq. 5)$$

$$d_n^{max} \leq \ddot{x}_n(t + \Delta t) \leq a_n^{max} \qquad (Eq. 6)$$

where

a_{ref} is the acceleration needed for the vehicle to reach its desired speed (m/sec^2)

a_n^{refv} is the acceleration based on the difference between the current and desired speed (m/sec^2)

a_n^{refd} is the acceleration based on the values of the current speed, desired speed, and distance to the downstream vehicle (m/sec^2)

a_n^{max} is the maximum acceleration (m/sec^2)

d_n^{max} is the maximum deceleration (m/sec^2)

t is time (sec)

$\dot{x}$ is the vehicle speed (m/sec)

$\ddot{x}$ is the vehicle acceleration (m/sec^2).

The difference between current and desired speed can be calculated using a constant-speed error factor (k), desired speed, and current speed in accordance with Equation 7:

$$a_n^{ref_v} = k(\dot{x}_n^{des} - \dot{x}_n(t)) \qquad (Eq.7)$$

where

a_n^{refv} is the difference between current and desired speed (m/sec)

$\dot{x}_n(t)$ is current speed (m/sec)

$\dot{x}_n^{des}$ is desired speed (m/sec)

k is the constant-speed error factor.

The difference between the current and desired speed and distance considers three factors: acceleration, speed, and space gap (see Eq. 8). First, the model takes the preceding vehicle's acceleration ($\ddot{x}_{n-1}$) into account. Second, the model takes the speed differences between the leading vehicle and the following vehicle ($\dot{x}_{n-1} - \dot{x}_n$) into account. Third, the model considers the gap between a reference space gap and current space gap ($(x_{n-1}(t) - x_n(t)) - s_n^{ref}$).

$$a_n^{ref_d} = k_a\ddot{x}_{n-1}(t) + k_v(\dot{x}_{n-1}(t) - \dot{x}_n(t)) + k_d\big((x_{n-1}(t) - x_n(t) - L_{n-1}) - s_n^{ref}\big) \quad (Eq.8)$$

where

k_a, k_v, k_d are model parameters

s_n^{ref} is the reference space gap between vehicle n and n-1 (m)

$\ddot{x}$ is vehicle acceleration (m/sec^2)

$\dot{x}$ is vehicle speed

x is vehicle position (m).

Equations 9 through 11 determine the reference gap:

$$s_n^{ref} = max\left(s_n^{safe}, s_n^{system}, s_n^{min}\right) \qquad (Eq. 9)$$

$$s_n^{safe} = \frac{(\dot{x}_n(t))^2}{2}\left(\frac{1}{d_{n-1}^{max}} - \frac{1}{d_n^{max}}\right) \qquad (Eq. 10)$$

$$s_n^{system} = T_n \dot{x}_n(t) \qquad (Eq. 11)$$

where

s_n^{safe} is safe following distance (m)
s_n^{system} is system time setting following distance (m)
s_n^{min} is minimum allowed distance (m)
T_n is desired time gap between vehicle n-1 and n (sec)
$\mathrm{d}_\mathrm{n}^\mathrm{max}$ is distance spacing between vehicle and upstream vehicle (m)
$\dot{x}$ is vehicle speed (m/sec).

The model parameters k, k_a, k_v, and k_d were given from the default model description (see Table 7). However, the parameters for CACC simulation were revised because the new parameters show the smoother and faster reaction of the CACC controller (van Arem et al., 2006). Accordingly, the study applied the modified model parameters for LVs, AVs, and CAVs.

Table 7. MIXIC Parameters

Parameter	Default Value	Value From van Arem et al. (2006)
k	0.3	0.3
k_a (acceleration)	1.0	1.0
k_v (velocity)	3.0	0.58
k_d (distance)	0.2	0.1

Operational Parameters

Table 8 summarizes the vehicle's operational parameters, which were informed from previous research. To reflect adequately the diverse operating conditions of AVs and CAVs, ranges for each parameter were considered. This assumption is important because it is likely that different vehicle manufacturers would have different settings for different vehicles. Vehicles will also have passenger-determined settings for comfort, much like those seen in today's ACC systems.

There are four levels of parameters used to reflect the different operational parameters of the vehicles. The intermediate parameters represent the average parameters of previous research. The conservative and aggressive parameters represent two cases where the passengers could set the parameters based on their comfort level. A very conservative condition based on manufacturer crash liability is considered. It is expected that the first AV will operate in this manner unless legal frameworks are changed significantly.

Table 8. Operational Parameters of Passenger Vehicles

Scenario		Manufacturer Liability	Conservative	Intermediate (Base Parameters)	Aggressive
Vehicle length (ft)		14.70			
Desired speed (ft/s)		52.26**	52.26**	80.00	120.00*
Acceleration (ft/s^2)	Desired	2.29*	2.29*	4.93	9.08**
	Max.	3.28*	3.28*	7.16	13.12*
Deceleration (ft/s^2)	Desired	2.01*	2.01*	6.26	14.72**
	Max.	8.00	8.00	13.36	25.62**
Time gap (s)	AV	2.00	1.40*	1.07	0.70*
	CAV	2.00	1.16*	0.65	0.42**
Space gap (ft)	AV	21.00	21.00	16.05	10.50
	CAV	17.40	17.40	9.75	6.30
Standstill spacing (ft)		5.00			
Communication delay (ms)		100.00			

** Value from $\mu \pm 2\sigma$; * Value from min./max.
AV = automated vehicles; CAV = connected automated vehicles.

The operational parameters for the LVs are the default distribution of human driving behavior found in VISSIM. Equations 12 and 13 were used to determine the conservative and aggressive parameters based on what was found in past research:

$$P_C^i = \max\left(P_{min}^i, P_\mu^i - 2P_\sigma^i\right) \qquad (Eq. 12)$$

$$P_C^i = \max\left(P_{max}^i, P_\mu^i + 2P_\sigma^i\right) \qquad (Eq. 13)$$

where

P_C^i is Parameter i's conservative scenario value
P_A^i is Parameter i's aggressive scenario value
P_{min}^i is Parameter i's minimum value from the literature
P_{max}^i is Parameter i's maximum value from the literature
P_μ^i is Parameter i's average value from the literature
P_σ^i is Parameter i's standard deviation value from the literature.

Equations for aggressive and conservative scenarios are swapped for time and space gap, where small values represent aggressive scenarios. In the case of the space gap, the same methods as were used in the intermediate parameters are applied, meaning an average bounded with the minimum and maximum distributed normally. Last, the communication delay was used as a uniform value because of the lack of studies and simulation resolution available.

In the case of HVs (light trucks [LTs] and heavy trucks [HTs]), the research team collected operational parameters for trucks from the previous studies and used the average values as the intermediate case. However, since the operational parameters in the literature were limited, this study estimated the different levels of operational parameters based on the ratio of passenger vehicles' different levels of operational parameters. The power and weight values represent ranges in the simulation. The values for these vehicles are presented in Tables 9 and 10.

Table 9. Operational Parameters of Light Trucks

Scenario		Manufacturer Liability	Conservative	Intermediate (Base Parameters)	Aggressive
Vehicle length (ft)		30.00			
Weight (lb)		7000-30000			
Desired speed (ft/s)		48.99	48.99	75.00	112.50
Acceleration (ft/s^2)	Desired	1.22	1.22	2.62	4.83
	Max.	1.75	1.75	3.81	6.98
Deceleration (ft/s^2)	Desired	1.07	1.07	3.33	7.83
	Max.	4.26	4.26	7.11	13.63
Time gap (s)	AV	3.50	2.62	2.00	1.31
	CAV	3.50	2.14	1.20	0.78
Space gap (ft)	AV	39.25	39.25	30.00	19.63
	CAV	32.12	32.12	18.00	11.63
Standstill spacing (ft)		10.00			
Communication delay (ms)		100.00			
Power (hp)		200.00-536.00			

AV = automated vehicles; CAV = connected automated vehicles.

Table 10. Operational Parameters of Heavy Trucks

Scenario		Manufacturer Liability	Conservative	Intermediate (Base Parameters)	Aggressive
Vehicle length (ft)		55.00			
Weight (lb)		26000-80000			
Desired speed (ft/s)		45.73	45.73	70.00	105.00
Acceleration (ft/s^2)	Desired	0.61	0.61	1.31	2.41
	Max.	0.87	0.87	1.90	3.48
Deceleration (ft/s^2)	Desired	0.95	0.95	2.96	6.96
	Max.	3.78	3.78	6.32	12.12
Time gap (s)	AV	3.50	2.62	2.00	1.31
	CAV	3.50	2.14	1.20	0.78
Space gap (ft)	AV	39.25	39.25	30.00	19.63
	CAV	32.12	32.12	18.00	11.63
Standstill spacing (ft)		10.00			
Communication delay (ms)		100.00			
Power (hp)		400.00-600.00			

AV = automated vehicles; CAV = connected automated vehicles.

Vehicle Longitudinal Movement

Movement of LVs and AVs

The difference between LVs and AVs is that the AV has a shorter time headway. Also, the desired speeds of LVs and AVs are different because each LV has a different desired speed since human drivers have different speed preferences whereas AVs follow traffic rules, such as the speed limit. These two parameters act differently in MIXIC.

First, the time headway affects system time setting following distance in MIXIC. If the time headway (T_n) is larger than the system time setting, following distance (s_n^{system}) is likely to be chosen as the reference space gap ($\mathrm{s}_\mathrm{n}^\mathrm{ref}$). If the difference between current and desired speed and distance ($\mathrm{a}_\mathrm{n}^{\mathrm{ref}_\mathrm{d}}$) is smaller, then the model will choose that acceleration since the model compares and chooses the minimum value between the current and desired speed and distance ($\mathrm{a}_\mathrm{n}^{\mathrm{ref}_\mathrm{d}}$) and the difference between current and desired speed (a_n^{refv}).

The difference between the current speed and the desired speed affects the vehicle's acceleration. MIXIC uses differences between desired and current speed $\left(\dot{\mathrm{x}}_\mathrm{n}^\mathrm{des} - \dot{\mathrm{x}}_\mathrm{n}(\mathrm{t})\right)$ to determine the subject vehicle's acceleration. If all the vehicles have the same desired speed and if the traffic has no congestion, all the vehicles drive at the desired speed with string stability. However, if all of the vehicles have different desired speeds, some vehicles may accelerate faster than other vehicles, but the overall speed decreases due to the shock wave.

Desired Speeds

There are different desired speeds for each of the scenarios. The research team assumed that the AVs and CAVs would travel as fast as legally allowed, and this assumption is reflected in the desired speed for vehicles. The desired speeds for each scenario are as follows:

- Basic freeway segment: according to Figures 8, 9, and 10
- I-95: the speed limit as posted (55-60 mph)
- I-81: 70 mph, the posted speed limit.

CAV Movement

ACC

ACC is a technology that adjusts the vehicle speed automatically to maintain a set distance, often expressed as a time gap, from the vehicle directly ahead of the ACC vehicle. The driver sets the maximum speed, and then a radar sensor measures the distance from the vehicle ahead and adjusts the acceleration of the vehicle to stay the user-set distance from the vehicle ahead. Current ACC-equipped vehicles have between three and seven distance settings depending on the make and model. ACC is usually paired with other driver assistance features such as emergency braking and collision avoidance.

CACC

CACC is an enhancement of the ACC system with wireless communication to preceding vehicles or infrastructure to augment the ACC sensing capability. CACC technology enables the vehicle to reduce its headway because of the communication-enabled short reaction times. Each platoon has three different roles: a leader (first vehicle), members, and a tail (last vehicle). The leader of the platoon acts as an AV. The distance between platoons needs to be significantly longer than that between vehicles in the platoon. In the model, the CAV leader is determined by adjacent vehicle type and its distance. If the subject CAV has a follower within a certain distance and the following vehicle is also a CAV, the subject CAV becomes the leader of the platoon. Members of the platoon are the CAVs between the leader and the tail. The headway of a member is shorter than that of the leader because of communication capability. The tail of the platoon drives the same as a member, and the maximum platoon size determines the length of the platoon. Figure 1 shows each role in a platoon.

The CACC system determines the vehicle status based on the headway and the space gap between two consecutive CAVs. The model requires that the two CAVs are close enough to maintain a platoon based on time or space headway. If the two consecutive CAVs are not close enough to maintain a platoon, the following vehicle tries to join a platoon from a significant distance. If the two consecutive CAVs are close enough to maintain a platoon, the following vehicle tries to keep that position. Figure 2 shows the CACC maneuvering algorithm.

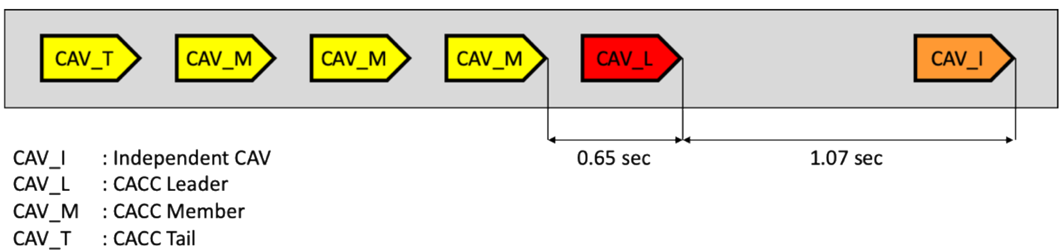


Figure 1. The Roles Within a CAV Platoon. CAV = connected automated vehicle; CACC = cooperative adaptive cruise control.

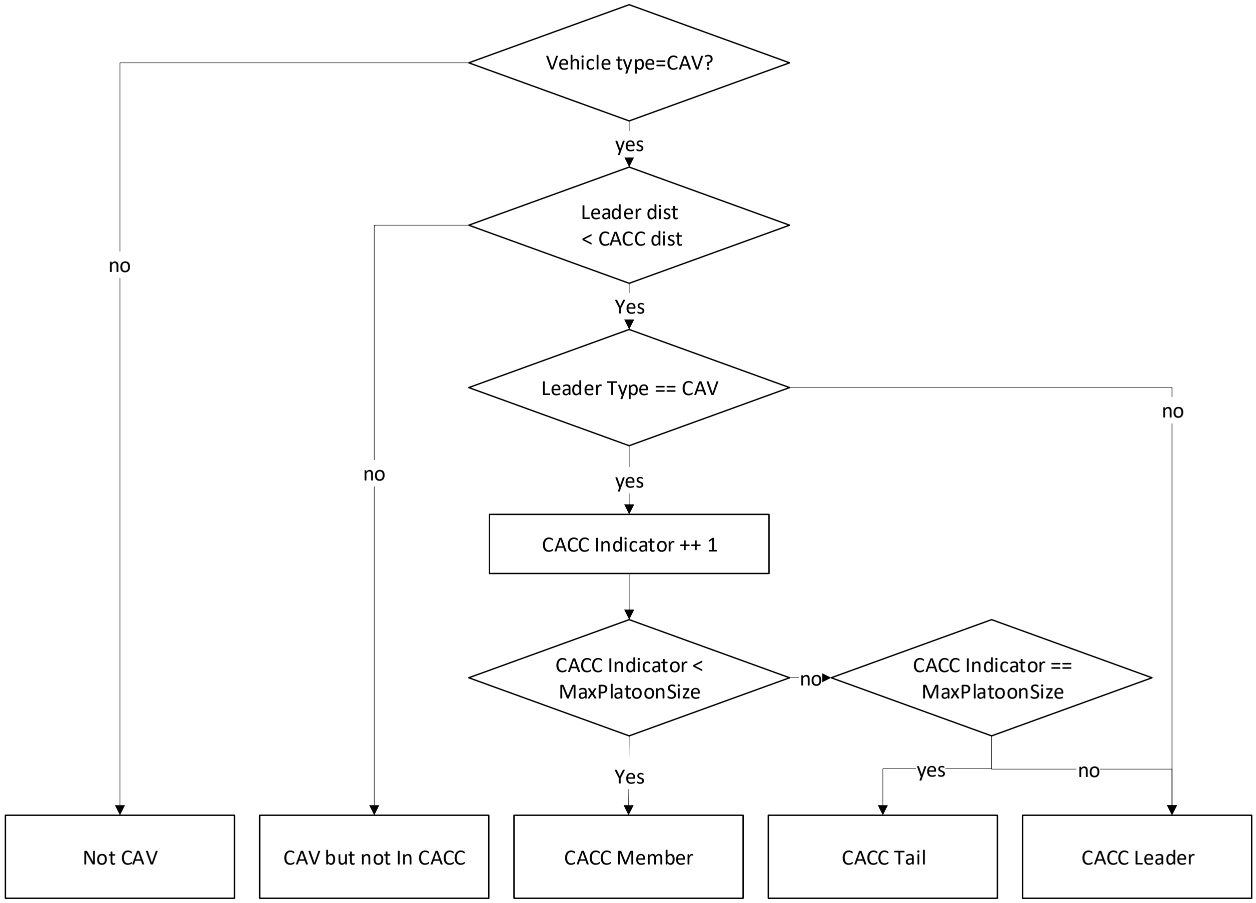


Figure 2. CACC Platoon Forming Algorithm. CACC = cooperative adaptive cruise control; CAV = connected automated vehicle; dist. = distance.

CACC Maneuvers

Members and tails of the platoon can make CACC maneuvers. The leader follows a predefined car-following model with the same headway as an AV. The CACC joining maneuver is made only when the joining vehicle is moving slower than the desired speed and the leading vehicle is a platoon leader. The following CAV follows the leading vehicle to make a platoon. AVs and CAVs are required to obey traffic laws (speed limits), whereas LVs can disobey traffic laws. Once the vehicle is in a platoon, the subject vehicle drives with the platoon unless (1) the subject vehicle's desired route is not same as the platoon's desired route; (2) the space gap between the subject vehicle and the leading vehicle is too far; or (3) the subject vehicle's desired lane is not the current lane, due to the upstream congestion.

The CACC system determines the vehicle status based on the headway and the space gap between two consecutive CAVs. The model requires that the two CAVs drive close enough to maintain a platoon based on time headway or space headway. If the two consecutive CAVs are not close enough to maintain a platoon, the following vehicle tries to join a platoon from a significant distance. Figure 3 shows the CACC maneuvering algorithm.

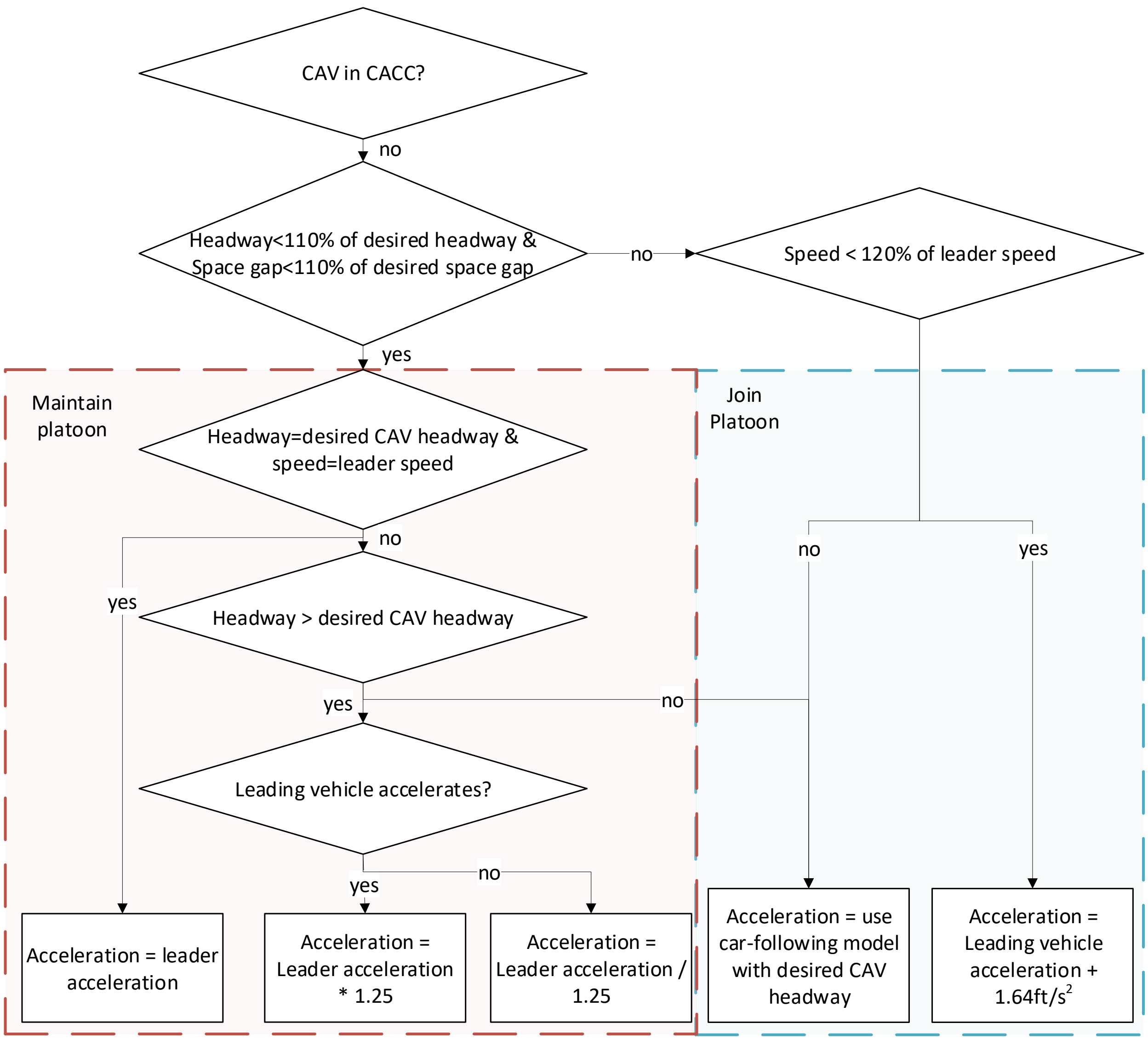


Figure 3. CACC Maneuvering Algorithm. CACC = cooperative adaptive cruise control; CAV = connected automated vehicle.

Vehicle Lateral Movement

Vehicle Platooning

Vehicle platooning is defined as a group of vehicles that travel closely together in an actively coordinated formation. Previous research has shown that vehicle platooning increases fuel and traffic efficiency, safety, and driver comfort (Bergenhem et al., 2012; Kanaris et al., 1997). CACC and vehicle platooning have many things in common. Both strategies try to make a platoon with adjacent vehicles to reduce headway and increase capacity. However, the difference between CACC and platooning is the vehicle's lateral movement; vehicle platooning changes vehicles' lanes, but CACC does not.

Platooning Algorithms

Any independent CAV (a CAV not in a platoon) can join a vehicle platoon. The CAV tries to find a platoon in an adjacent lane and tries to join the platoon. If the CAV finds the platoon on the left and the CAV itself is independent, the CAV tries to conduct a platooning maneuver. If the CAV could not find the platoon in the left lane, the CAV searches for a platoon on the right. The vehicle searches adjacent lanes until a potential platoon is found. If there is a platoon on these far-left or far-right lanes, the CAV tries to change lanes to the left or right. Once the located platoon is to the lane immediately left or right of the CAV, the CAV can then initiate a platooning maneuver.

There are three different platooning maneuvers: joining the front of the platoon, joining the end of the platoon, and joining the middle of the platoon. The platooning maneuvers are determined by the location of the platoon and the CAV that wants to join the platoon. If a platoon is behind the independent CAV on the right, the independent CAV can join to the front of the platoon by changing lanes. If the independent CAV in the right lane is between the platoon's leader and the tail, the CAV may "consider" a cut-in maneuver. If the independent CAV is behind the tail of the platoon, the CAV can join to the end of the platoon. Figure 4 shows examples of the platooning maneuvers.

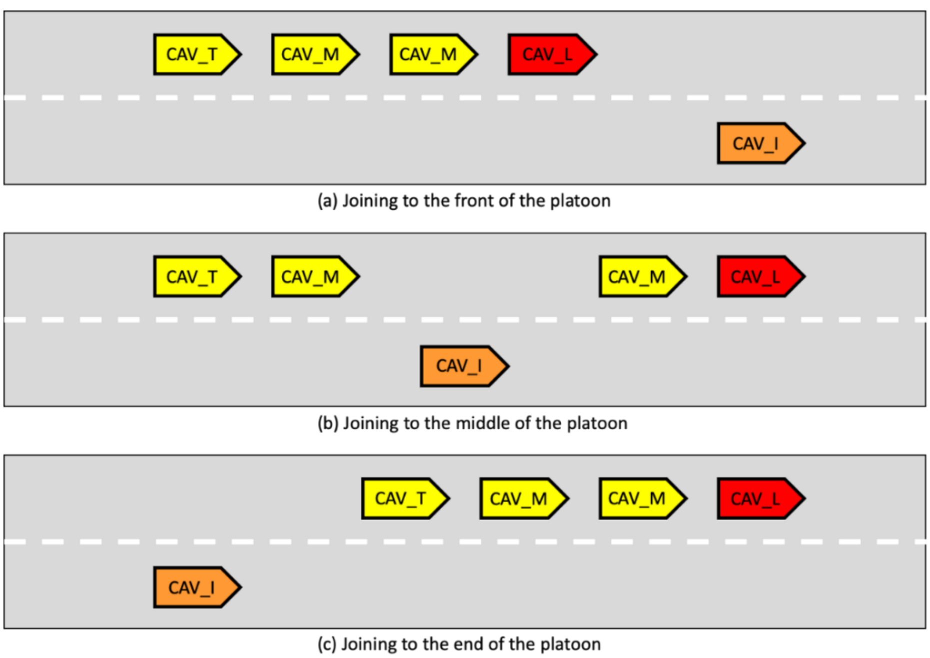


Figure 4. Examples of Three Platooning Maneuvers. CAV_T = connected automated vehicle in the tail position; CAV_M = connected automated vehicle as a platoon member; CAV_L = connected automated vehicle as a platoon leader; CAV_I = connected automated vehicle entering vehicle.

The lane change occurs when safety can be guaranteed. The model determines safety status by using the time headway between the independent CAV and the leading vehicle in the platoon and the independent CAV and the following vehicle in the platoon (Desiraju et al., 2015). The equations for lane changing are found in Desiraju et al. (2015). Based on the Desiraju et al. study, this study adopted 1 second as a safe headway. In other words, if the time headway between the subject vehicle and leading vehicle on the left (or right) is less than 1 second, the subject vehicle cannot change its lane. If the safe time headway is not guaranteed, the model reduces the following vehicle's acceleration to make a safe space. From the literature review, the maximum number of vehicles in a platoon varies from 2 to 20 (Kesting et al., 2008; Milanés and Shladover, 2014; Songchitruksa et al., 2016; Zhao and Sun, 2013). The maximum platoon size of passenger vehicles for this study was set to 5 based on the previous referenced research. Further, this study allowed forming a platoon with passenger CAVS and light truck CAVS because the operational characteristics are similar. However, in the case of the HT CAVs, the vehicle cannot form a platoon with passenger CAVs or light truck CAVs. In addition, the number of vehicles in an HT CAV platoon is restricted to three for safety reasons. Figure 5 shows the platooning algorithm used in this study.

Simulation Scenario Development

This section describes the simulation testing plan used in the study, including the development of the customized simulation tool used to integrate AVs and CAVs into the traffic stream. Three different simulation scenarios were developed: a generic urban freeway segment with a merge; a section of I-95 near Richmond, Virginia; and a segment of I-81 near Lexington, Virginia. The developed algorithms were tested on the basic test network to ensure that the driver behavior models were replicating the vehicle behavior as expected. Measures examined included car-following behavior, merging behavior, speeds, and capacity values. For each of the networks developed (Basic Freeway, I-81, and I-95), detailed validation procedures are provided.

Basic Freeway Segments

The basic freeway segments consisted of two networks that aimed to provide information on the relationships among LV, AV, and CAV capacities. Figure 6a shows a test network and the lane configurations for the simulation, where the ramp traffic must yield to the mainline traffic. This network exists to show how much capacity would be able to flow when there is little to no merging on the roadway. In this scenario, the ramp exists only to ensure (nearly) that the occupancy of the roadway was near the highest possible. In this network, vehicles would merge only if there was a significant gap in the traffic flow on the mainline. This closely approximates full capacity without a bottleneck. Figure 6b shows the lane configurations for the simulation, which simulates a forced merge scenario that could occur at the end of a ramp acceleration lane (as modeled in this study) or a lane drop on a freeway segment. This model will illuminate capacity as traditionally measured after a lane drop. The models were calibrated by using values from the HCM for capacity in both scenarios for LVs and by output speed and following distances for AVs and CAVs.

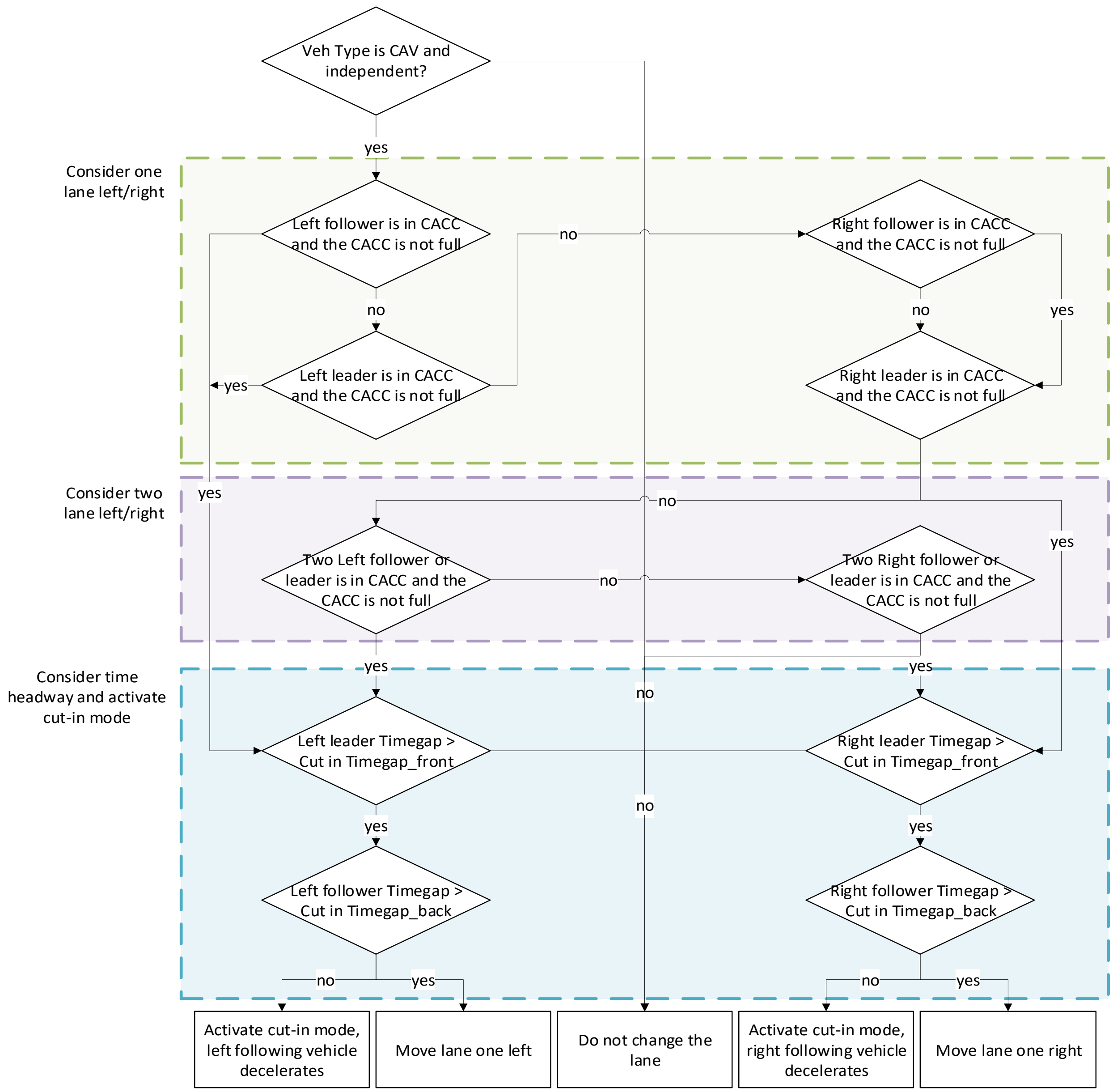
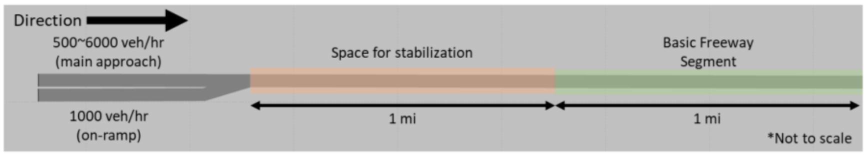
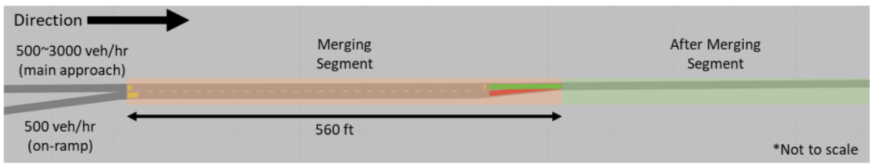


Figure 5. Platooning Algorithm. CAV = connected automated vehicle; CACC = cooperative adaptive cruise control; Timegap_front = time gap in front of subject vehicle; Timegap_back = time gap behind the subject vehicle in order to join platoon.

The input volume is 500 veh/hr to 6,000 veh/hr, incremented by 500 veh/hr every 5 minutes, and the on-ramp volume is 1,000 veh/hr. The merging segment in the basic freeway segment scenario has no priority rules so that the mainline always maintains priority. After 1 mile, the throughput is collected to measure the capacity. The merging segment has one main approach and one on-ramp approach with the addition of a 560-ft acceleration lane. The input traffic is 500 veh/hr for both on-ramps and 500 veh/hr to 3,000 veh/hr, incremented by 500 veh/hr every 5 minutes, for the mainline. Unlike the basic freeway segment, VISSIM’s priority rules for merging are implemented at the merge point to simulate forced merging behavior. On both networks, traffic volume and density were collected every 500 ft. A total of eight simulations per each scenario were conducted to account for randomness within the simulation. Average values are reported in the "Results and Discussion" section. Default merging behavior for ramps were used within VISSIM, using the ramp merging scenario option in the link intersection settings.



(a) Test Network, Basic Freeway Segment



(b) Test Network, Merging Freeway Segment

Figure 6. Test Networks for Model Verification

I-81 Segment

The section of I-81 modeled in this study follows the Appalachian Mountains and has varying grades. The study section is 7.8 miles long and is located between Exit 188B (US 60 East, Lexington) and Exit 180B (US 11, Natural Bridge). This section of roadway does not have any interchanges between the start and finish of the segment. The section has a 31% truck volume (VDOT, 2018b). Elevation data for I-81 were obtained from Google Earth and were used to compute the grades. The segment has a downhill grade of -3.9% (0.8 miles) followed by a 3.58% uphill (0.9 miles). Grades were relatively flat before and after the extended grade section. The location of the I-81 scenario is shown in Figure 7.

The I-81 study area was modeled in VISSIM and used to simulate performance in the presence of grades with consideration for HVs. INRIX data for the segment were used to set the desired speed for the network calibration (70 mph). For the modeling of HVs, 12% LT and 88% HT were entered (VDOT, 2018a). Power and weight parameters of HTs and LTs were modified in VISSIM to account for the U.S. fleet characteristics.

The demand volume was set between 3,000 veh/hr and 6,000 veh/hr in each direction with increments of 1,000 veh/hr (2,400-second total simulation with a 600-second warm-up seeding period). Volume results were measured every 1,000 ft over nine simulation periods used to estimate capacity.

Figure 7. I-81 Segment Location

I-95 Segment

A 15-mile segment of I-95 in Virginia between Richmond and Chesterfield was selected to simulate LVs, AVs, and CAVs on an urban interstate segment. This corridor runs from Exit 74A at SR 195 (Downtown Expressway) to Exit 61 at Route 10, including seven interchanges. The study focused on PM peak, from 4:45 PM to 5:45 PM. This network was calibrated from another study conducted by a consultant. The calibration was conducted in accordance with the guidelines in VDOT's *Traffic Operations and Safety Analysis Manual (TOSAM)* (VDOT, 2015). To be more specific, traffic volumes, speeds, and travel times were used for calibrating freeway segments. Where the volume was more than 1,000 veh/hr, the calibrated threshold for traffic volume was set to ±5%. In the case of speed, ±7 mph was used, and for the travel time, ±20% was used for the calibration threshold. The research team confirmed that the volumes and speeds were realistic for the simulation by comparing the volumes to those of VDOT count stations and the speeds to INRIX data supplied by VDOT. The location of the I-95 scenario is shown in Figure 8.

The study focused on the PM peak, from 4:45 PM to 5:45 PM. For the simulation, the study had 30 minutes of the warm-up period and 2 hours of the peak period, including the peak hour. Also, simulation results were collected by 15-minute periods. The demand for this network was from the calibrated model with observed variation in the peak period timeframe. Table 11 shows the simulation periods for this study, with analysis being conducted in the peak hour only.

Figure 8. I-95 Segment Location

Table 11. Simulation Periods for I-95

Warm-up Period	Peak Period	Network Peak Hour
3:30 to 4:00	4:00 to 6:00	4:45 to 5:45

Simulation Plan

The simulation plan was based on baseline scenarios that were implemented only on the basic freeway segments. In the other two scenarios, the plan was modified as stated here.

Vehicle Penetration Rates and Baseline Scenarios

The MP is a percentage of vehicles on the roadway that can be classified as AVs, CAVs, or LVs. AV and CAV penetration rates were tested at varying levels. Similar efforts have been investigated for AVs and CAVs (Shladover et al., 2012; Zhao and Sun, 2013).

Table 12 illustrates a total of 21 MP levels used in this study, in which emphasis was placed on AVs and CAVs, but the anticipated low penetration in the early stages of deployment was also considered. When AV and CAV MP levels were considered, an equal distribution of the various determined vehicle behavior models were considered to investigate the mixed effects of AVs or CAVs with different operational parameters from Table 8.

In addition, for the HV simulation, buses and single-unit trucks were treated as LTs and trailer trucks were treated as HTs as specified in the latest HCM (Transportation Research Board, 2016). Based on volume and classification data from Virginia interstate highways (VDOT, 2018b), buses, two-axle trucks, and three-axle trucks were treated as a single-unit truck (LT), and all trailers were treated as trailer trucks (HTs). The operational parameters of LTs can be found in Table 9, and the operational parameters of HTs can be found in Table 10.

Table 12. Market Penetration Distribution

MP Scenario	LV	AV	CAV
0	100%	0%	0%
1	80%	20%	0%
2	80%	0%	20%
3	60%	40%	0%
4	60%	20%	20%
5	60%	0%	40%
6	40%	60%	0%
7	40%	40%	20%
8	40%	20%	40%
9	40%	0%	60%
10	20%	80%	0%
11	20%	60%	20%
12	20%	40%	40%
13	20%	20%	60%
14	20%	0%	80%
15	0%	100%	0%
16	0%	80%	20%
17	0%	60%	40%
18	0%	40%	60%
19	0%	20%	80%
20	0%	0%	100%

MP = market penetration; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

Baseline Scenarios

The baseline scenarios are provided here for each of the three simulations conducted in this study. The details provided are the percentages of LVs, AVs, and CAVs; the amount of HVs; and the amount of demand on the roadways.

Basic Freeway Segments

The baseline scenario for this simulation was 100% LV with VISSIM standard driver behavior. The input demand for this was set to a very high value to ensure that there would be much more demand than the roadway could accommodate in order to measure capacity. There were scenarios that varied the amount of LVs, AVs, and CAVs that are detailed in Table 13. These scenarios were expanded in order to take into consideration the type of vehicle movement aggressiveness, which is detailed in Table 14. The scenarios shown in Table 13 were then expanded to account for 5%, 10%, and 15% HV in those scenarios. The results of the HV simulations are provided in Table 15. In addition, all the simulations used intermediate aggressiveness parameters from Table 8.

Table 13. Capacity Simulation Results

	Market Penetration (%)			Capacity (veh/hr/ln)	
Scenario No.	**LV**	**AV**	**CAV**	**Basic Freeway Segment**	**Merging Freeway Segment**
100	100	0	0	2286	1753
101	80	20	0	2410	1863
102	80	0	20	2477	1979
103	60	40	0	2524	1930
104	60	20	20	2581	1999
105	60	0	40	2746	2139
106	40	60	0	2653	2186
107	40	40	20	2723	2217
108	40	20	40	2906	2270
109	40	0	60	3139	2264
110	20	80	0	2789	2340
111	20	60	20	2855	2245
112	20	40	40	3041	2371
113	20	20	60	3322	2358
114	20	0	80	3757	2505
115	0	100	0	2942	2602
116	0	80	20	3029	2597
117	0	60	40	3241	2483
118	0	40	60	3523	2620
119	0	20	80	3963	2682
120	0	0	100	4373	2802

LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.
Intermediate driver behavior was used.

Table 14. Results of the Capacity Simulations With Different Aggressiveness Settings (veh/hr)

Market Penetration (%)			Intermediate		Aggressive		Conservative		Manufacturer Liability	
LV	**AV**	**CAV**	**Basic**	**Merging**	**Basic**	**Merging**	**Basic**	**Merging**	**Basic**	**Merging**
100	0	0	2286	1753	-	-	-	-	-	-
80	20	0	2410	1863	2565	1924	2219	1824	2172	1799
80	0	20	2477	1979	2616	1934	2241	1900	2175	1882
60	40	0	2524	1930	2853	1930	2184	1983	2034	1871
60	20	20	2581	1999	2905	2063	2208	2013	2035	1874
60	0	40	2746	2139	3071	2141	2270	2005	2046	1892
40	60	0	2653	2186	3196	2089	2188	2091	1912	1873
40	40	20	2723	2217	3251	2158	2218	2079	1917	1846
40	20	40	2906	2270	3441	2323	2283	2041	1929	1821
40	0	60	3139	2264	3654	2397	2414	2052	1944	1827
20	80	0	2789	2340	3630	2262	2226	2214	1798	1820
20	60	20	2855	2245	3674	2313	2251	2117	1803	1798
20	40	40	3041	2371	3847	2473	2315	2130	1810	1753
20	20	60	3322	2358	4188	2517	2441	2165	1825	1776
20	0	80	3757	2505	4407	2556	2618	2232	1846	1800
0	100	0	2942	2602	4181	2267	2320	2309	1686	1754
0	80	20	3029	2597	4246	2305	2359	2232	1693	1721
0	60	40	3241	2483	4345	2726	2437	2154	1705	1708
0	40	60	3523	2620	4379	2878	2552	2244	1722	1687
0	20	80	3963	2682	4391	3056	2696	2306	1742	1722
0	0	100	4373	2802	4393	2933	2859	2408	1762	1762

LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; - = not applicable.
The driver behavior noted in the columns were for AV and CAV only. LV used VISSIM driver behavior distributions.

I-81 Scenarios

Scenarios varied by vehicle composition with HV percentages of 0%, 30%, and 50%. In each of the three HV scenarios, MPs of AVs and CAVs were increased by intervals of 20%, resulting in 21 MP scenarios per case (LV, AV, CAV combinations, as shown in Table 12). Each HV percentage contained LTs and HTs in accordance with the traffic count data (VDOT, 2018a). In addition, the operational parameters for LTs and HTs were adopted from Tables 9 and 10, respectively. Scenarios were numbered 100 to 120 (for 0% HV), 300 to 320 (for 30% HV), and 500 to 520 (for 50% HV).

I-95 Scenarios

The simulation was conducted with the current demand as a baseline. Demand was increased to 150% and 200% for all ramps and mainline inputs to the simulation of the current demand to understand capacity better and to see how increasing demand in future years would be affected by the AV and CAV technologies.

Table 15. The Simulation-Based Capacities With Heavy Vehicles (veh/hr)

Market Penetration (%)			Passenger Vehicles		5% HV		10% HV		15% HV	
LV	AV	CAV	Basic	Merging	Basic	Merging	Basic	Merging	Basic	Merging
100	0	0	2286	1753	2209	1893	2125	1829	2047	1771
80	20	0	2410	1863	2300	1954	2190	1897	2106	1829
80	0	20	2477	1979	2340	2067	2221	2028	2119	2025
60	40	0	2524	1930	2393	2026	2282	1978	2196	1966
60	20	20	2581	1999	2440	2143	2324	2142	2220	2088
60	0	40	2746	2139	2558	2319	2424	2208	2328	2205
40	60	0	2653	2186	2502	2078	2385	2089	2273	2025
40	40	20	2723	2217	2533	2224	2416	2173	2298	2132
40	20	40	2906	2270	2651	2312	2537	2270	2405	2252
40	0	60	3139	2264	2879	2378	2724	2365	2554	2381
20	80	0	2789	2340	2603	2300	2496	2191	2393	2111
20	60	20	2855	2245	2641	2241	2532	2252	2433	2217
20	40	40	3041	2371	2803	2366	2648	2377	2530	2347
20	20	60	3322	2358	3022	2437	2842	2581	2670	2495
20	0	80	3757	2505	3393	2561	3148	2714	2960	2622
0	100	0	2942	2602	2725	2270	2608	2216	2486	2212
0	80	20	3029	2597	2778	2535	2649	2339	2525	2298
0	60	40	3241	2483	2939	2559	2772	2489	2654	2438
0	40	60	3523	2620	3187	2593	2970	2659	2792	2579
0	20	80	3963	2682	3600	2638	3339	2788	3090	2798
0	0	100	4373	2802	4127	2886	3773	2947	3506	2936

HV = heavy vehicles; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.
The driver behavior noted in the columns were for AVs and CAVs only. LVs used VISSIM driver behavior distributions.

The scenarios were considered with 100% AV and 100% CAV only. Truck volumes were converted to passenger cars by the HCM method of passenger car equivalents. In addition, all the simulations used intermediate aggressiveness parameters from Table 8.

Analysis of Test Networks

Performance Metrics

Consideration of other measures of effectiveness (MOEs) helps shape a picture of how changes in traffic composition will affect operations on interstate highways. Capacity is widely used to demonstrate the effect of AV and CAV technologies on traffic performance (Arnaout and Bowling, 2011; Ntousakis et al., 2015; Shladover et al., 2012; VanderWerf et al., 2001). Shladover et al. (2012) demonstrated how a 100% CACC penetration rate could increase the capacity up to 4,000 veh/hr/ln.

Other MOEs also appeared in the literature. These MOEs can be classified into macroscopic and microscopic measures. Under the macroscopic measures, speed and density have been evaluated (Melson et al., 2018; Milanés and Shladover, 2014; van Arem et al., 2006).

Under the microscopic measures, factors such as travel time (Arnaout and Arnaout, 2014; Kesting et al., 2008) and delay (Bierstedt et al., 2014) were used. This study concentrated on throughput and speed as MOEs.

Sample Size Calculations

The sample size for the number of simulations needed for each case study was computed based on the Federal Highway Administration (2016) equation (Eq. 14) that estimates the minimum required number of replications of a simulation:

$$N_{min} = (\frac{t_{n-1,95\%}s}{e\bar{x}})^2 \qquad (Eq. 14)$$

where

N_{min} is required number of model runs
n is number of initial model runs (i.e., 4)
$\bar{x}$, s is mean and standard deviation of the initial runs
$t_{n-1,95\%}$ is *t* statistic for *n-1* degrees of freedom and 95% confidence level
e is tolerance error.

Tolerance error, *e*, is the maximum of the two calculated tolerance errors at the two critical time intervals. It is computed in accordance with Equation 15 as follows:

$$e = \frac{t_{n-1,95\%} \frac{s}{\sqrt{n}}}{\bar{x}} \qquad (Eq. 15)$$

For each scenario in each of the three case studies, the two critical periods were used to compute the tolerance error. The critical period was assumed to correspond to the time intervals resulting in the two most significant throughput values.

The required sample size was computed for each scenario, and the selected sample size for the case study was the maximum of the obtained required sample sizes. For instance, for I-81's link 27, scenario 504 resulted in the largest required sample size, which turned out to be 7.

Then, for the entire sample consisting of four random seed results at the critical time periods:

$\bar{x}$ = 3271.59
s = 131.51
E = max (0.0169, 0.0074) = 0.0169 (smaller than 5%)→ use 0.05.

$N_{min} = (\frac{t_{n-1,95\%}s}{e\bar{x}})^2 = (\frac{3.182*131.51}{0.05*3271.59})^2$= 6.54; round up to 7.

After the first four runs for each of the three case studies were conducted, the sample size was computed. The basic highway segment required four runs (but five were modeled), the urban interstate required nine, and the rural interstate required seven.

Analysis Methods

This study aimed to compare the impacts on operations under different technology distributions. For that reason, when the outcomes of the MOEs were compared, a paired two-tailed t-test was performed to determine whether or not the difference between results was significant. The assumption was that p-values smaller than 0.1 caused a rejection of the null hypothesis (which assumes equal sample means) or that compared samples were significantly different. The t-tests were chosen to contrast different scenarios with similar characteristics, varying one variable.

Paired Sample t-Test

A paired sample t-test is a statistical method used to compare two sample means. The goal is to determine whether or not the mean difference between the two sets of results is zero. In a paired t-test, the null hypothesis will be that the true mean difference is zero. Thus, if the null hypothesis is rejected, the means from the two samples are considered to be significantly different. In order to accept or reject the null hypothesis, a p-value for the test statistic is obtained. The test statistic is computed in accordance with Equation 16 as follows:

$$t_{obs} = \frac{\overline{y_d}}{s_d/\sqrt{n}} \qquad \text{(Eq. 16)}$$

where

$\overline{y_d}$ is the sample mean difference (average of the differences between each pair of observations from the two compared samples)

s_d is the sample standard deviation for the differences

N is the sample size.

The t-distribution tables were then used to compare the obtained t_{obs} value to the t_{n-1} distribution. This gave the p-value for the paired t-test, which is the probability of finding the observed or more extreme results when the null hypothesis is confirmed. With a p-value greater than α (assumed to be 0.1 in this study), the null hypothesis is not rejected (equal sample means) and there is insufficient evidence to suggest that results from the scenarios are significantly different. The comparison for this research was the average of the eight simulations using the maximum 1 hour volume as the unit of measure.

RESULTS AND DISCUSSION

Corridor Simulation Networks

Model Verification

The information in the following sections pertains to information for the non-merging scenario. The merging scenario was verified using the knowledge of the research team and staff of the Virginia Transportation Research Council (VTRC) to verify that the model was producing results that were realistic for LVs, AVs, and CAVs. The theoretical values shown here are with headways that do not reflect safety constraints seen in field implementation of vehicles. These capacity values are theoretical upper bounds for capacity, which are much higher than field-measured values.

LVs

As discussed previously, LVs represent human-driven vehicles without any automation features. From the previous studies listed in Appendix A, the headway (T_n) of the LV was chosen as 1.41 seconds. In an ideal case, the capacity of the single-lane road can be calculated by Equation 17. In this case, the capacity of LVs will be 2,553 veh/hr/ln. This capacity is for the basic freeway segment; a merging scenario would reduce the capacity based on the vehicle interactions.

$$C = \frac{3600}{T_n} \qquad (Eq. 17)$$

AVs

As discussed previously, the headway of AVs was chosen to be 1.07 seconds (see Table 3) and was governed by the same car-following model as for LVs. AVs may have additional automated driving features such as lane-keeping assistance, emergency braking, or parking assistance, but those applications do not affect the theoretical maximum road capacity where vehicles do not change lanes. The only factor that affects road capacity is the desired speed, and all AVs have the same desired speed equivalent to the speed limit. By Equation 13, the capacity of AVs in an ideal case is 3,365 veh/hr/ln. This capacity is for the basic freeway segment; a merging scenario would reduce the capacity based on the vehicle interactions. It is expected that the merging scenarios for AVs would be more orderly and would have a higher capacity.

CAVs

CAVs are AVs with communication capability. CAVs can generate CAV platoons and reduce headways by communicating their intentions and actions with each other directly and with low latency. Each CAV platoon consists of a leader vehicle, a tail vehicle, and (if there are more than two vehicles) a member vehicle. The leader represents the first CAV in a platoon and follows AVs or LVs and therefore must use AV headways. The member and tail vehicles follow other CAVs and may use CAV headways, which are set at 0.65 seconds. Detailed characteristics are discussed in the next section. The capacity of the CAV is determined by the maximum platoon size, headway of the AV for the CAV leader, and headway of the CAV for CAV members. Equation 18 shows the theoretical capacity of a CAV. According to the equation, when the maximum platoon size is five, the capacity is 4,904 veh/hr/ln. This calculation assumes no HVs and 100% of vehicles in platoons.

$$C = \frac{3600P^{max}}{T_{AV} + (P^{max} - 1)T_{CAV}} \qquad (Eq. 18)$$

where

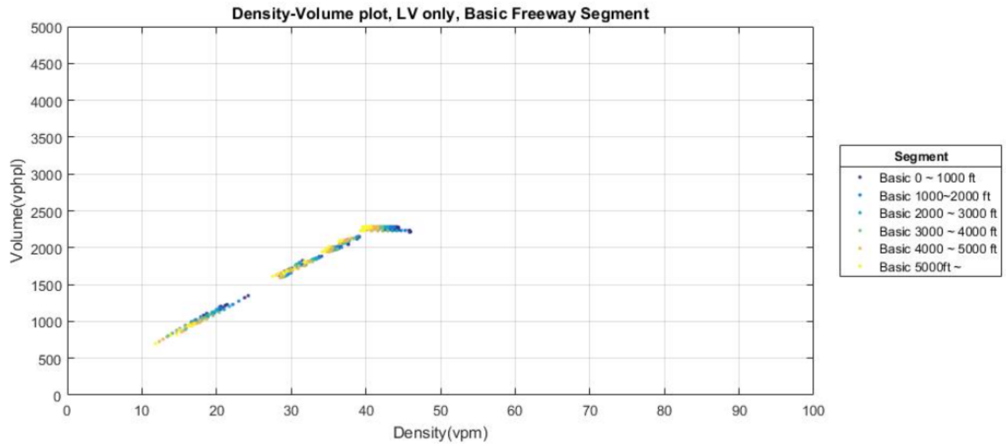
P^{max} is the platoon size (number of vehicles).

Simulation Plan

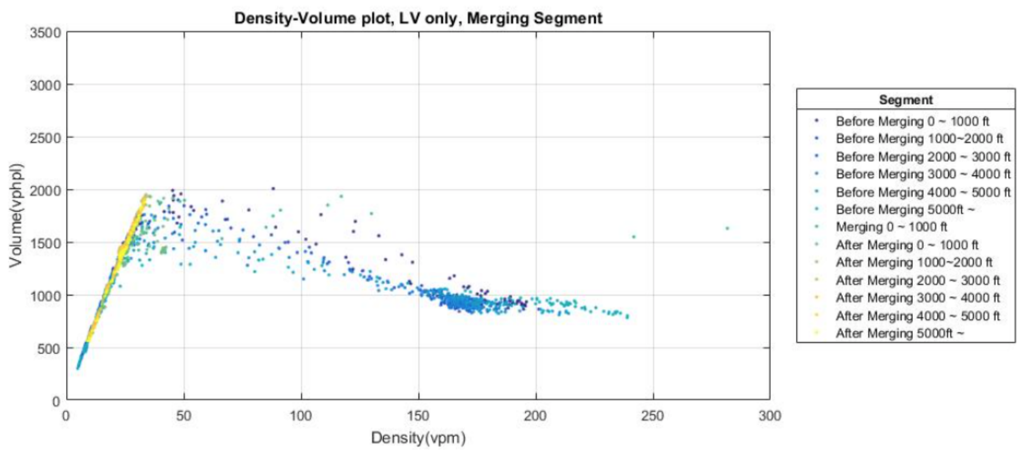
Basic Highway Segment

The capacities of LVs, AVs, and CAVs were examined on the sample networks. Twenty-one scenarios, numbered 100 to 120, were developed to test different MP rates for each vehicle. Table 12 shows the scenarios tested. The operational parameters in Table 8 were used for measuring the capacity for the passenger LVs, AVs, and CAVs. The results for each scenario are expressed as an average of the results from the number of repetitions calculated from the sample size calculation provided previously.

Scenario 100, which represents the LV only scenario, shows a theoretical maximum capacity of 2,553 veh/hr/ln; however, the capacity from the basic freeway segment is 2,286 veh/hr/ln and the capacity from the merging freeway segment is 1,753 veh/hr/ln. The difference between the capacities for the basic freeway segment and the merging freeway segment comes from the gap due to the merging process. The HCM states that the capacity under the queue discharge situation is substantially below the basic highway capacity of 2,400 veh/hr/ln (Transportation Research Board, 2016). The simulation adopted different operational parameters for each vehicle to mimic real traffic flow. Therefore, the observed capacity was less than the theoretical capacity. Indeed, the capacity of the basic freeway segment from the latest HCM showed 2,400 veh/hr/ln when the segment's free-flow speed was 75 mph (Transportation Research Board, 2016). Therefore, the capacity from the simulation seems reasonable. In Figure 9, the capacity is shown between a density of 40 to 50 vehicles per mile. Oversaturation was not observed in the basic freeway segment since there was no delay downstream. However, in the case of the merging segment, the lane before the merge point had congestion as needed to measure the capacity at the merge point.



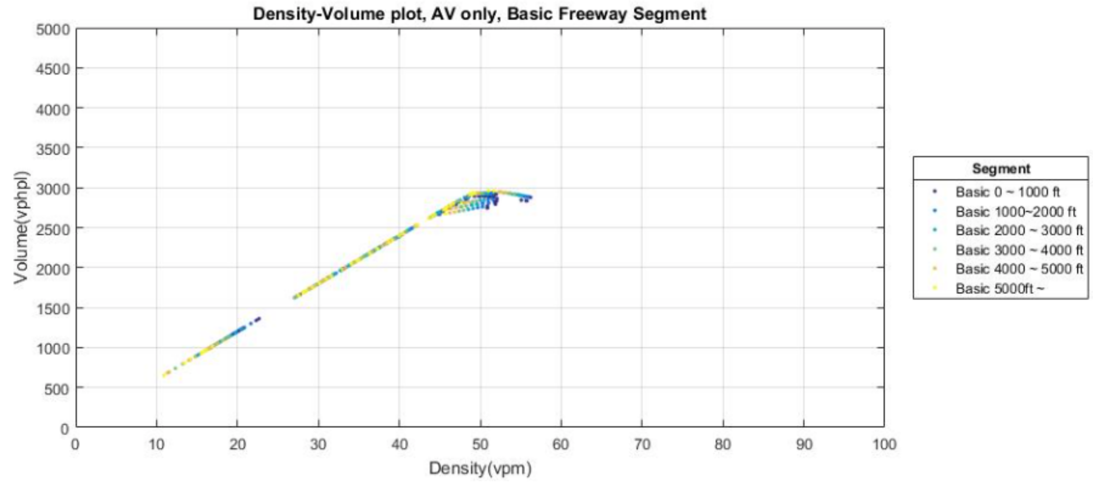
(a) Basic Freeway Segment, LV Only (0 ft is the beginning of the roadway)



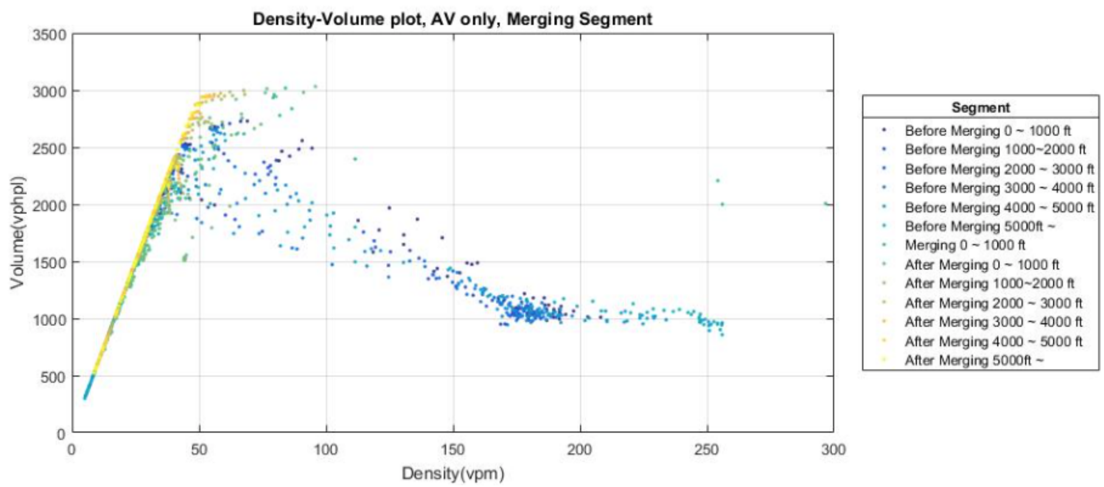
(b) Merging Freeway Segment, LV Only

Figure 9. Density-Volume Plot for LV Only Scenario. LV = legacy vehicles.

In the theoretical case for AVs, the capacity was calculated as 3,365 veh/hr/ln. According to scenario 115, which represents the AV only scenario, the capacities were 2,942 veh/hr/ln for the basic freeway segment and 2,602 veh/hr/ln for the merging freeway segment. In both segments, there was merging behavior that would reduce capacity. The merging freeway segment, being 700 less than the theoretical, showed a similar percentage reduction in the theoretical capacity from the LV only scenario. Similarly, the theoretical capacity of CAVs was 4,904 veh/hr/ln; the measured capacity of the basic freeway segment was 4,373 veh/hr/ln; and the capacity of the merging freeway segment was 2,802 veh/hr/ln. Based on the simulation results and confirmed from previous studies, the model outputs were reasonable since most of the studies revealed the capacity of 100% CACC vehicles to be near 4,000 veh/hr/ln. Figures 10 and 11 show that AVs and CAVs can sustain higher densities than LVs because all AVs and CAVs have the same desired speed and can achieve the speed precisely due to the computer controlling the driving behavior.



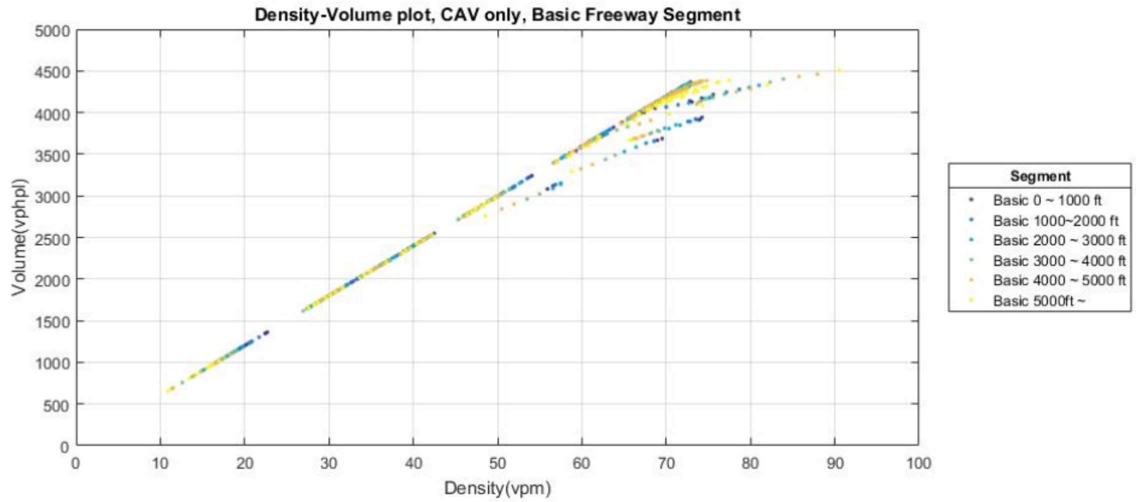
(a) Basic Freeway Segment, AV Only (0 ft is the beginning of the roadway)



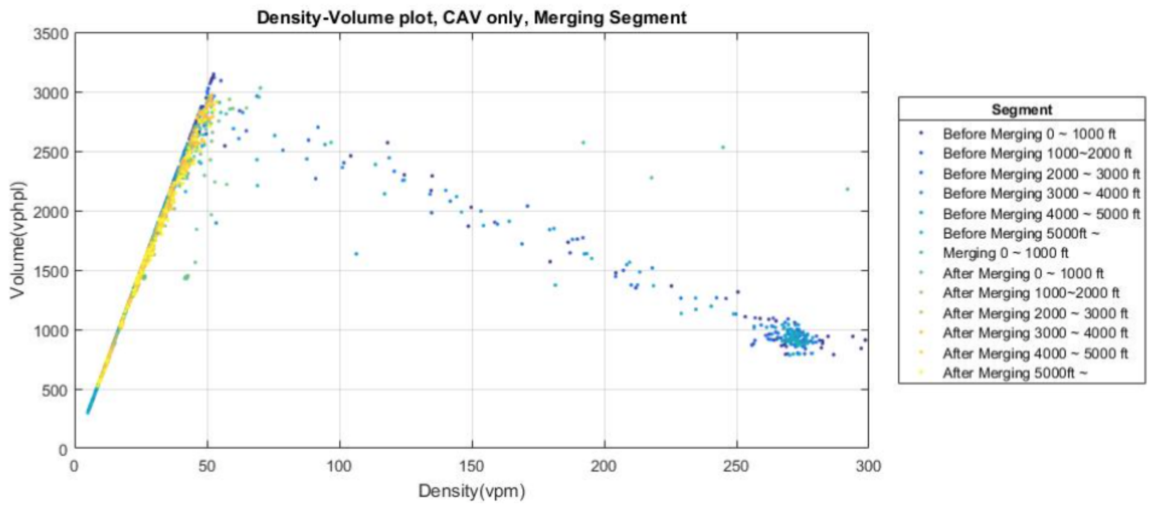
(b) Merging Freeway Segment, AV Only

Figure 10. Density-Volume Plot for AV Only Scenario. AV = automated vehicles.

The simulation shows that the introduction of AVs could increase the capacity even at low penetration rates. Compared with 100% LV, traffic consisting of 80% LV and 20% AV would increase capacity by 5.4% at basic freeway segments and 6.3% at merging freeway segments. The effects of CAVs at low penetration rates were larger than for AVs. When the percentage of LVs was 80% and the percentage of CAVs was 20%, the capacity was increased by 8.3% at the basic freeway segments and 12.9% at the merging segments. In the case of higher penetration rates of AVs and CAVs, the increased capacity was significant. With 100% AV, the capacity increased 28.7% at the basic freeway segments and 48.4% at the merging freeway segments. With 100% CAV, the capacity increased 91.3% at the basic freeway segments and 59.8% at the merging segments. The merging segment capacity shows less of an improvement with higher CAV penetration rates when compared to basic freeway segments because CAV platooning does not occur in merging segments and cannot improve capacity.



(a) Basic Freeway Segment, CAV Only (0 ft is the beginning of the roadway)



(b) Merging Freeway Segment, CAV Only

Figure 11. Density-Volume Plot for CAV Only Scenario. CAV = connected automated vehicles.

Table 13 shows the effect of the vehicle fleet mix on capacity from the basic highway segment simulations.

Aggressiveness Levels

The previous simulations tested LVs, AVs, and CAVs with the same driving characteristics, such as desired speed, desired time headway, and acceleration/deceleration capability. One likely scenario is that next-generation vehicles will have varying driving characteristics based on manufacturer preferences and vehicle type. Also, it is expected that vehicles will have passenger comfort settings for speed and aggressiveness, much like the ACC systems do today. In order to test these different parameters, four different levels of operational parameters—aggressive, conservative, intermediate, and manufacturer liability—were examined on the test network. Table 14 shows the capacities for different levels of operational parameters assuming all vehicles are using the aggressiveness settings shown in the column of the table.

The specific operational parameters for each vehicle will be decided by the passenger and the manufacturer, with boundary conditions determined by law. The passengers may select the operational parameters that mimic human driving and feel familiar. These parameters may be similar to the intermediate or conservative settings. Manufacturers may be incentivized to avoid crashes and the resulting civil liability and may select the manufacturer liability scenarios.

The aggressive scenario increased the capacity up to 42% at the basic freeway segment and increased it up to 13.9% at the merging freeway segment. However, in some merging cases, the aggressive driving decreased capacity because the aggressive driving interrupted smooth merging. However, conservative driving decreased the capacity of the roadway up to 34.6% at the basic freeway segment and up to 14.4% at the merging freeway segment based on the 100% LV scenario. Likewise, under the manufacturer liability case, capacity reductions reached 59.7% at the basic freeway segment and 37.1% at the merging freeway segment compared to the 100% LV scenario.

The benefits from the aggressive scenarios were achieved for combinations with high AV percentages. CAVs did not benefit as much from aggressive scenarios because the coordination between vehicles produced efficient results under intermediate conditions due to their ability to form platoons. CAVs were also the most negatively affected by more conservative parameter settings with increased headways.

HVs

HV proportions of 5%, 10%, and 15% were considered for simulation because the average percentage of HVs on Virginia interstate highways in 2018 was 11.6% (VDOT, 2018b). The aggressiveness was set at the intermediate level for these simulations. In each scenario, the HVs consisted of 18% LT and 82% HT, based on the 2018 Virginia annual average daily traffic. Simulations were conducted on the same network with the same input volume. Each scenario was simulated 5 times with different random seeds to produce an average capacity value. AVs and CAVs were distributed at the same percentages for HVs and passenger vehicles.

Table 15 shows the capacities for different percentages of HVs. The capacity trend in the presence of HVs is similar to that of passenger vehicles: a larger percentage of AVs or CAVs achieves a higher capacity. The introduction of HVs, however, resulted in a decrease in capacity across all combination scenarios when compared to passenger vehicles only. The reduction in capacity increased with increasing HV percentage. In the case of the merging freeway segment, the lower acceleration and deceleration rates of HVs produced larger gaps during the frequent stop-and-go traffic and therefore lower capacities.

T-tests were conducted for all scenarios. All scenarios were calculated to be statistically significant at the 90% confidence interval. The detailed scenario descriptions for the HV simulations are provided in Appendix B, and the t-test results are provided in Appendix C. Scenarios 200 to 220 represent 5% HV, scenarios 300 to 320 represent 10% HV, and scenarios 400 to 420 represent 15% HV.

Analysis of Test Networks

This section provides the analysis and discussion for the I-95 and I-81 test networks. Different tests were conducted on each network to understand how AVs and CAVs responded to the unique characteristics of each network. The I-95 tests focused on congestion due to traffic demand, and the I-81 scenario focused on the impact of trucks. Detailed statistical results for all scenarios on both networks are provided in Appendix C.

I-95 Network

An analysis of throughput and speed on the I-95 corridor was conducted with 100% LV, 100% AV, and 100% CAV. The intermediate car-following behavior was implemented for the AV and CAV scenarios.

Speed

Speed is one of the MOEs used to evaluate the impact of AVs and CAVs on the operations of the highway. Figures 12 through 14 show that at low demand, especially in the 100% demand scenarios and in the off-peak northbound direction, the average speed of LVs is usually higher than that of AVs or CAVs because LVs can drive at the free-flow speed, which is usually above the posted speed limit. In contrast, AVs and CAVs are programmed to follow all traffic rules; therefore, they could not drive above the posted speed limit. At more congested segments, AVs showed the most significant improvements in speed results over LVs. Speed increased by up to 18% during the 150% demand case and up to 14% during the 200% demand case.

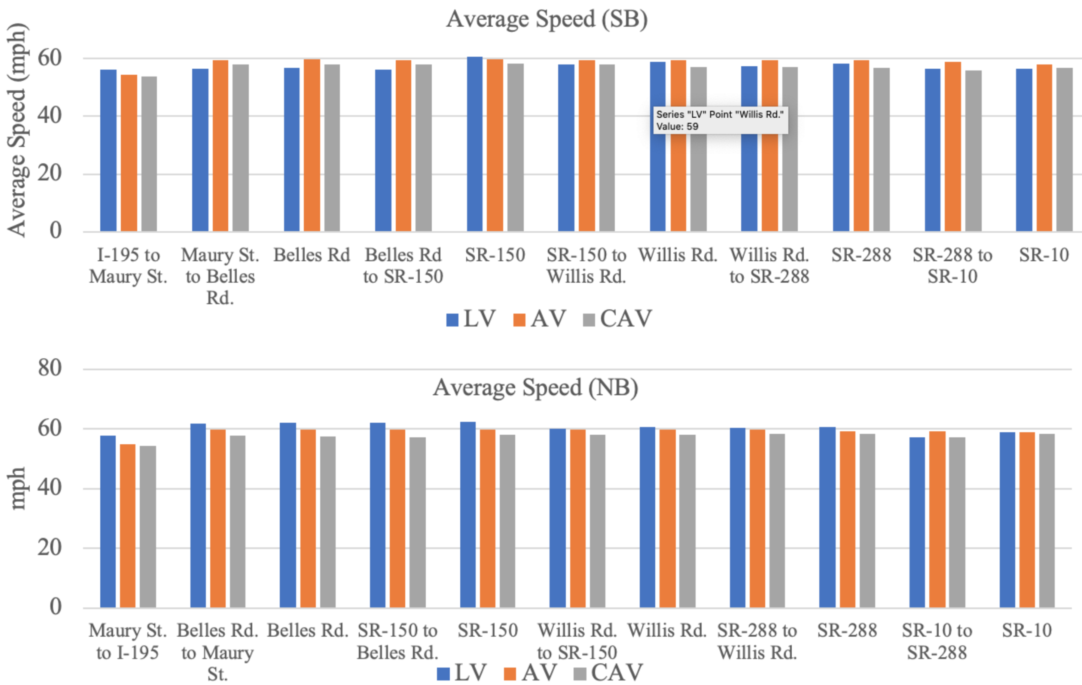
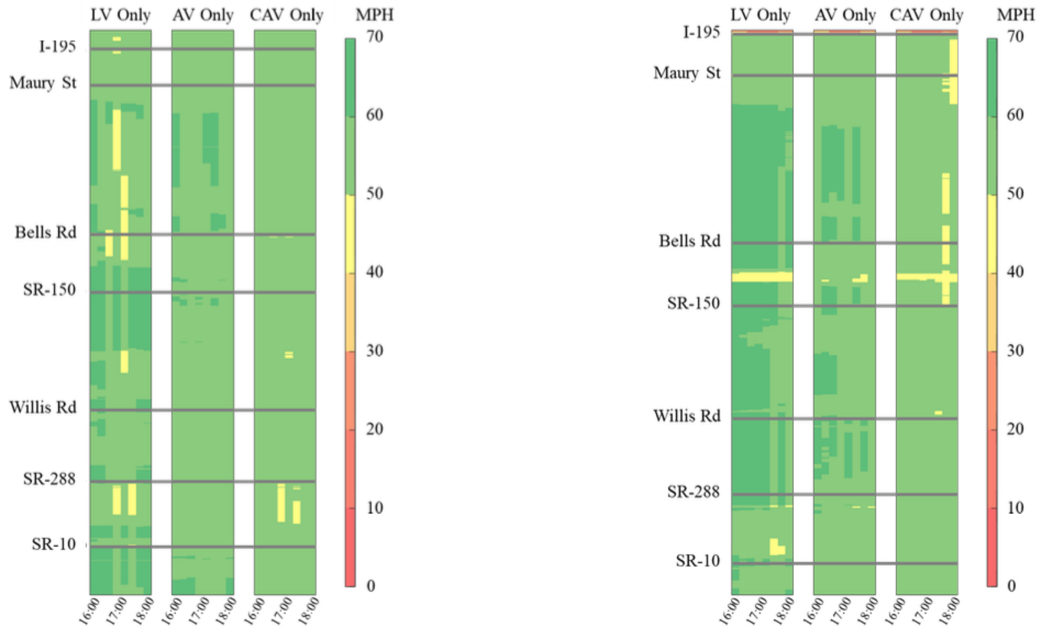


Figure 12. 100% Demand Average Speed. SB = southbound; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; NB = northbound.

Figure 13. 150% Demand Average Speed. SB = southbound; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; NB = northbound.

Figure 14. 200% Demand Average Speed. SB = southbound; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; NB = northbound.

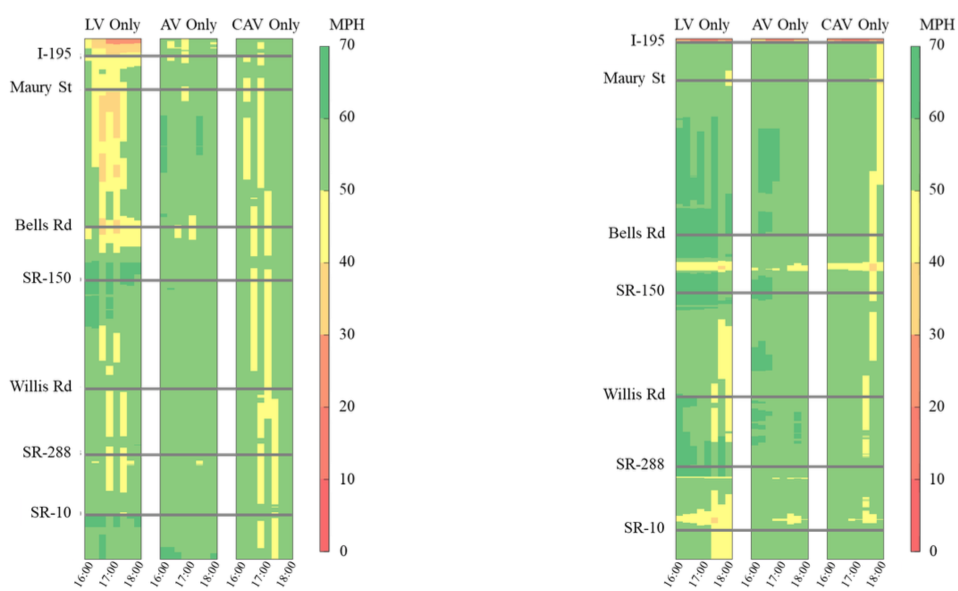
The speed heatmaps provided in Figures 15 through 17 show the average speed at each segment at each 15-minute evaluation period during the peak period. In these heatmaps, each small square represents a 100-ft segment of roadway, and the period is 15 minutes. In the uncongested segments, the LV speed was higher than the AV or CAV speed because the simulation allowed for LVs to drive above the speed limit. In the congested periods, LVs drove slower than AVs or CAVs; however, in uncongested areas, the simulation allowed for “human” drivers to exceed the speed limit where the AVs were assumed to obey the speed limit strictly. CAVs showed lower speeds than AVs, because of the platooning process. The platooning process of CAVs was beneficial in the case of basic freeway segments, but for complex segments, such as on- and off-ramp and weaving segments, AVs and CAVs may not be as efficient as human drivers due to safety rules and less ability to adapt. These segments reduce platoon speeds as vehicles maneuver into and out of the platoon, and this affects the speed of all of the following vehicles due to their short headways. In addition, at the weaving segment, every independent CAV will attempt to join or form a platoon, and this additional lateral movement can impede the movement of non-platooned vehicles. In the case of AVs, their desired speeds are the same as CAVs, but they do not need to change their lane for platooning so that vehicles can drive with a small amount of interaction with other vehicles. The northbound heatmaps also show similar results.



(a) Southbound

(b) Northbound

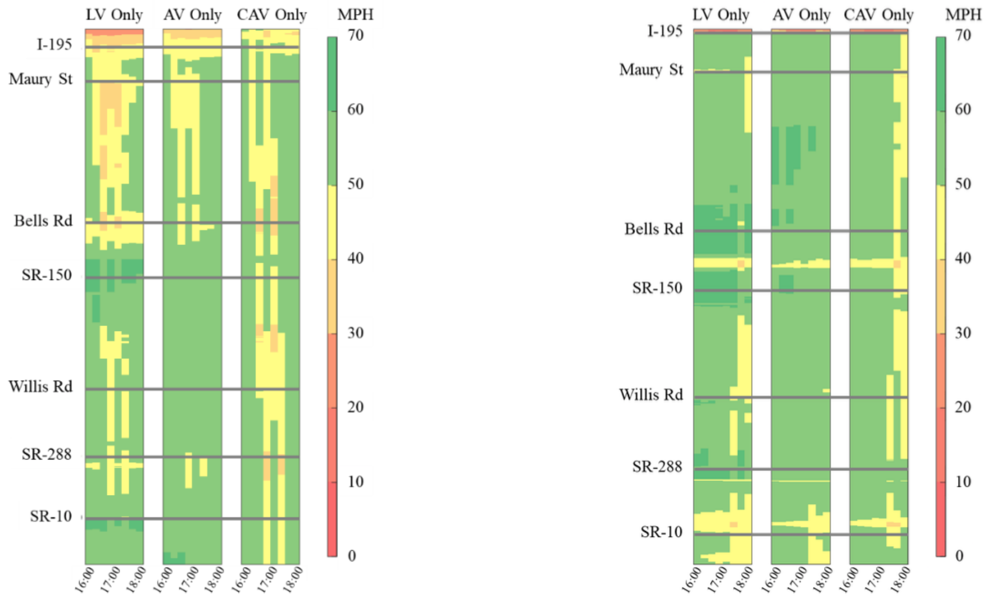
Figure 15. 100% Demand, Speed Heatmap for I-95. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.



(a) Southbound

(b) Northbound

Figure 16. 150% Demand, Speed Heatmap for I-95, 150% of Traffic Demand. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.



(a) Southbound (b) Northbound

Figure 17. 200% Demand, Speed Heatmap for I-95, 200% of Traffic Demand. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

Throughput

Throughput, measured in vehicles per hour per lane, was used to evaluate the impacts of AVs and CAVs on I-95. The initial analysis in this network was based on the input volumes from the calibrated I-95 model. After the base simulations were conducted, the input volume was increased to 150% and then 200% of the current traffic demand.

Throughput results were collected for both the southbound and northbound directions. For the southbound direction, which was the peak direction during the PM peak period, throughput results for the 100% demand scenarios (current day demand) for LVs, AV%, and CAVs are presented in Figure 18. On all segments, the 100% LV scenario showed the best performance compared to the 100% AV and 100% CAV scenarios. In the case of the southbound direction, AVs and CAVs showed 4% and 6% lower throughput than LVs; in the case of the northbound direction, AVs and CAVs showed 1% and 5% lower throughput than LVs, respectively. Notably, the 100% CAV scenario showed lower throughputs, which was the opposite of the test network result. The reason is that when the platoons of vehicles enter sections of roadway where there are weaving sections, the flow of vehicles becomes unstable as vehicles seek to join platoons. This could be a limitation of the modeling strategy as CAVs would most likely not try to form platoons in weaving areas. However, the result is interesting as it shows a weakness of the CAV technology. The throughput per lane is far below the highway capacity for these vehicles because of the weaving section.

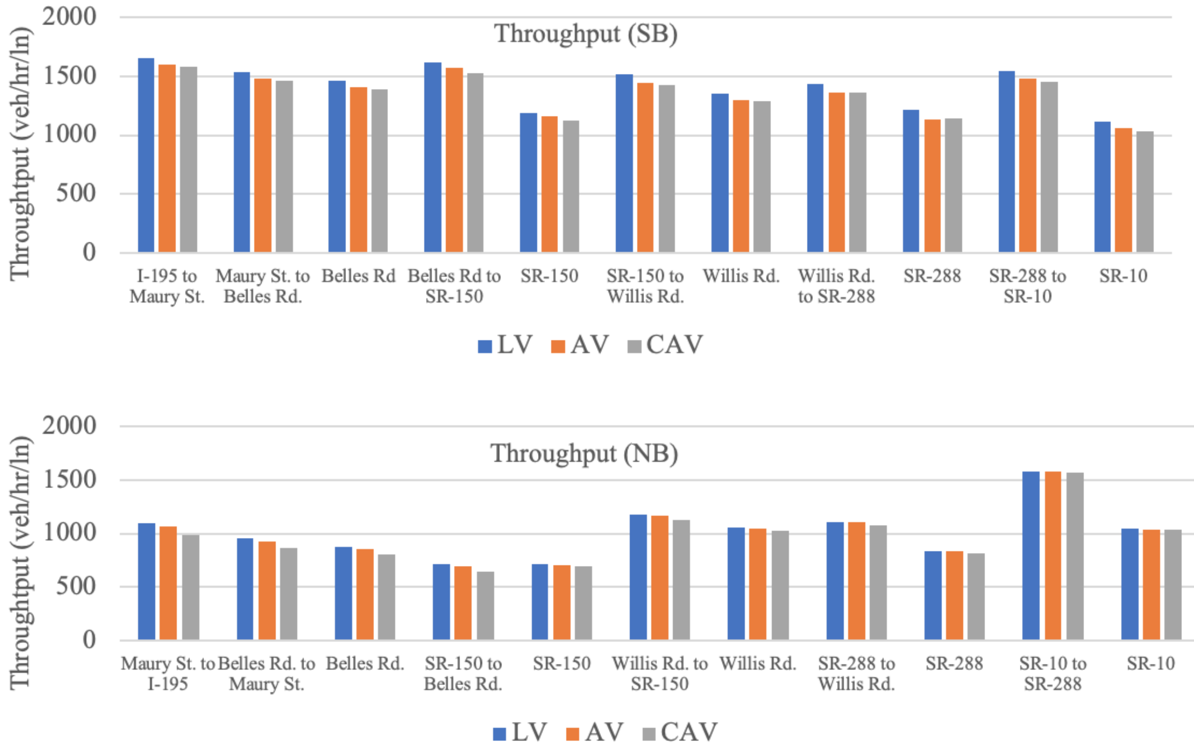


Figure 18. 100% Demand Southbound (SB) and Northbound (NB) Throughput. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

Figure 19 shows the results of the 150% traffic demand. Congestion starts to form, and the benefits of AVs and CAVs over LVs are seen. The peak southbound direction showed more significant benefits of AVs and CAVs as compared to the northbound direction, which had less congestion. The AV and CAV scenarios both increased throughput in the southbound direction as compared to the 100% LV scenario. However, the AV scenario resulted in the best performance, in this case, reaching a 10% increase in throughput along the Belles Rd. to SR-150 segment.

Figure 20 shows that at 200% demand, CAVs proved to be more beneficial. Under more congested conditions, CAVs, as compared to LVs, produced a throughput increase of between 16% and 27% (298 to 818 veh/hr/ln increase). AVs, on the other hand, increased throughput between 15% and 21% (284 to 594 veh/hr/ln increase). Similarly, in the northbound direction, both AVs and CAVs proved to be more beneficial than LVs. AVs yielded better throughput in the less congested segments, whereas CAVs gave the best performance with more congestion. The percentage increase reached 21% for AVs and 25% for CAVs. These scenarios showed that AVs are better in less congested conditions and CAVs are better in more highly congested conditions.

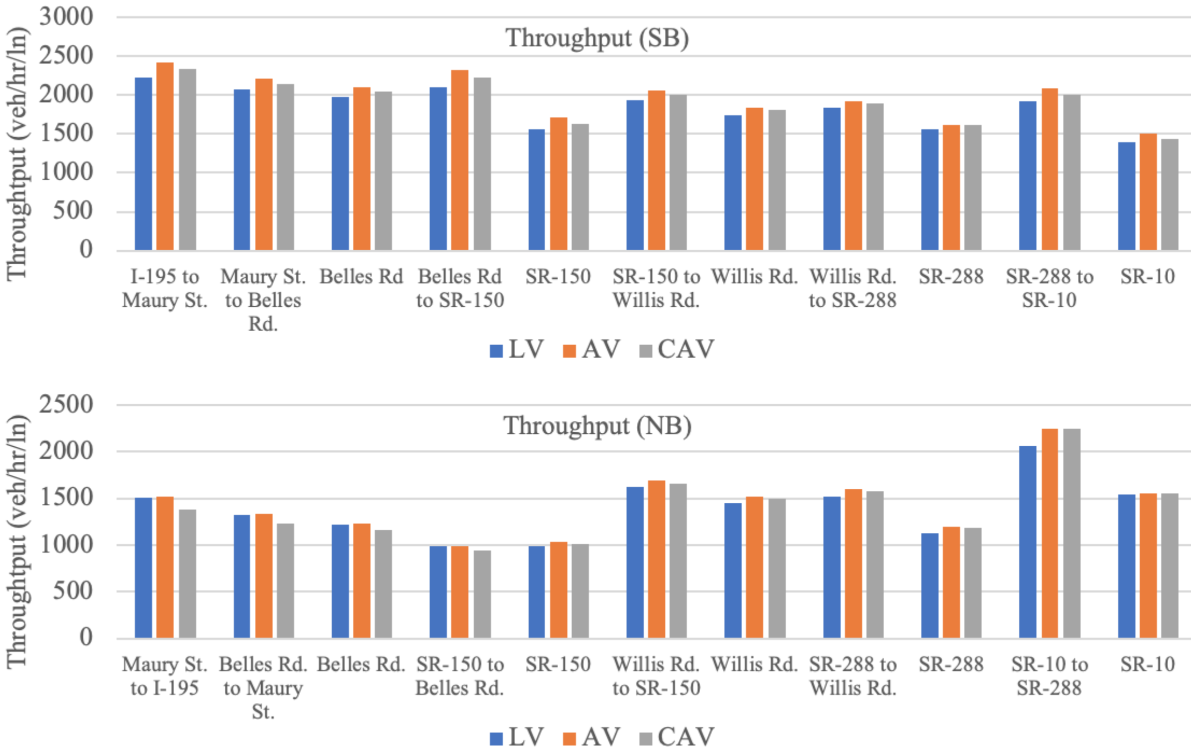


Figure 19. 150% Demand Southbound (SB) and Northbound (NB) Throughput. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

The presence of weaving maneuvers at interchanges on I-95 showed the need for specialized algorithms and processes for maneuvering vehicles in these complex areas. Implementation of specialized algorithms to move platoons away from the weaving segments or to make platoons break approaching a weaving segment could alleviate some of the throughput issues seen in the simulation. OEMs are leveraging machine learning and artificial intelligence research techniques to combat this challenging issue currently, and the research that will come and policies from departments of transportation will inform how vehicles maneuver in these complex areas.

Throughput results with increased demand of 150% and 200% show the benefits of AVs and CAVs over LVs with increased congestion. CAVs proved to be most beneficial under the more congested conditions with their increased ability to communicate and decrease unnecessary stop-and-go occurrences, and AVs increased throughput in lightly congested conditions by contributing to a smoother traffic flow. The results showed that the impact of the different vehicle technologies is seen more clearly at the 200% demand level. At the 100% and 150% demand levels, there were points along the corridor where there was not a significant difference between the technologies on throughput.

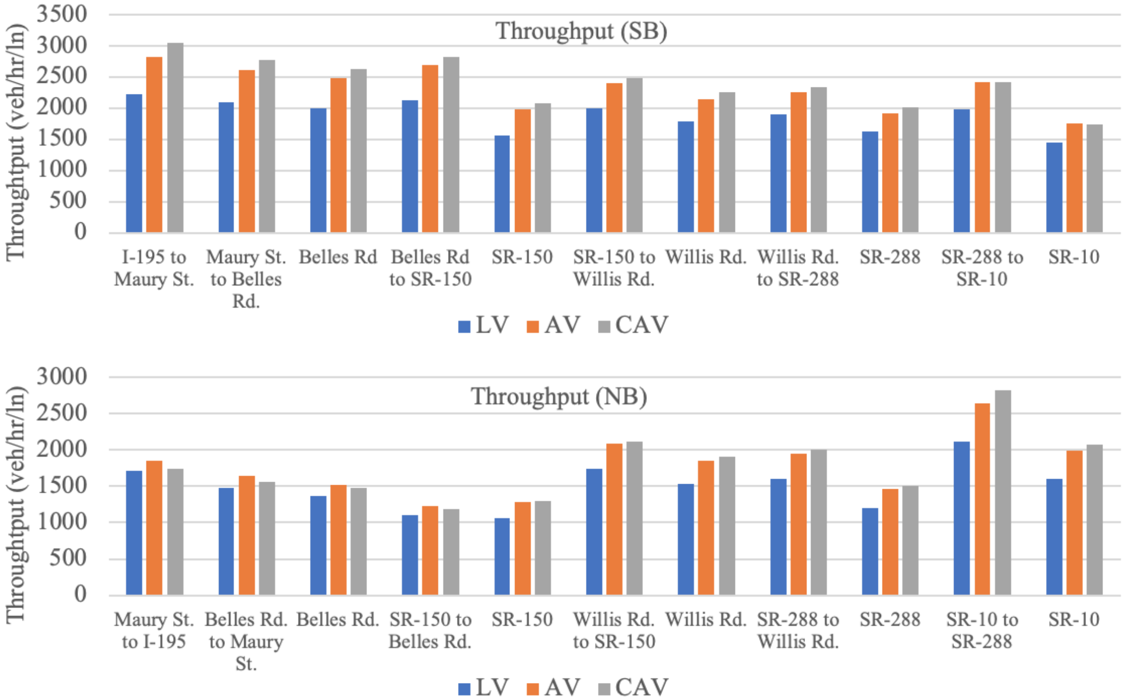


Figure 20. 200% Demand Southbound (SB) and Northbound (NB) Throughput. LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

I-81 Analysis

Capacity

For the I-81 segment, the simulation was conducted to understand the effect of grade, HV technology, and AV technology on capacity. In this case study, the input volume was increased from 6,000 to 12,000 with 1,000-veh/hr increments to obtain capacity results. Output volume values were collected in VISSIM over nine 300-second time intervals every 1,000 ft, and the maximum values were recorded to represent capacity.

Four data collection points were considered for the analysis. The first data collection point (DC1) was located on the flat section preceding the extended grade section. The second point (DC2) was located on the downhill segment, DC3 was located on the uphill segment, and DC4 measured the volume on the flat section following the uphill grade. Figure 21 shows the locations.

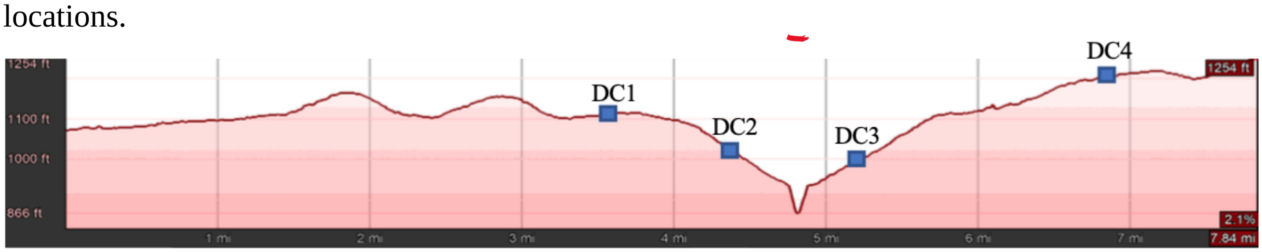


Figure 21. Elevation Profile and Data Collection Points

Results showed a decrease in capacity for all vehicles on the downhill segments because vehicles made maneuvers due to the change in speed of the trucks. This behavior was confirmed by the research team's observations of the roadways. The downhill grade affected the lighter cars differently than the HTs where the mass of the vehicle often caused the HTs to move faster than the passenger cars. The simulation results that showed turbulent traffic flow (and reduced capacity) because of this phenomenon were confirmed by the research team's anecdotal experience driving through this segment of roadway. The uphill segment further reduced capacity as HVs slowed on the uphill.

The scenarios in Appendices B and C labeled in the 100s correspond to the 0% HV cases, in the 300s to the 30% HV cases, and in the 500s to the 50% HV cases. Similar trends of capacity variation were observed for the segment for the different combinations. The values themselves varied based on the modeled scenario. Table 16 shows capacity variations of the 100% LV, AV, and CAV scenarios along the data collection points. In Table 16, DC3 is considered for the comparison of capacity values across scenarios.

A significant decrease in capacity was observed upon the introduction of HVs, as shown in Table 17. The capacity reduction was observed at 36% from the 0% to the 30% HV scenario, which accounts for the space the HVs occupy and the operational characteristics of the vehicles creating uneven traffic flow. Between the 30% and 50% HV scenarios, capacity reductions were still significant but did not exceed 14%. The highest capacity differences resulting from the penetration of HVs occurred at lower LV and higher AV and CAV scenarios, especially CAVs with reduced capabilities to form longer platoons.

AVs and CAVs were capable of improving capacity at any MP for all HV cases, as shown in Table 18. Better results were obtained with LV percentages less than those for AVs and CAVs. The best performance was achieved for the 100% CAV case, reaching 86%, 65%, and 63% capacity increases, as compared to the 100% LV case, in the 0%, 30%, and 50% HV scenarios, respectively.

Table 16. Capacity Differences Along Data Collection Points

% HV	Scenario	Capacity Difference (veh/hr/ln)		
		DC1-DC2	**DC2-DC3**	**DC3-DC4**
0% HV	100% LV	34.75	9.12	-17.11
	100% AV	45.06	11.93	-29.89
	100% CAV	65.27	14.71	-24.92*
30% HV	100% LV	33.14	18.01	-27.49
	100% AV	18.61	18.6*	-29.44
	100% CAV	62.46	30.46	-26.94
50% HV	100% LV	15.92	26.03	-44.66
	100% AV	25.63	16.06	-55.34
	100% CAV	35.9	11.54*	-91

HV = heavy vehicles; DC = data collection point; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.
* P-value > 0.1, indicating no significant difference.

Table 17. Percentage Capacity Reductions With Increase in HV% (veh/hr/ln)

Compared Scenarios			% Difference Between 0% and 30%	Compared Scenarios			% Difference Between 30% and 50% HV
100	vs.	300	25%	300	vs.	500	12%
115	vs.	315	31%	315	vs.	515	13%
116	vs.	316	32%	316	vs.	516	13%
117	vs.	317	33%	317	vs.	517	14%
118	vs.	318	34%	318	vs.	518	14%
119	vs.	319	36%	319	vs.	519	13%
120	vs.	320	34%	320	vs.	520	13%

HV = heavy vehicles.

Table 18. Percentage Capacity Increases Due to AVs and CAVs

			0% HV		30% HV		50% HV	
LV	**AV**	**CAV**	**Capacity (veh/hr/ln)**	**% Difference From LV Only**	**Capacity (veh/hr/ln)**	**% Difference From LV Only**	**Capacity (veh/hr/ln)**	**% Difference From LV Only**
100%	0%	0%	2253	0%	1680	0%	1478	0%
0%	100%	0%	2912	29%	2003	19%	1752	18%
0%	80%	20%	2990	33%	2043	22%	1773	20%
0%	60%	40%	3190	42%	2152	28%	1843	25%
0%	40%	60%	3473	54%	2292	36%	1979	34%
0%	20%	80%	3880	72%	2501	49%	2166	46%
0%	0%	100%	4199	86%	2769	65%	2405	63%

HV = heavy vehicles; LV = legacy vehicles; AV = automated vehicles; CAVs = connected automated vehicles.

Speed

Speeds were also recorded and compared on the uphill data collection point. Results showed increased speeds with increasing AV and CAV MPs. However, at higher LV percentages (more than 60%), changes in speed were not significant, especially in the 0% HV scenarios. Higher MPs of AVs and CAVs always resulted in better speed results. At lower speeds, with increased percentages of HVs, AVs and CAVs were more capable of showing significant speed increases (up to 49% for the CAV only case). Still, the highest speeds were recorded for the highest CAV scenarios under any HV condition. The average speed values for each scenario are shown in Table 19. CAV platooning raised the average speed significantly for the entire traffic stream.

Table 19. Speed Results Across Scenarios

LV	AV	CAV	0% HV Speed (mph)	0% HV % Difference From LV Only	30% HV Speed (mph)	30% HV % Difference From LV Only	50% HV Speed (mph)	50% HV % Difference From LV Only
100%	0%	0%	63.99	0%	37.10	0%	35.89	0%
80%	20%	0%	64.10	0%	39.69	7%	36.65	2%
80%	0%	20%	64.08	0%	41.80	13%	38.39	7%
60%	40%	0%	64.23	0%	39.01	5%	39.21	9%
60%	20%	20%	64.37	1%	44.13	19%	40.22	12%
60%	0%	40%	64.37	1%	42.52	15%	42.39	18%
40%	60%	0%	64.76	1%	38.56	4%	39.10	9%
40%	40%	20%	64.46	1%	41.87	13%	42.40	18%
40%	20%	40%	64.72	1%	45.57	23%	42.49	18%
40%	0%	60%	64.92	1%	46.93	27%	44.56	24%
20%	80%	0%	65.42	2%	39.73	7%	40.43	13%
20%	60%	20%	65.65	3%	44.04	19%	41.85	17%
20%	40%	40%	65.54	2%	45.51	23%	43.20	20%
20%	20%	60%	65.65	3%	48.12	30%	45.63	27%
20%	0%	80%	65.06	2%	52.66	42%	48.47	35%
0%	100%	0%	69.96	9%	41.76	13%	41.16	15%
0%	80%	20%	69.70	9%	44.47	20%	43.06	20%
0%	60%	40%	69.66	9%	47.33	28%	46.39	29%
0%	40%	60%	69.20	8%	48.62	31%	46.52	30%
0%	20%	80%	69.29	8%	51.85	40%	48.68	36%
0%	0%	100%	69.92	9%	55.18	49%	52.70	47%

HV = heavy vehicles; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

CONCLUSIONS

- *Virginia statutes do not explicitly prohibit platooning at close following distances.* Virginia does not specify any following distance or cut-in requirements for vehicles, relying instead on the reasonable and prudent standard; therefore, Virginia comprises a permissive regulatory environment for most platooning applications. The desired following distance selected by AVs may vary based on a vehicle's braking ability, assumptions about the braking behaviors of other vehicles, interpretations of legal concepts such as the ACDA doctrine, industry standards, consumer preference, recommended driver training distances, or a range of other factors.

- *CAVs and AVs outperformed LVs in most scenarios, and CAVs outperformed AVs during congestion.* The operations of LVs, AVs, and CAVs at 100% MP were compared on a selected segment of I-95 during the PM peak. The overall results showed a better performance of AVs and CAVs as compared to LVs except in cases where LVs broke the speed limit due to VISSIM driver behavior modeling. However, in congested conditions, AVs presented a lower performance, with reduced speeds and increased travel times. AVs have smaller headways than LVs, and under congestion, these short headways would increase the frequency of stop-and-go occurrences and thus negatively affect speeds and travel times. This issue of unnecessary stop-and-go due to short headways was fixed in the case of CAVs because of their ability to communicate and increase string stability.

- *CAVs underperformed AVs in weaving scenarios on I-95.* The results of the simulation showed that CAV traffic flow is less stable than AV traffic flow in weaving areas. This resulted in reduced speed and throughput in the weaving areas as compared to the basic freeway segments. This shows that CAV algorithms will need to be flexible and smart in order to maintain flow in urban areas with high amounts of weaving sections. Having regulations that allowed for platoons moving to the left lane would allow for mitigation of this phenomenon.

- *AVs and CAVs improve performance in corridors with extended grades and high truck volumes.* In the case of extended grades, and even in the presence of high percentages of HVs, AVs and CAVs seemed to have a high potential of improving operations. AVs and CAVs, even at low MPs, were still capable of mitigating the impact of grades on performance. However, the best results were achieved at the highest MPs of AVs and CAVs in the absence of LVs. Mostly, AVs and CAVs had similar impacts on improving the values of the different MOEs such as speed and travel time, even in the presence of grades and HVs. CAVs, however, particularly at high MPs, with their communication capabilities, were capable of achieving the most capacity increases on the selected I-81 segment.

- *There are opportunities for significant capacity increases due to the introduction of AV technology.* These advantages are seen most in the CAV cases, where communication is leveraged in order to gain safe and efficient car-following, which allows for the additional capacity. The transition from LVs to CAVs could have stages where capacity is reduced, however. These scenarios include (1) AVs where car-following is very conservative due to liability concerns of the vehicle manufacturers and tier one suppliers, and (2) AVs that are programmed for user optimal behavior, which could cause increased stop-and-go driver behavior based on the programming of the automated driving algorithms.

RECOMMENDATIONS

1. *VDOT's Connected and Automated Vehicle Program Manager and VTRC should continue to monitor AV car-following behavior models.* As new developments occur, the information should be shared with VDOT's Traffic Engineering Division (TED) to ensure that VDOT simulation models reflect the existing and anticipated vehicle fleet.

2. *VDOT's TED should use the capacities provided in this report as guidance when calibrating models of CVs and AVs in simulations of freeway corridors.* In cases where models are being developed for future conditions, the information in this report can be used to provide guidance on car-following behavior and expected capacity for calibration. Modifications to

VDOT's *Traffic Operations and Safety Analysis Manual (TOSAM)* are not recommended at this time but may be warranted in the future as more AVs become commercially available.

3. *VDOT's Connected and Automated Vehicle Program Manager and VTRC should investigate methods to estimate proportions of vehicles on Virginia roads operating with connected and automated functionality.* The results of this study suggest that the impact of AVs and CAVs on capacity is correlated with their MP, yet neither VDOT nor the Virginia DMV has a procedure to estimate the proportion of vehicles with connected or automated capabilities. Tracking sales or registration of vehicle models is inadequate, as after-market add-on or over-the-air vehicle software updates may allow for increasing automation. This effort should also consider surrogate measures such as user surveys, inspection data from other states, federal data, and insurance industry data to develop estimates for Virginia.

4. *VDOT's TED and VTRC should investigate regulation of the operation of AVs and CAVs in weaving areas.* Additional research should be conducted to understand the operations of AV movement in weaving areas. This research should survey OEMs for their implementation of machine learning and artificial intelligence to assist in complex driving maneuvers.

IMPLEMENTATION AND BENEFITS

Implementation

For Recommendation 1, VDOT's Connected and Automated Vehicle Program Manager and VTRC are actively monitoring research developments in automated driving through participation in the Transportation Research Board, the Connected Vehicle Pooled Fund Study, NCHRP efforts, and a continuous review of the scientific literature. This effort will continue with an emphasis on new developments in car-following and capacity modeling of CVs and AVs based on empirical data.

For Recommendation 2, VDOT's TED, when developing transportation models that incorporate automated driving, will use the capacities described in this report when the modeled conditions are similar to those in the study scenarios. These capacities can be used until they are considered outdated and replaced by new capacities discovered as part of implementing Recommendation 1 or a future study. In the next 2 years, VTRC will report on the potential to incorporate the models developed in this study or in other future studies of VDOT's *Traffic Operations and Safety Analysis Manual (TOSAM).*

For Recommendation 3, VDOT's Connected and Automated Vehicles Program Manager and VTRC will investigate potential data sources, best practices, and potential policy that will allow reasonable estimates of the percentage of vehicles on Virginia roads employing connected and automated technologies. This might involve leveraging data sources from outside Virginia such as insurance industry records, estimates from other states, manufacturer data, and survey results. Alternatively, estimates could be obtained through policy changes and partnering with other state agencies such as the Virginia State Police and the Virginia DMV. The selected methodology can be used to develop an evolving estimate of both the percentage of vehicles on the road with automated and connected functions and the precise capabilities of these technologies and their rate of use. For example, although many cars may be equipped with ACC, a smaller percentage are also equipped with lane-keeping technology, and an even lower percentage of drivers may actually use these capabilities at any given time. The resulting estimates can be used to validate capacity models developed as part of this study. VDOT may begin to discuss policy changes in anticipation of greater capacities with increased CAV penetration. The work to define this methodology should begin within 1 year of the publication of this report.

For Recommendation 4, VTRC staff should work with the research team, other university partners, industry partners, and VDOT staff to build a research statement to be voted on at the next meeting of VTRC's System Operations Research Advisory Committee. The research statement should address AV operations in complex situations and have an outcome of informing policy within Virginia, at the national level, and in AASHTO committees.

Benefits

The benefit of implementing Recommendation 1 is that leveraging new research on forthcoming vehicle technologies ensures that VDOT uses the most accurate models of autonomous vehicle behavior and capacity. With more accurate models, VDOT can make more informed decisions on planning-level needs, investments in infrastructure, and freeway capacities as the vehicle fleet continues to evolve with more automation and connectivity of the driving task.

The benefits of implementing Recommendation 2 are more accurate models of freeway capacity under an increasing AV and CV fleet. By implementing sophisticated capacity models into long-range planning efforts, VDOT can make more informed decisions regarding future infrastructure needs. By continuously revising, updating, and using these models, VDOT can ensure that investment decisions rely on the latest validated estimates from empirical data. This will produce second order benefits of reducing costs and risks while maximizing the benefits and opportunities of vehicle automation.

The benefits of implementing Recommendation 3 are that VDOT will make better decisions on investments in the rehabilitation, reconstruction, and building of new roadway infrastructure. Capacity models developed in this study depend on the percentage of vehicles with automation and connectivity and the characteristics of automated driving systems. With estimates of CAV attributes and percentages in the fleet, VDOT will have more reliable capacity estimates, which will allow VDOT to make more informed decisions on infrastructure improvements needed to manage demand. This will allow VDOT to plan infrastructure improvements to coincide with capacity changes due to increasing automation, thereby reducing costs while managing congestion.

The benefits of implementing Recommendation 4 are that VDOT will be able to propose regulation of vehicle operations in complex operational scenarios and will have a deeper understanding of the machine learning and artificial intelligence used to inform driving decision algorithms. This research could provide a greater opportunity for VDOT to work with OEMs to ensure safe and efficient operation of AVs in Virginia. Any new regulations that would come from this research should be developed in concert with OEMs and other transportation stakeholders in Virginia.

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APPENDIX A

VALUES OBTAINED FROM PREVIOUS RESEARCH

Table A1. Operational Parameters From Previous Research

Source	Vehicle Automation (N/A, LV, AV, CAV)	Vehicle Type	Vehicle Length (ft)	Speed (ft/s)		Comfort. Accel. (ft/s^2)		Max. Accel. (ft/s^2)		Comfort. Decel. (ft/s^2)		Max. Braking (ft/s^2)		Desired Headway (sec)		Desired Spacing (ft)		Min. Distance, Standstill Distance (ft)	
				L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U
Raza and Ioannou 1996	CAV	P		88		4.83				3.22				0.416					
	AV	P		88		4.83				3.22				0.72					
Carbaugh et al. 1998	N/A	P		65.62	131.23	13.12	32.81			13.12	32.81								
Treiber et al. 2010	LV	P	16.4	109.34		2.39	5.48			2.39	5.48			1.6					
Huang et al. 2000	LV	P		82.02								15							
	AV	P		82.02								15		1.0		32.81			
VanderWerf et al. 2001	LV	P																	
	AV	P												1.4					
	CAV	P												0.5					
VanderWerf et al. 2002	AV	P		95.14		9.65				9.65				1.4					
	CAV	P		95.14		9.65				9.65				0.5					
	LV	P		95.14										1.1					
van Arem et al. 2006	LV	P				6.56				8.2				1.4					
	CAV	P				6.56				6.56				0.5					
Kesting et al. 2008	N/A	P		77.47	109.36	2.29	6.56			2.29	6.56								
	LV	P	16.4	52.82	53.81	4.99	5.18			2.01	2.48			1.3	1.39			3.41	5.28
Kesting et al. 2010	LV	P		77.47	109.36	2.29	6.56			2.29	6.56			1.5	2				
	LV	P		109.36				4.59		6.56		8		1.5				6.56	
	LV	T		77.46				2.3		6.56				2				13.12	
Arnaout and Bowling 2011	CAV	P	13.12																
	CAV	P	13.12											0.5	1				
	LV	P	16.4	110				8.2				8.2							
Shladover et al. 2012	LV	P	15.42	95.33		6.56				6.56				1.48	1.8				
	AV	P	15.42	95.33		6.56				6.56				1.1	2.2				
	CAV	P	15.42	95.33		6.56				6.56				0.6	1.1				
Fishelson et al. 2013	CAV	P		98.42								19.69	39.37						
Zhao and Sun 2013	AV	P												1.4					
	CAV	P												0.5					
Desiraju et al. 2015	N/A	P		16.4	98.4	0	6.56				6.56								

Delis et al. 2015	AV	P		100.25	118.48									1	2				
	CAV	P		100.25	118.48									1	2				
Ntousakis et al. 2015	LV	P		109.36										0.8	2				
	AV	P		109.36										0.8	2				
	AV	P		119.99		4.43	5.91												
Le Vine et al. 2016	LV	P		45.57															
	AV	P		26.43				4.43				4.43							
	AV	P		10.94				1.9				1.77							
Meissner et al. 2016	CAV	P	16.4	85.3	111.55	9.18	10.5			9.18	10.5								
Talebpour and Mahmassani 2016	CAV	P		82.02				13.12		18.02				2				6.56	
	CAV	P		82.02				4.59		6.56				1.5				6.56	
	LV	P		82.02				13.12				26.25							
Shelton et al. 2016	LV	P		85.07	105.6														
	CAV	P		85.07	105.6														
Songchitruksa et al. 2016	CAV	P		95.33	102.67							11.15		0.6	1.1				
Li et al. 2017	LV	P	16.4	109.36		9.18	15.748			9.18	15.748			1.6					
	CAV	P	16.4	109.36		9.18	15.748			9.18	15.748			0.6	1.6				
van Maarseveen 2017	N/A	P	13.75	118.47		4.1				19.69				1.2					
	N/A	T (Light)	27.89	77.46		2.62				14.76				1.2					
	N/A	T (Heavy)	54.13	77.46		1.31				13.12				1.5					
	CAV	T (Heavy)	54.13	77.46		1.31				13.12				1.5					
Melson et al. 2018	LV	P	14.6	73.33												6.5			
	CAV	P	14.6	73.33										0.6					

N/A = not applicable; LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles; P = passenger vehicles; T = trucks; Comfort. = comfortable; Accel. = acceleration; decel = deceleration; U = upper value; L = lower value.

APPENDIX B

HEAVY VEHICLE MARKET PENETRATION SCENARIOS

Heavy Vehicles on the Test Network

Scenarios 200 to 220 represent 5% HV, scenarios 300 to 320 represent 10% HV, and scenarios 400 to 420 represent 15% HV.

Table B1. Market Penetration of Heavy Vehicle Scenarios

	Percentage of Passenger Vehicles			Percentage of Light Trucks			Percentage of Heavy Trucks		
Scenario No.	**LV**	**AV**	**CAV**	**LV**	**AV**	**CAV**	**LV**	**AV**	**CAV**
200	95.00	0.00	0.00	0.90	0.00	0.00	4.10	0.00	0.00
201	76.00	19.00	0.00	0.72	0.18	0.00	3.28	0.82	0.00
202	76.00	0.00	19.00	0.72	0.00	0.18	3.28	0.00	0.82
203	57.00	38.00	0.00	0.54	0.36	0.00	2.46	1.64	0.00
204	57.00	19.00	19.00	0.54	0.18	0.18	2.46	0.82	0.82
205	57.00	0.00	38.00	0.54	0.00	0.36	2.46	0.00	1.64
206	38.00	57.00	0.00	0.36	0.54	0.00	1.64	2.46	0.00
207	38.00	38.00	19.00	0.36	0.36	0.18	1.64	1.64	0.82
208	38.00	19.00	38.00	0.36	0.18	0.36	1.64	0.82	1.64
209	38.00	0.00	57.00	0.36	0.00	0.54	1.64	0.00	2.46
210	19.00	76.00	0.00	0.18	0.72	0.00	0.82	3.28	0.00
211	19.00	57.00	19.00	0.18	0.54	0.18	0.82	2.46	0.82
212	19.00	38.00	38.00	0.18	0.36	0.36	0.82	1.64	1.64
213	19.00	19.00	57.00	0.18	0.18	0.54	0.82	0.82	2.46
214	19.00	0.00	76.00	0.18	0.00	0.72	0.82	0.00	3.28
215	0.00	95.00	0.00	0.00	0.90	0.00	0.00	4.10	0.00
216	0.00	76.00	19.00	0.00	0.72	0.18	0.00	3.28	0.82
217	0.00	57.00	38.00	0.00	0.54	0.36	0.00	2.46	1.64
218	0.00	38.00	57.00	0.00	0.36	0.54	0.00	1.64	2.46
219	0.00	19.00	76.00	0.00	0.18	0.72	0.00	0.82	3.28
220	0.00	0.00	95.00	0.00	0.00	0.90	0.00	0.00	4.10
300	90.00	0.00	0.00	1.80	0.00	0.00	8.20	0.00	0.00
301	72.00	18.00	0.00	1.44	0.36	0.00	6.56	1.64	0.00
302	72.00	0.00	18.00	1.44	0.00	0.36	6.56	0.00	1.64
303	54.00	36.00	0.00	1.08	0.72	0.00	4.92	3.28	0.00
304	54.00	18.00	18.00	1.08	0.36	0.36	4.92	1.64	1.64
305	54.00	0.00	36.00	1.08	0.00	0.72	4.92	0.00	3.28
306	36.00	54.00	0.00	0.72	1.08	0.00	3.28	4.92	0.00
307	36.00	36.00	18.00	0.72	0.72	0.36	3.28	3.28	1.64
308	36.00	18.00	36.00	0.72	0.36	0.72	3.28	1.64	3.28
309	36.00	0.00	54.00	0.72	0.00	1.08	3.28	0.00	4.92
310	18.00	72.00	0.00	0.36	1.44	0.00	1.64	6.56	0.00
311	18.00	54.00	18.00	0.36	1.08	0.36	1.64	4.92	1.64
312	18.00	36.00	36.00	0.36	0.72	0.72	1.64	3.28	3.28
313	18.00	18.00	54.00	0.36	0.36	1.08	1.64	1.64	4.92
314	18.00	0.00	72.00	0.36	0.00	1.44	1.64	0.00	6.56
315	0.00	90.00	0.00	0.00	1.80	0.00	0.00	8.20	0.00
316	0.00	72.00	18.00	0.00	1.44	0.36	0.00	6.56	1.64
317	0.00	54.00	36.00	0.00	1.08	0.72	0.00	4.92	3.28

Scenario No.	Percentage of Passenger Vehicles			Percentage of Light Trucks			Percentage of Heavy Trucks		
	LV	AV	CAV	LV	AV	CAV	LV	AV	CAV
318	0.00	36.00	54.00	0.00	0.72	1.08	0.00	3.28	4.92
319	0.00	18.00	72.00	0.00	0.36	1.44	0.00	1.64	6.56
320	0.00	0.00	90.00	0.00	0.00	1.80	0.00	0.00	8.20
400	85.00	0.00	0.00	2.70	0.00	0.00	12.30	0.00	0.00
401	68.00	17.00	0.00	2.16	0.54	0.00	9.84	2.46	0.00
402	68.00	0.00	17.00	2.16	0.00	0.54	9.84	0.00	2.46
403	51.00	34.00	0.00	1.62	1.08	0.00	7.38	4.92	0.00
404	51.00	17.00	17.00	1.62	0.54	0.54	7.38	2.46	2.46
405	51.00	0.00	34.00	1.62	0.00	1.08	7.38	0.00	4.92
406	34.00	51.00	0.00	1.08	1.62	0.00	4.92	7.38	0.00
407	34.00	34.00	17.00	1.08	1.08	0.54	4.92	4.92	2.46
408	34.00	17.00	34.00	1.08	0.54	1.08	4.92	2.46	4.92
409	34.00	0.00	51.00	1.08	0.00	1.62	4.92	0.00	7.38
410	17.00	68.00	0.00	0.54	2.16	0.00	2.46	9.84	0.00
411	17.00	51.00	17.00	0.54	1.62	0.54	2.46	7.38	2.46
412	17.00	34.00	34.00	0.54	1.08	1.08	2.46	4.92	4.92
413	17.00	17.00	51.00	0.54	0.54	1.62	2.46	2.46	7.38
414	17.00	0.00	68.00	0.54	0.00	2.16	2.46	0.00	9.84
415	0.00	85.00	0.00	0.00	2.70	0.00	0.00	12.30	0.00
416	0.00	68.00	17.00	0.00	2.16	0.54	0.00	9.84	2.46
417	0.00	51.00	34.00	0.00	1.62	1.08	0.00	7.38	4.92
418	0.00	34.00	51.00	0.00	1.08	1.62	0.00	4.92	7.38
419	0.00	17.00	68.00	0.00	0.54	2.16	0.00	2.46	9.84
420	0.00	0.00	85.00	0.00	0.00	2.70	0.00	0.00	12.30

LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

HVs on the I-81 Corridor

Scenarios 100 to 120 represent passenger vehicles only, scenarios 300 to 320 represent 30% HV, and scenarios 500 to 520 represent 50% HV.

Table B2. Market Penetration of Heavy Vehicle Scenarios

Scenario No.	Percentage of Passenger Vehicles (%)			Percentage of Light Trucks (%)			Percentage Heavy Trucks (%)		
	LV	AV	CAV	LV	AV	CAV	LV	AV	CAV
100	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
101	80.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
102	80.00	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00
103	60.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
104	60.00	20.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00
105	60.00	0.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00
106	40.00	60.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
107	40.00	40.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00
108	40.00	20.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00
109	40.00	0.00	60.00	0.00	0.00	0.00	0.00	0.00	0.00

Scenario No.	Percentage of Passenger Vehicles (%)			Percentage of Light Trucks (%)			Percentage Heavy Trucks (%)		
	LV	AV	CAV	LV	AV	CAV	LV	AV	CAV
110	20.00	80.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
111	20.00	60.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00
112	20.00	40.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00
113	20.00	20.00	60.00	0.00	0.00	0.00	0.00	0.00	0.00
114	20.00	0.00	80.00	0.00	0.00	0.00	0.00	0.00	0.00
115	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
116	0.00	80.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00
117	0.00	60.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00
118	0.00	40.00	60.00	0.00	0.00	0.00	0.00	0.00	0.00
119	0.00	20.00	80.00	0.00	0.00	0.00	0.00	0.00	0.00
120	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
300	70.00	0.00	0.00	10.50	0.00	0.00	19.50	0.00	0.00
301	56.00	14.00	0.00	8.40	2.10	0.00	15.60	3.90	0.00
302	56.00	0.00	14.00	8.40	0.00	2.10	15.60	0.00	3.90
303	42.00	28.00	0.00	6.30	4.20	0.00	11.70	7.80	0.00
304	42.00	14.00	14.00	6.30	2.10	2.10	11.70	3.90	3.90
305	42.00	0.00	28.00	6.30	0.00	4.20	11.70	0.00	7.80
306	28.00	42.00	0.00	4.20	6.30	0.00	7.80	11.70	0.00
307	28.00	28.00	14.00	4.20	4.20	2.10	7.80	7.80	3.90
308	28.00	14.00	28.00	4.20	2.10	4.20	7.80	3.90	7.80
309	28.00	0.00	42.00	4.20	0.00	6.30	7.80	0.00	11.70
310	14.00	56.00	0.00	2.10	8.40	0.00	3.90	15.60	0.00
311	14.00	42.00	14.00	2.10	6.30	2.10	3.90	11.70	3.90
312	14.00	28.00	28.00	2.10	4.20	4.20	3.90	7.80	7.80
313	14.00	14.00	42.00	2.10	2.10	6.30	3.90	3.90	11.70
314	14.00	0.00	56.00	2.10	0.00	8.40	3.90	0.00	15.60
315	0.00	70.00	0.00	0.00	10.50	0.00	0.00	19.50	0.00
316	0.00	56.00	14.00	0.00	8.40	2.10	0.00	15.60	3.90
317	0.00	42.00	28.00	0.00	6.30	4.20	0.00	11.70	7.80
318	0.00	28.00	42.00	0.00	4.20	6.30	0.00	7.80	11.70
319	0.00	14.00	56.00	0.00	2.10	8.40	0.00	3.90	15.60
320	0.00	0.00	70.00	0.00	0.00	10.50	0.00	0.00	19.50
500	50.00	0.00	0.00	17.50	0.00	0.00	32.50	0.00	0.00
501	40.00	10.00	0.00	14.00	3.50	0.00	26.00	6.50	0.00
502	40.00	0.00	10.00	14.00	0.00	3.50	26.00	0.00	6.50
503	30.00	20.00	0.00	10.50	7.00	0.00	19.50	13.00	0.00
504	30.00	10.00	10.00	10.50	3.50	3.50	19.50	6.50	6.50
505	30.00	0.00	20.00	10.50	0.00	7.00	19.50	0.00	13.00
506	20.00	30.00	0.00	7.00	10.50	0.00	13.00	19.50	0.00
507	20.00	20.00	10.00	7.00	7.00	3.50	13.00	13.00	6.50
508	20.00	10.00	20.00	7.00	3.50	7.00	13.00	6.50	13.00
509	20.00	0.00	30.00	7.00	0.00	10.50	13.00	0.00	19.50
510	10.00	40.00	0.00	3.50	14.00	0.00	6.50	26.00	0.00
511	10.00	30.00	10.00	3.50	10.50	3.50	6.50	19.50	6.50
512	10.00	20.00	20.00	3.50	7.00	7.00	6.50	13.00	13.00
513	10.00	10.00	30.00	3.50	3.50	10.50	6.50	6.50	19.50
514	10.00	0.00	40.00	3.50	0.00	14.00	6.50	0.00	26.00

Scenario No.	Percentage of Passenger Vehicles (%)			Percentage of Light Trucks (%)			Percentage Heavy Trucks (%)		
	LV	AV	CAV	LV	AV	CAV	LV	AV	CAV
515	0.00	50.00	0.00	0.00	17.50	0.00	0.00	32.50	0.00
516	0.00	40.00	10.00	0.00	14.00	3.50	0.00	26.00	6.50
517	0.00	30.00	20.00	0.00	10.50	7.00	0.00	19.50	13.00
518	0.00	20.00	30.00	0.00	7.00	10.50	0.00	13.00	19.50
519	0.00	10.00	40.00	0.00	3.50	14.00	0.00	6.50	26.00
520	0.00	0.00	50.00	0.00	0.00	17.50	0.00	0.00	32.50

LV = legacy vehicles; AV = automated vehicles; CAV = connected automated vehicles.

APPENDIX C

STATISTICAL RESULTS

T-Tests

P-value results from the paired two-tailed t-test were obtained from Excel. P-values greater than 0.1 indicate an insignificant difference between compared samples. The results for each case study are summarized here. Only results indicating insignificant difference p-value > 0.1 were reported in this case; all other (unreported) outputs indicated p-value < 0.1.

I-95

Table C1. T-Test From Throughput for 100% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
Willis Rd. and SR-288	0%	9.21E-01*	-2%	2.48E-05
SR-288	0%	9.73E-01*	-2%	2.26E-06
SR-288 and SR-10	0%	3.48E-01*	-1%	9.84E-03

* P-value > 0.1.

Table C2. T-Test From Throughput for 150% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
Maury St. and I-195	0%	2.7E-01*	-10%	2.6E-04
Belles Rd	1%	1.7E-01*	-5%	4.0E-05
Belles Rd and SR-150	0%	4.0E-01*	-6%	2.5E-07

* P-value > 0.1.

Table C3. T-Test from Throughput for 200% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
Maury St. and I-195	7%	3.41E-06	1%	3.73E-01*

* P-value > 0.1.

Table C4. T-Test From Average Speed for 100% Demand Southbound

Southbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
SR-150 and Willis Rd.	3%	5.2E-05	0%	8.7E-01*
Willis Rd. and SR-288	3%	1.5E-05	-1%	3.6E-01*
SR-288 and SR-10	4%	5.1E-06	-1%	4.9E-01*
SR-10	3%	2.4E-06	1%	2.3E-01*

* P-value > 0.1.

Table C5. T-Test From Average Speed for 100% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
SR-150 and Willis Rd.	-1%	1.4E-01*	-4%	2.4E-03
SR-288 and SR-10	3%	4.7E-07	0%	4.2E-01*
SR-10	0%	2.6E-01*	-1%	2.5E-04

* P-value > 0.1.

Table C6. T-Test from Average Speed for 150% Demand Southbound

Southbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
Willis Rd.	6%	5.62E-08	-2%	2.00E-01*
Willis Rd. and SR-288	9%	8.58E-08	2%	2.12E-01*
SR-288	7%	1.72E-05	-1%	5.22E-01*
SR-288 and SR-10	8%	8.15E-07	1%	6.05E-01*
SR-10	2%	8.59E-05	0%	9.76E-01*

* P-value > 0.1.

Table C7. T-Test from Average Speed for 150% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
SR-150 and Willis Rd.	5%	2.13E-05	1%	5.14E-01*
Willis Rd.	3%	5.79E-03	-1%	5.33E-01*
Willis Rd. and SR-288	2%	3.22E-03	-1%	2.99E-01*

* P-value > 0.1.

Table C8. T-Test from Average Speed for 200% Demand Northbound

Northbound	% Difference Between AV and LV	P-Value	% Difference Between CAV and LV	P-Value
Maury St. and Belles Rd.	1%	1.29E-01*	-5%	6.01E-04
Belles Rd	0%	6.07E-01*	-7%	2.53E-04
Willis Rd.	4%	4.54E-03	-1%	5.27E-01*
Willis Rd. and SR-288	3%	8.34E-04	-1%	1.11E-01*

* P-value > 0.1.

I-81

Scenarios varied by vehicle composition with HV percentages of 0%, 30%, and 50%. In each of the three HV composition cases, MPs of AVs and CAVs were increased by intervals of 20 percentage points, resulting in 21 MP scenarios per case (LV, AV, CAV combinations, as shown in Table B2). Scenarios were numbered 100 to 120 (for 0% HV), 300 to 320 (for 30% HV), and 500 to 520 (for 50% HV).

Table C9. T-Test From Speed Across Scenarios

Scenario	Speed (mph)	% Difference From LV Only	P-Value
100	63.99	0%	
101	64.10	0%	2.57E-01*
102	64.08	0%	3.85E-01*
103	64.23	0%	1.67E-01*
105	64.37	1%	1.13E-01*
303	39.01	5%	1.48E-01*
306	38.56	4%	3.06E-01*
501	36.65	2%	6.29E-01*
502	38.39	7%	1.43E-01*

* P-value > 0.1.

Table C10. T-Test from Speed Across Heavy Vehicle Scenarios

Compared Scenarios			% Difference Between HV%	P-Value
300	vs.	500	3%	3.8E-01*
301	vs.	501	8%	1.2E-01*
303	vs.	503	-1%	8.0E-01*
305	vs.	505	0%	9.3E-01*
306	vs.	506	-1%	7.6E-01*
307	vs.	507	-1%	6.1E-01*
309	vs.	509	5%	1.2E-01*
310	vs.	510	-2%	4.8E-01*
311	vs.	511	5%	1.2E-01*
315	vs.	515	1%	3.9E-01*
316	vs.	516	3%	2.3E-01*
317	vs.	517	2%	4.3E-01*
318	vs.	518	4%	1.5E-01*
320	vs.	520	5%	2.5E-01*

* P-value > 0.1.

Speed Results

Table C11. Speed Comparison Across Heavy Vehicle Scenarios

Compared Scenarios			% Difference Between 0% and 30% HV	Compared Scenarios			% Difference Between 30% and 50% HV
100	vs.	300	42%	300	vs.	500	3%
101	vs.	301	38%	301	vs.	501	8%
102	vs.	302	35%	302	vs.	502	8%
103	vs.	303	39%	303	vs.	503	-1%
104	vs.	304	31%	304	vs.	504	9%
105	vs.	305	34%	305	vs.	505	0%
106	vs.	306	40%	306	vs.	506	-1%
107	vs.	307	35%	307	vs.	507	-1%
108	vs.	308	30%	308	vs.	508	7%
109	vs.	309	28%	309	vs.	509	5%
110	vs.	310	39%	310	vs.	510	-2%
111	vs.	311	33%	311	vs.	511	5%
112	vs.	312	31%	312	vs.	512	5%
113	vs.	313	27%	313	vs.	513	5%
114	vs.	314	19%	314	vs.	514	8%
115	vs.	315	40%	315	vs.	515	1%
116	vs.	316	36%	316	vs.	516	3%
117	vs.	317	32%	317	vs.	517	2%
118	vs.	318	30%	318	vs.	518	4%
119	vs.	319	25%	319	vs.	519	6%
120	vs.	320	21%	320	vs.	520	5%