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Data and Methods to Estimate Connected and Automated Vehicle Penetration Rates

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16. Abstract:

Automated driving systems are becoming increasingly prevalent on Virginia roadways. These vehicles rely on radar, lidar, and machine vision to operate and may detect road markings, barriers, and other vehicles in ways that human drivers do not. Vehicles may also leverage wireless communication to assist in driving, path planning, and communicating with roadside infrastructure. Recent research has investigated the impact of an increasingly connected and automated vehicle (CAV) fleet on safety and capacity, but these estimates rely on accurate measurements of the volumes or proportions of vehicles on the road equipped with and using these technologies.

The Virginia Department of Transportation (VDOT) does not currently have a way to estimate the volume of connected vehicles, automated vehicles, or CAVs operating on Virginia roadways. The purpose of this study was to identify data required for VDOT to estimate accurately the proportion of vehicles equipped with and using vehicle automation technologies that may affect safety and operations. The study also investigated practical ways to collect these data using both available data sources and proprietary and future data sources. Using existing data sources, the study estimated that in 2022, 16% of the vehicle fleet was equipped with adaptive cruise control, 16% with automatic emergency braking, 22% with forward collision prevention, 8% with lane centering assist, 15% with lane departure prevention, and 25% with pedestrian automatic emergency braking. These percentages were further adjusted to reflect observed driver activation rates.

The study concluded that there are currently quality estimates of penetration of certain vehicle automation features available, and there are several methods to obtain reasonable estimates of other automation technologies. No methods were found that could directly measure technology usage rates in actual on-road driving, although an upper estimate can be calculated based on observed rates of system activation for vehicles brought in for service.

The study recommends continued dialogue with research partners to obtain access to aggregated or anonymized CAV penetration data in proprietary datasets. The study also recommends continued monitoring of ongoing research in on-road CAV technology usage rates from either naturalistic driving studies, industry data, or federal data collection efforts. Implementing these recommendations would benefit VDOT by providing more accurate data on the rate of CAVs in the vehicle fleet, allowing the development and calibration of existing empirical models of the effect of CAVs on traffic flow, capacity, safety, and infrastructure planning.

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FINAL REPORT

DATA AND METHODS TO ESTIMATE CONNECTED AND AUTOMATED VEHICLE PENETRATION RATES

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In Cooperation with the U.S. Department of Transportation
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ABSTRACT

Automated driving systems are becoming increasingly prevalent on Virginia roadways. These vehicles rely on radar, lidar, and machine vision to operate and may detect road markings, barriers, and other vehicles in ways that human drivers do not. Vehicles may also leverage wireless communication to assist in driving, path planning, and communicating with roadside infrastructure. Recent research has investigated the impact of an increasingly connected and automated vehicle (CAV) fleet on safety and capacity, but these estimates rely on accurate measurements of the volumes or proportions of vehicles on the road equipped with and using these technologies.

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FINAL REPORT

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INTRODUCTION

Automated vehicles (AVs) are operating on Virginia roads today. At the most basic level, these vehicles combine lane centering technologies for lateral control and a combination of adaptive cruise control and automated emergency braking for longitudinal control. At a more advanced level, vehicles without a human driver are currently operating in California (Shepardson, 2022) and Arizona (Flanagan and Leslie, 2020), with human monitoring from remote locations.

Connected vehicles (CVs) are vehicles equipped with short-range radios that can communicate the vehicle's position, speed, heading, and other attributes to nearby equipped vehicles and infrastructure using established protocols and a dedicated radio spectrum. These technologies allow vehicles to communicate without line of sight, aiding in both crash avoidance and platooning. The U.S. Department of Transportation (DOT) has funded research into these technologies since 1999 (U.S. Government Accountability Office, 2022).

Connected and automated vehicles (CAVs) are expected to have significant impacts on safety and capacity, with these impacts being dependent on both the characteristics of each vehicle's automation technology and the proportion of vehicles on the road with automation technologies. In one example, in microscopic simulation, a freeway segment with 100% AVs was shown to increase capacity by 28% compared to conventional vehicles, compared to only a 10% capacity increase with 40% AV penetration. The same segment showed a 92% capacity increase with 100% CAVs compared to a 20% capacity increase with 40% CAV penetration (Heaslip et al., 2020). By knowing the percentages of current and expected CAV usage, VDOT can more accurately estimate future roadway capacities, allowing more informed investment decisions. Similar estimates of CAV crash reductions allow for better prioritization of investments in safety infrastructure (Li and Kockelman, 2018).

Although connected and automated driving technologies will significantly affect roadway capacity, safety, and operations, there is currently no way to measure the proportion of vehicles registered in Virginia equipped with various forms of connectivity and automation. The registration system of the Virginia Department of Motor Vehicles (DMV) does not include fields for CAV technologies. Although each vehicle is assigned a Vehicle Identification Number (VIN), the number indicates only the manufacturer, the model, and certain characteristics of the vehicle and often does not indicate the presence or capabilities of specific automation technologies. These data could be partially reconstructed by cross-checking different vehicle model years with published automation features, but the complexity of vehicle features across similar model years, as well as some features included as optional packages and mid-production adjustments due to supply chain issues, introduces a high degree of complexity and uncertainty. In addition, some manufacturers provide wireless software updates, allowing vehicles to be equipped (or unequipped) with automation technologies months or years after manufacture.

Several attempts have been made to estimate the proportion of various automation technologies in the U.S. vehicle fleet. The most common method to estimate the market penetration of vehicle technologies is to compare vehicle registration model years with databases of manufacturer model years for vehicles with the target technology available as a standard or optional feature. The Highway Loss Data Institute (HLDI) (2020) has estimated penetration rates for various vehicle safety features by using this method. The researchers estimating these rates acknowledged limitations in accuracy as adoption of optional features had to be estimated from known adoption rates of similar class vehicles using linear regression models.

Although many vehicles might be equipped with CAV features, individual drivers may choose to disable passive features or not engage active features. To estimate the percentage of those vehicles equipped with the technology that has not been deactivated, researchers observed vehicles brought in for service at 14 Washington, D.C., metro area dealerships (Reagan et al., 2018). They found activation rates of 93% for vehicles equipped with automatic emergency braking, 57% for vehicles equipped with adaptive cruise control, and 8% for vehicles equipped with lane departure prevention. Although this study identified systems that were deactivated by the driver, it did not estimate the actual use of the systems, as drivers might have adaptive cruise control "active" but rarely use it in practice. System usage information is not currently available from existing sources such as Wejo, and manufacturers have increasingly reduced the amount of data available from a vehicle's controller area network bus. In order to estimate the actual use of certain CAV technologies, more data are needed on real-time on-road usage.

PURPOSE AND SCOPE

The objectives of this study were as follows:

1. Identify agency CAV data needs with respect to the capabilities, market penetration, and usage rates of various forms of vehicle connectivity and automation on Virginia roads. Throughout this report, "CAV data needs" refers to the automation status, configuration, and capabilities of a vehicle and not specific data obtained from a vehicle's sensors such as position, pavement roughness, or video.

2. Identify currently available sources of data for addressing agency CAV data needs and determine their availability, costs, coverage, and accuracy.

3. Identify practical ways to collect CAV data directly from field measurements or a registration system.

For estimating percentages of equipped vehicles, the scope was limited to passenger vehicles.

METHODS

To accomplish the study objectives, six tasks were performed.

1. Conduct a literature review.
2. Interview stakeholders.
3. Categorize and prioritize CAV features and identify data sources.
4. Estimate CAV market penetration using existing data sources.
5. Investigate the potential to estimate CAV feature market penetration from field data.
6. Use the findings from Tasks 1 through 5 to identify potential data collection methods.

Literature Review

A review of the literature was conducted to summarize research on the topics of CAV market penetration, impact on operations, and registration systems. Scientific research articles and publications from government agencies, universities, and consulting companies were reviewed through searches of Google Scholar, the Transport Research International Documentation (TRID) database, and forward and backward citations of relevant articles.

Categorize and Prioritize CAV Features and Identify Data Sources

This task investigated various CAV taxonomies to classify connectivity and automation features that are relevant to VDOT and other state agencies. The taxonomy may be based on SAE International (SAE) standards (SAE International, 2021a), other standards, registration systems, and legal frameworks from the United States and abroad. Categorizing various connected and automated features in a consistent framework allows for more comprehensive data collection of vehicle capabilities.

The second part of this task prioritized these categories based on their relevance to stakeholders and their anticipated impact on traffic safety and capacity. By evaluating the magnitude of the impact for a given technology, one can begin to rank the importance of various CAV features on safety and capacity. These rankings informed later methods to estimate the penetration rate of high-priority technologies.

The third part of this task identified potential CAV penetration rate data sources, either publicly available or from third parties. Available data sets were evaluated regarding their coverage, accuracy, and applicability.

Estimate CAV Market Penetration Using Existing Data Sources

This task developed a methodology to estimate the penetration rate of various CAV technologies in Virginia using the datasets identified prior tasks. Methods to estimate penetration rates differed based on varying data availability. These methods were then applied to available data to produce estimates of vehicles equipped with high-priority CAV features.

Investigate Potential to Estimate CAV Feature Market Penetration From Field Data

Although vehicle volumes, speeds, and travel times are generally measured directly from roadside sensors, data on CAV features generally are not. Further, the extent to which it is possible to measure CAV features in the field is unknown, as automation features are generally not directly observable. To address these unknowns, this task investigated the potential to measure CAV penetration rates using data from roadside sensors through interviews with subject matter experts.

Identify Potential Data Collection Methods

This task identified methods to collect CAV data going forward, based on the findings in prior tasks. Methods were assessed based on their relative strengths and weaknesses, primarily data limitations, quality of estimates, and level of effort. Potential methods using currently unavailable but potential future datasets were also identified and assessed.

RESULTS AND DISCUSSION

Literature Review

CAV Taxonomy

Before CAVs are recorded or registered, a consistent terminology for the range of CAV technologies must be established. The literature provides a range of terminology and classification schemas for CAVs.

Connected Vehicle Taxonomy

Connectivity taxonomy is rarely discussed in the literature but seems divided between dedicated short-range communications (DSRC), described in 47 CFR, Part 90, Subpart M, and cellular networks. DSRC uses the 5.9 GHz spectrum and has a range of approximately 400 meters from a roadside unit. Cellular communication is more common and may be part of vehicle connectivity via pre-installed systems such as those used by Tesla (2023) for over-the-air updates and crash reporting; third party systems such as General Motors' OnStar system for crash reporting and lock-out services (OnStar, 2023); and even cell phone apps for navigation and in-vehicle entertainment (Goodall and Lee, 2019). The bulk of the literature review focuses instead on vehicle automation technologies.

Automated Driving System Taxonomy

The most widely used classification scheme is the SAE levels of driving automation (SAE International, 2021a). First introduced in 2014, adopted by the National Highway Traffic Safety Administration (NHTSA) in 2016, and most recently revised in 2021, the SAE guidance classifies vehicle automation technologies into six levels. SAE published a graphic providing additional details (SAE International, 2021b), shown in Figure 1.

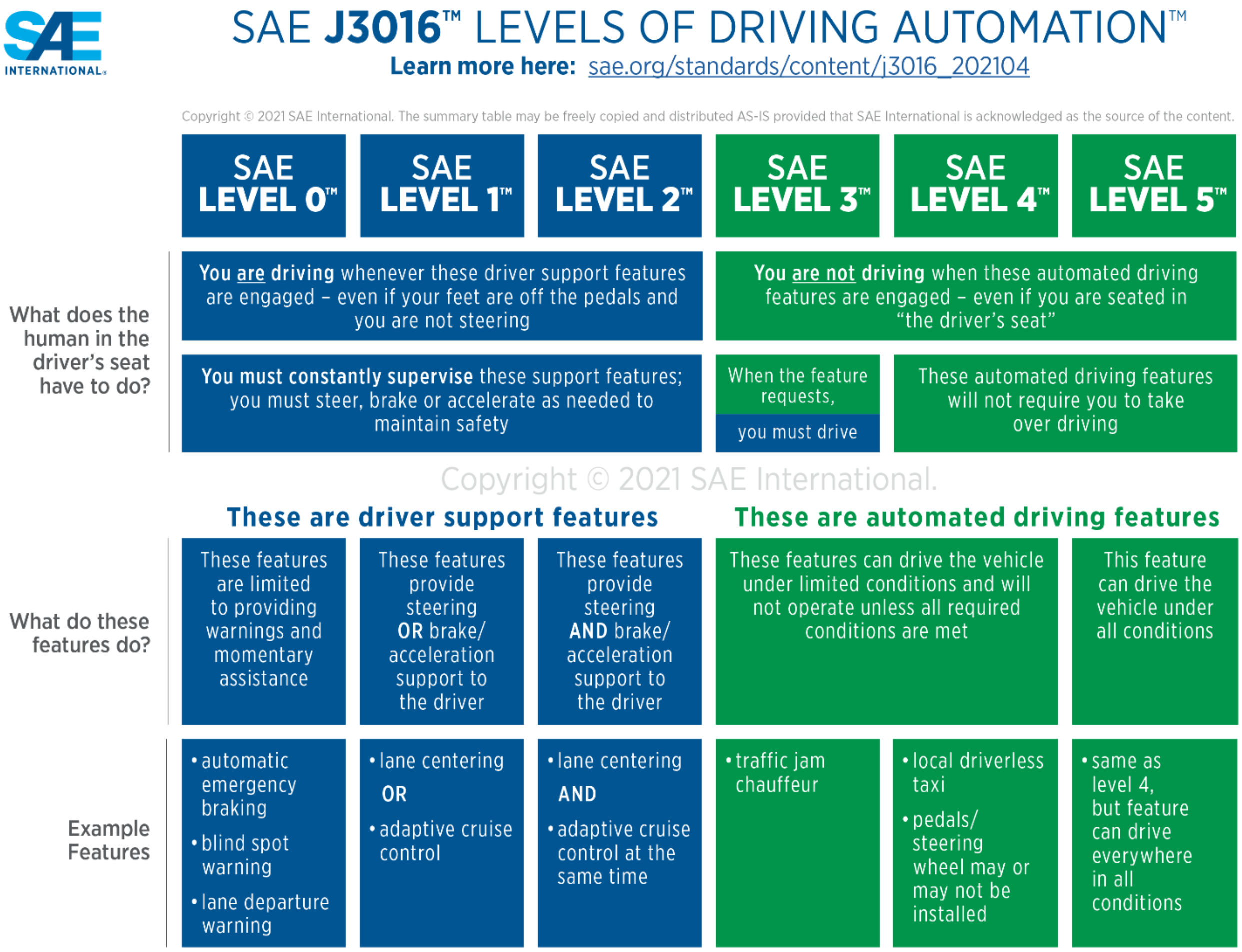

Figure 1. SAE Levels of Driving Automation. SAE = SAE International.

Vehicles operating at Levels 3–5 are referred to as having automated driving systems (ADS), and vehicles operating at Levels 1–2 have one or more advanced driver assistance systems (ADAS). ADS is distinguished from Level 2 ADAS by the systems' responsibility for object and event detection and response, with the human driver required as fallback (SAE International, 2021a). According to NHTSA (2022), all vehicles available for sale to consumers as of April 2023 are Level 2 or below. There are several examples of Level 3 vehicles in testing and in operation as driverless taxis in San Francisco, California, and Phoenix, Arizona (Weise, 2023).

Although a true Level 3 vehicle may not be purchasable, many vehicles have Level 3 functions in limited domains. For example, a vehicle may need no oversight in parking assistance functions and therefore may have Level 3 functionality in those limited circumstances. The different automation levels a vehicle might exhibit across different domains, as well as the Level 3 requirement that an ADS will issue a "request to intervene" in time for a human driver to safely take over, have invited criticism of the SAE levels (Inagaki and Sheridan, 2019).

In 2010, the German Federal Highway Research Institute adopted a general classification scheme for both lower and higher level ADS (Gasser et al., 2012). The definitions were similar to the SAE levels, with "Full Automation" encompassing SAE Levels 4 and 5. The definitions were as follows:

- driver only
- driver assistance, e.g., driver permanently controls either lateral or longitudinal control
- partial automation, e.g., system controls combined lateral and longitudinal with driver monitoring
- high automation, e.g., partial automation but driver as fall back, no monitoring required
- full automation, e.g., driver unnecessary.

ADAS Taxonomy

Gasser et al. (2016) proposed a different classification scheme for ADAS, based on the functionality of the system. Although never formally adopted by regulators, these classifications provide a useful way of grouping ADAS into practical areas. Their three broad groups are as follows:

1. *Operation Type A:* informing warnings and functions, e.g., lane departure warning
2. *Operation Type B:* continuously automating functions, e.g., adaptive cruise control
3. *Operation Type C:* intervening emergency functions (near-crash situations), e.g., automatic emergency braking.

Gouribhatla and Pulugurtha (2022) conducted a literature review of the effect of ADAS on driver behavior. As part of their study, they identified eight unique ADAS technologies.

1. Blind spot warning (BSW)
2. Lane departure warning (LDW)
3. Over speed warning (OSW)
4. Forward collision warning (FCW)
5. Adaptive cruise control (ACC)
6. Cooperative ACC (CACC)
7. Lane keeping assist (LKA)
8. Automated emergency braking (AEB).

NHTSA researched the availability of ADAS features on production vehicles from 38 manufacturers (National Center for Statistics and Analysis, 2023). Although ADAS features are not encoded directly in a VIN, NHTSA researches these features independently and stores them as part of their Product Information Catalog and Vehicle Listing (vPIC) database (National Center for Statistics and Analysis, 2023). The included features are as follows:

- Adaptive Cruise Control (ACC)
- Adaptive Driving Beam (ADB)

- Adaptive Headlights
- Anti-lock Braking System (ABS)
- Automatic Crash Notification (ACN) / Advanced Automatic Crash Notification (AACN)
- Automatic Pedestrian Alerting Sound (for Hybrid and EV only)
- Auto-Reverse System for Windows and Sunroofs
- Backup Camera
- Blind Spot Intervention
- Blind Spot Warning (BSW)
- Crash Imminent Braking (CIB)
- Daytime Running Light (DRL)
- Dynamic Brake Support (DBS)
- Electronic Stability Control (ESC)
- Event Data Recorder (EDR)
- Forward Collision Warning (FCW)
- Headlamp Light Source
- Keyless Ignition
- Lane Centering Assistance
- Lane Departure Warning (LDW)
- Lane Keeping Assistance (LKA)
- Parking Assist
- Pedestrian Automatic Emergency Braking (PAEB)
- Rear Automatic Emergency Braking
- Rear Cross Traffic Alert
- Semiautomatic Headlamp Beam Switching
- Tire Pressure Monitoring system (TPMS)
- Traction Control.

Pradhan et al. (2022) conducted a study of ADAS technologies for the Massachusetts DOT. Based on a review of press releases and vehicle user manuals from 30 manufacturers, 207 manufacturer-unique systems were identified, which could be classified as 1 of 51 unique ADAS features. The 51 technologies are listed in Table 1.

Rates of AV Technologies Installed

Virginia does not have any laws requiring testers of Level 3–5 AVs to report their activities (Gordon, 2022), so any features added to production vehicles enabling this type of automation would be unknown to the government in the absence of voluntary reporting by the tester. Virginia would be able to obtain information on Level 1–2 ADAS by cross checking vehicle registrations against manufacturer records, although the task is resource intensive as no comprehensive database exists for ADAS installations in production vehicles.

Table 1. Common ADAS Technologies

ADAS Technology Name	Description
Adaptive Cruise Control	Controls acceleration and/or braking to maintain a prescribed distance between it and a vehicle in front. May be able to come to a stop and continue.
Adaptive Headlights	Adapts to changing roadway conditions—such as curves—to help illuminate the roadway along driver's path.
Anti-lock Braking Systems	Helps prevent wheels from locking up—possibly allowing the driver to steer to safety.
Automatic Crash Notification	Detects either that an air bag has deployed or that there has been a dramatic and sudden deceleration and connects to an emergency operator. Also sends basic information and location about the car, without any passenger or driver input.
Automatic Emergency Braking	Senses slow or stopped traffic ahead and urgently applies the brakes if the driver fails to respond. Automatic.
Emergency Steering	Detects potential collision and automatically controls steering to avoid or lessen the severity of impact.
Automatic High Beams	Deactivates or orients headlamp beams automatically based on lighting, surroundings, and traffic.
Automatic Parallel Parking	Helps guide driver into a parallel parking spot after searching and finding a viable option. Does not brake or monitor surroundings.
Back Up Warning	Alerts driver of objects behind the car as driver back out of spaces such as driveways or parking spots.
Back Up Camera	Shows a wide view behind the car while in reverse, even at night.
Bicycle Detection	Alerts driver of a potential collision with a bicyclist ahead.
Blind Spot Warning	Detects vehicles to rear in adjacent lanes while moving and alerts driver to their presence.
Brake Assist	Detects driver slamming the brakes and applies maximum force to the brakes to help make sure the car stops as quickly as possible.
Cruise Control	Allows driver to maintain a constant vehicle speed without keeping foot on the accelerator pedal.
Curve Speed Warning	Uses GPS to warn driver when approaching a curve or exiting the road too quickly.
Driver Drowsiness Monitoring Systems	Alerts driver if drowsy and suggests driver take a break when it is safe to do so.
Driver Monitoring Systems	Alerts driver when signs of drowsiness or distraction are detected.
Dynamic Brake Support and Crash Imminent Braking	Supplements driver's braking in an effort to avoid a crash. If the driver does not take any action to avoid the crash, automatically applies the vehicle's brakes to slow or stop the car, avoiding the crash or reducing its severity.
Dynamic Driving Assistance	Controls vehicle acceleration, braking, and steering. The SAE standard's definition of L2 Autonomous Systems outlines this functionality.
Electronic Stability Control	Helps prevent drivers from losing control of the direction of the car due to a spin out or plow out. When effective, this also significantly reduces the risk of being in a rollover—one of the most dangerous types of single-vehicle crashes.
Forward Automatic Emergency Braking	Detects potential collisions while traveling forward and automatically applies brakes to avoid or lessen the severity of impact.
Forward Collision Warning	Detects impending collision while traveling forward and alerts driver.
Fully Automated Parking Assistance	Controls acceleration, braking, steering, and shifting during parking. May be capable of parallel and/or perpendicular parking.
High Speed Alert	Coordinates the car's position, via GPS, with a database of speed limit information to alert driver if speeding.
Highway Pilot	Maintains vehicle's lane position and following distance by automatically braking and accelerating as needed.
Hill Descent Control or Assist	Helps keep vehicle at a steady speed when going down a hill or other decline.
Hill Start Assist	Helps prevent roll-back when starting up again from a stopped position on an incline.
Intersection Assistant	Warns driver of vehicles approaching from the sides at intersections, highway exits, or car parks and brakes the car if driver does not brake in time.
Lane Centering Assist	May gently steer driver back into driver's lane if driver begins to drift out of it.
Lane Departure Warning	Monitors vehicle's position within driving lane and alerts driver as the vehicle approaches or crosses lane markers.
Lane Keeping Assist	Controls steering to maintain vehicle within driving lane. May prevent vehicle from departing lane or continually center vehicle within the lane.
Night Vision	Aids driver vision at night by projecting enhanced images on instrument cluster or heads-up display.

Obstacle Detection	Uses sensors mounted in the front and/or rear bumpers to determine the distance between the car and nearby objects. In some versions, it will brake the car automatically. Does not work in low visibility weather conditions.
Parking Obstruction Warning	Detects obstructions in close proximity to vehicle during parking maneuvers.
Parking Sensors	Alert driver to the position of objects around the car as driver parks.
Pedestrian Automatic Emergency Braking	Provides automatic braking for vehicles when pedestrians are in front of the vehicle and the driver has not acted to avoid a crash.
Pedestrian Detection	Detects pedestrians in front of vehicle and alerts driver to their presence.
Push Start Button	Simplifies turning car on and off using a key fob unique to the driver.
Rain Sensor	Detects rainfall and activates windshield wiper.
Rear Cross Traffic Warning	Detects vehicles approaching from side and rear of vehicle while traveling in reverse and alerts driver.
Remote Parking	Parks vehicle without driver being present inside the vehicle. Automatically controls acceleration, braking, steering, and shifting.
Reverse Automatic Emergency Braking	Detects potential collision while traveling in reverse and automatically applies brakes to avoid or lessen the severity of impact.
Semi-Automated Parking Assistance	Controls steering during parking. Does not accelerate, brake, or change gear position. May be capable of parallel and/or perpendicular parking.
Sideview Camera	Shows driver an expanded view of a lane beside driver when driver uses turn signal or activates the feature manually.
Surround View Camera	Uses cameras located around vehicle to present view of surroundings.
Temperature Warnings	Alerts driver when the outside temperature is detected to be at or below freezing, which can impact the conditions of roadways.
Tire Pressure Monitoring	Warns driver if tires are under- or over-inflated, helping increase fuel economy and even potentially preventing a tire blowout. May not specify which tire needs attention.
Traction Control System	Helps wheels gain traction on slippery surfaces.
Traffic Jam Assist	Automatically accelerates and brakes the vehicle with the flow of traffic and keeps vehicle between lane markings—even in curves.
Trailer Assistance	Assists driver during backing maneuvers with a trailer attached.
Vibrating Seat Warnings	Vibrates driver's seat bottom cushion if a crash risk is detected. Helps hearing-impaired drivers.

Adapted from Pradhan et al. (2022). SAE = SAE International.

Pradhan et al. (2022) attempted to determine ADAS penetration rates using a database of VINs of vehicles registered in Massachusetts, but they were unsuccessful. They described the difficulties they encountered as follows:

> However, there is no straightforward and direct method to access information about the ADAS features available for specific automobiles. While the original plan was to extract information about a vehicle's ADAS features from each vehicle's unique vehicle identification number (VIN), it became clear to the project team that such information was not transparent nor readily discernable. After a significant effort was undertaken to try to gain insight into the VINs, including conversations with insurance providers, the Alliance of Automobile Manufacturers, and other institutes, the team realized that an alternate method would have to be designed to gain this information. To that end, we proposed randomly sampling vehicle registration data for any given year . . . and then cross-referencing the vehicle make, model, and year with publicly available manufacturer data about vehicle ADAS features (and whether they come standard or not) …While admittedly painstaking and burdensome, this may be the only (and most feasible) approach to understanding ADAS deployment (Pradhan et al., 2022).

An analysis of fatal crashes between 2016 and 2019 in NHTSA's Fatality Analysis Reporting System (FARS) was conducted by Gajera et al. (2023). For each 138,899 vehicles involved in fatal crashes in the database, the authors decoded the associated VINs of the involved vehicles in vPIC to identify any vehicles with optional or standard lane keeping assistance, lane centering, or adaptive cruise control features. The authors found that 2,428 vehicles (1.8%) had one or more of these technologies available as optional or standard features. The analysis, however, is undermined by NHTSA's methods of collecting information on automation technologies.

Manufacturers are not required to report the prevalence of automation technologies to NHTSA in accordance with 49 CFR, Part 565; however, some manufacturers may submit this information voluntarily. NHTSA researches automation features independently from press releases and vehicle manuals, but searches are limited to light-, medium-, and heavy-duty vehicles manufactured by 38 major light-duty vehicle manufacturers for model years 2017 and newer (National Center for Statistics and Analysis, 2023). Therefore, the 2016–2019 data analyzed by Gajera et al. (2023) would have extremely limited data for years 2016 to 2017, as few vehicles with vPIC automation data would have been on the road. Similarly, many crashes with automation features manufactured prior to 2017 would also be missing from the vPIC data.

HLDI (2023) has estimated penetration rates for various vehicle safety features using similar methods. HLDI maintains a proprietary database of vehicle feature availability by vehicle make, model, and year. Features are classified as standard, optional, or unavailable. In HLDI (2023), the authors mapped the HLDI features database to a private database of vehicle registration counts maintained by IHS Markit, now S&P Global (2023). The IHS Markit data are not public but are available for purchase.

When a feature was listed as optional for a given vehicle type, HLDI (2023) used another HLDI database of actual installed features by individual VIN obtained from 12 manufacturers. From these data, HLDI estimated the probability of actual installation on optional vehicles using regression models with factors such as model year, size, class, and vehicle base price. They estimated that in 2022, approximately 28% of the U.S. vehicle fleet was equipped with front crash prevention warning, 24% with lane departure warning, 22% with automatic emergency braking, and 4% with combined adaptive cruise control and lane centering (HLDI, 2023). Estimates for adaptive cruise control are not provided separately, but only as part of a combined category of adaptive cruise control and lane centering systems. HLDI issued its original report in 2012, with annual updates between 2014 and 2023.

Rates of AV Technology Usage

The prior section discussed studies attempting to estimate the rate of automation technologies available in production vehicles. Although vehicles may have technologies installed, individual drivers may choose to disable passive features or not engage active features while driving.

To estimate the percentage of vehicles equipped with the technology that has not been deactivated, Reagan et al. (2018) observed vehicles brought in for service at 14 Washington, D.C., metro area dealerships over a period of 7 months (4 weeks per dealership). The authors found activation rates of 93% for vehicles equipped with automatic emergency braking, 57% for vehicles equipped with adaptive cruise control, and 8% for vehicles equipped with lane departure prevention. Although this analysis identified systems that were deactivated by the driver, it did not estimate the actual use of the systems, as drivers might have "active" adaptive cruise control but rarely use it in practice.

Flannagan et al. (2016) collected data from approximately 2,000 General Motors vehicles equipped with forward collision warning and lane departure warning driven 19 million miles on public roads. Participants turned on lane departure warning approximately 50% of driving time and forward collision warning 91% of driving time.

From driver surveys, the main factors that affect usage rates of ADAS appear to be driver annoyance and understanding of system capabilities (Kidd and Reagan, 2019). Specifically, forward collision prevention warnings that are well understood by drivers and that have low false alarm rates are used at higher rates, and lane departure prevention systems with less annoying alerts and consistent pavement marking detection are used more frequently. Other studies suggested that vibratory warnings were seen as less annoying than auditory warnings (Flannagan et al., 2016; Reagan et al., 2018).

CAV Registration Systems

Based on an analysis of state vehicle automation laws (National Conference of State Legislatures, 2020), no states were identified that record vehicle automation features directly as part of vehicle registration. In an interview with the Virginia DMV conducted as part of this study, the DMV indicated that they were also unaware of other state registration systems.

Several states attempt to track vehicle automation through alternative methods. The California DMV (2018) initiated an autonomous vehicle testing program in 2014, requiring all AV developers testing on public roads in California to obtain a Manufacturer's Testing Permit. Permits are required for developers testing Level 3–5 ADS but are not required for Level 1 and 2 ADAS. Permit holders must report all VINs and autonomous mileages for permitted vehicles annually. In 2022, a total of 1,563 vehicles traveled 5.1 million miles in the autonomous mode with a safety driver. Over the same period, 552 registered vehicles traveled 620,830 miles without a human driver present. Recent year crash, mileage, and disengagement data are available on the California DMV's website (California DMV, 2023a, 2023b), and later years are available upon request. California DMV data are archived by the Autonomous Vehicle Operation Incident Dataset Project (Zheng et al., 2023).

Texas does not currently track automation technologies (Licensing and Registration Subcommittee of the Texas Connected and Autonomous Vehicles Task Force et al., 2021), but in April 2023, the Texas DOT (2023) added fields to their crash database for "Autonomous Level Engaged" with possible values of "Driver Assistance" and "Partial Automation." Another field of "Autonomous Unit – Reported" lists values of Yes and No. It is unclear precisely what technologies these fields correspond to, or how they are collected, e.g., from officers at the scene or an analysis of the vehicle's event data recorder (EDR). If these data prove to be of high quality, then they could be used to determine the percentage of vehicles involved in crashes with automated technologies either installed or running at the time of the crash. These figures could then be used as surrogates for all vehicles on the road.

Summary of Literature Review

An analysis of the literature suggested that there is no public, comprehensive central database for ADAS installations by vehicle make and model. Data on some features are collected by NHTSA for certain manufacturers for vehicles manufactured in 2017 or later. Similarly, there is no clear way to determine which features are actually installed in vehicles, as public databases list them only as standard or optional. Although HLDI has the most sophisticated estimates, given their proprietary data of actual installations from manufacturers based on a sample of VINs, these data are not public, and HLDI is unable to share them due to data-sharing agreements. There appear to be no state-maintained data on AV technologies in vehicle registration systems.

Categorization and Prioritization of CAV Features and Identification of Data Sources

Categorization

A review of the literature suggested three general types of automation technologies: warnings, continuous automation, and crash avoidance. When these features are combined in a way to allow continuous operation of both longitudinal and lateral control, the system can be described as Level 2. When the driver is no longer required to monitor the system actively according to the developer, then the system can be described as Level 3.

An example grouping of the most relevant ADAS technologies identified in Pradham et al. (2022) is shown in Table 2. Each independent system may be limited in its operational design domain. As one example, many adaptive cruise control systems are recommended only for use on controlled access freeways.

Table 2. Classification of Common ADAS Technologies

Warnings	Continuous Automation	Crash Avoidance
• Back Up Warning • Bicycle Detection • Blind Spot Warning • Curve Speed Warning • Driver Drowsiness Monitoring Systems • Driver Monitoring Systems • Forward Collision Warning • High Speed Alert • Lane Departure Warning • Parking Obstruction Warning • Parking Sensors • Pedestrian Detection • Rear Cross Traffic Warning • Vibrating Seat Warnings	• Adaptive Cruise Control • Adaptive Headlights • Automatic High Beams • Automatic Parallel Parking • Cruise Control • Dynamic Driving Assistance • Fully Automated Parking Assistance • Highway Pilot • Hill Descent Control or Assist • Hill Start Assist • Lane Centering Assist • Lane Keeping Assist • Remote Parking • Semi-Automated Parking Assistance • Traffic Jam Assist	• Anti-lock Braking Systems • Automatic Crash Notification • Automatic Emergency Braking • Emergency Steering • Brake Assist • Dynamic Brake Support and Crash Imminent Braking • Electronic Stability Control • Forward Automatic Emergency Braking • Intersection Assistant • Pedestrian Automatic Emergency Braking • Reverse Automatic Emergency Braking • Traction Control System

Prioritization

VDOT is responsible for the maintenance and operation of public roads within Virginia, with the objectives of supporting safe and efficient transportation. The automation features with the most relevance to VDOT, therefore, are systems that have the greatest impact on safety and capacity on public roads. Data collection on prevalence of automation features should focus on those systems.

Many ADAS features are primarily used in backing or parking operations, which have limited impact on VDOT's operations as they often occur in private facilities such as driveways, parking lots, and city streets (10,561 miles of urban streets are maintained by cities and towns with the help of state funds). Data on systems such as rear collision avoidance and parking assistance are therefore of less value to VDOT.

Research indicates that warning systems have lesser impacts on crash rates than continuous automation systems and crash prevention systems. Data from on-road studies showed only a 16% reduction in rear-end striking crashes for forward collision alerts but a 45% reduction for front automatic braking (Flannagan and Leslie, 2020). Similarly, lane departure warnings resulted in a 3% reduction in lane departure crashes, but lane keep assist resulted in a 30% reduction (Flannagan and Leslie, 2020). Other studies have reported similar findings (Cicchino, 2017). Data on continuous automation and crash prevention systems should therefore be prioritized over those for warnings systems.

Discussions with VTRC's Office of Strategic Innovation confirmed an interest in features with the greatest impact on safety and mobility. Specific technologies of interest were adaptive cruise control, front collision warnings, and lane keeping assist.

Level 2 ADAS involves the combination of lateral and longitudinal vehicle control, which can be represented as a combination of two separate ADAS, i.e., lane centering assist and adaptive cruise control. By tracking individual ADAS, a database can record both Level 1 and Level 2 vehicles, as Level 2 vehicles are simply vehicles that allow simultaneous use of these lateral and longitudinal control ADAS functions. Adaptive cruise control has also been shown through simulation to have significant effects on freeway capacity at high usage rates (Heaslip et al., 2020). Adaptive cruise control and lane centering can be considered high-priority features for tracking.

Forward collision prevention systems such as automatic emergency braking have been shown to reduce rear-end striking crashes by 45%, representing some of the highest safety improvements of any ADAS technology. For this reason, forward collision prevention systems can also be considered high priority.

Using these guidelines, ADAS data collection can be prioritized as shown in Table 3.

Table 3. Potential Vehicle Automation Feature Data Collection Priorities for VDOT

High	Medium	Low
• Adaptive Cruise Control • Automatic Emergency Braking • Forward Collision Prevention • Lane Centering Assist • Lane Keeping Assist • Pedestrian Automatic Emergency Braking	• Lane Departure Warning • Forward Collision Warning • Blind Spot Warning • Intersection Assistant • Traffic Jam Assist	All other systems

Data Sources

vPIC Database

For databases that include VINs, some information on automation technology may be obtained from NHTSA's Product Information Catalog and Vehicle Listing (vPIC) database (National Center for Statistics and Analysis, 2023). The vPIC database consists primarily of data reported by manufacturers as part of submissions under 49 CFR, Part 565. Some of the reported data are mandatory—for passenger cars, manufacturers must report "make, line, series, engine type, and all restraint devices and their location" (49 CFR, Part 565, Table I). Some manufacturers submit additional information on a voluntary basis, which is incorporated into vPIC.

For certain areas of interest, NHTSA conducts independent research to add supplementary data (National Center for Statistics and Analysis, 2023). NHTSA searches manufacturer websites for press releases and vehicle manuals to identify ADAS that may be standard or optional equipment on vehicles by make, model, year, and trim level. The search is performed for light-, medium-, and heavy-duty vehicles for model years 2017 and newer for the 38 vehicle manufacturers shown in Table 4.

Table 4. Vehicle Manufacturers With NHTSA-Added Automation Features in vPIC

Vehicle Manufacturers		
Acura	GMC	MINI
Alfa Romeo	Honda	Mitsubishi
Audi	Hyundai	Nissan
Bentley	Infiniti	Porsche
BMW	Jaguar	Ram
Buick	Jeep	Rolls-Royce
Cadillac	Kia	Smart
Chevrolet	Land Rover	Subaru
Chrysler	Lexus	Tesla
Dodge	Lincoln	Toyota
Fiat	Maserati	Volkswagen
Ford	Mazda	Volvo
Genesis	Mercedes-Benz	

NHTSA = National Highway Traffic Safety Administration.

Although data are not available on an individual vehicle level as with the HLDI database, vPIC is publicly available. The data types collected are as follows:

- Adaptive Cruise Control (ACC)
- Adaptive Driving Beam (ADB)
- Adaptive Headlights
- Anti-lock Braking System (ABS)
- Automatic Crash Notification (ACN) / Advanced Automatic Crash Notification (AACN)
- Automatic Pedestrian Alerting Sound (for Hybrid and EV only)
- Auto-Reverse System for Windows and Sunroofs
- Backup Camera
- Blind Spot Intervention
- Blind Spot Warning (BSW)
- Crash Imminent Braking (CIB)
- Daytime Running Light (DRL)
- Dynamic Brake Support (DBS)
- Electronic Stability Control (ESC)
- Event Data Recorder (EDR)
- Forward Collision Warning (FCW)
- Headlamp Light Source
- Keyless Ignition
- Lane Centering Assistance
- Lane Departure Warning (LDW)
- Lane Keeping Assistance (LKA)
- Parking Assist
- Pedestrian Automatic Emergency Braking (PAEB)
- Rear Automatic Emergency Braking
- Rear Cross Traffic Alert
- Semiautomatic Headlamp Beam Switching
- Tire Pressure Monitoring system (TPMS)
- Traction Control.

VINs can be searched or “decoded” in bulk by using an Application Programming Interface (API) or downloading vPIC as a standalone database. Gajera et al. (2023) used this approach to analyze the prevalence of partial automation technologies in fatal crashes.

VINs in Virginia can be obtained from Virginia DMV registration records. Nationally, a representative sample of VINs is available from FARS. FARS contains more than 140 data fields and can be queried using the Fatality and Injury Reporting System Tool (FIRST) NHTSA, 2023a).

HLDI Estimates

HLDI is a nonprofit organization funded by a consortium of insurance companies that conducts studies on economic losses of vehicle operation using insurance data. As described in the literature review, HLDI estimates penetration rates for ADAS annually. Estimates are based on HLDI's internal database of available features by vehicle make/model/year, vehicle registration counts maintained by IHS Markit, and a sample of individual-vehicle-level equipped rates obtained from 12 manufacturers. HLDI also projects adoption rates through 2050. As of 2023, HLDI estimates the following features:

- Rear camera
- Rear parking sensors
- Front crash prevention
- Blind spot monitoring
- Lane departure warning
- Front automatic emergency braking
- Curve adaptive headlights
- Adaptive cruise control with lane centering.

Estimation of CAV Market Penetration Using Existing Data Sources

Estimating market penetration of a non-standard vehicle technology is a challenging task, as technologies do not have consistent nomenclatures or operational domains. Further, automation technologies are not included in vehicle registration databases or as part of the VIN. In short, for most vehicles, there is no way to determine which automation technologies are installed without direct inspection. This section presents and compares two methods to estimate automation prevalence using existing data sources.

Estimation of Equipped Vehicle Rates

HLDI Estimated Equipped Rates

The most common method to estimate the market penetration of vehicle technologies is to compare vehicle registration model years with databases of manufacturer model year vehicles with the target technology available as a standard or optional feature. HLDI (2023) has estimated penetration rates for various vehicle safety features by using this method, using their own database of standard vs. optional features on different vehicle makes, models, and years cross-referenced with vehicle registration counts maintained by IHS Markit, now S&P Global (2023). HLDI further calculates the probability of an optional feature being installed by analyzing another HLDI database of actual installed features by VIN obtained from 12 manufacturers. The probability of actual installation on optional vehicles was calculated using regression models with factors such as model year, size, class, and vehicle base price.

HLDI's (2023) most recent estimates for front crash prevention, lane departure warning, automatic emergency braking, and combined adaptive cruise control and lane centering are shown in Figure 2.

HLDI reports provide the prevalence of penetration rates in future years out to 2050. To evaluate the accuracy of these predictions, predictions of 2022 vehicle equipped rates from the 2018 report (HLDI, 2018) were compared with the 2022 estimates in the 2023 report (HLDI, 2023). The results are shown in Figure 2. In all cases, predictions were highly accurate, even when technologies increased by 400% in the vehicle fleet over the 5-year timeline.

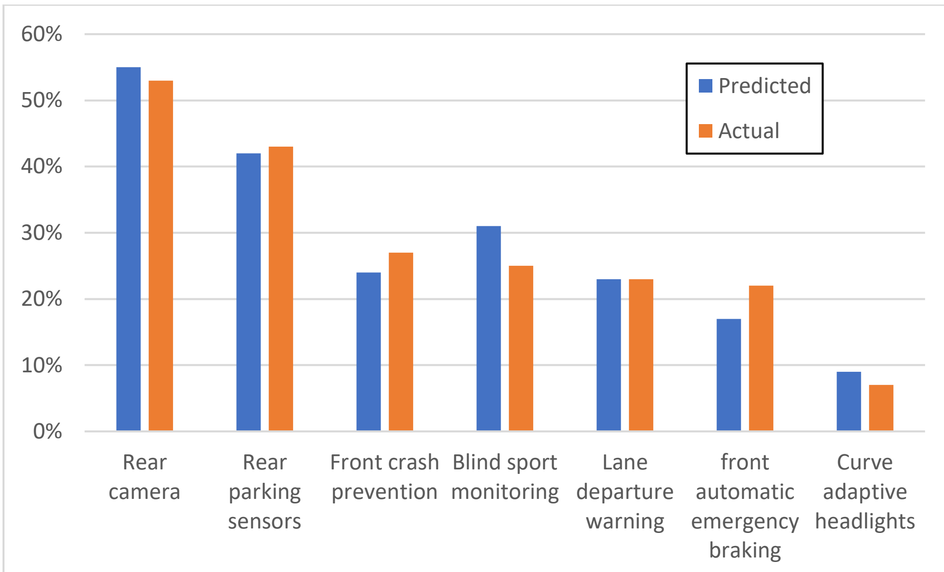

Figure 2. HLDI Predictions of 2022 Vehicle Equipped Rates From 2018 vs. HLDI Estimated 2022 Equipped Rates From 2022. HLDI = Highway Loss Data Institute.

Estimating From Comparable HLDI New Vehicle Installation Rates of Similar Technologies

Adaptive cruise control, lane keep assist, lane centering, and pedestrian automatic emergency braking rates were not estimated in the HLDI report. Two of these features, adaptive cruise control and lane keep assist, are discussed in a different HLDI (2019) report showing the prevalence of these technologies in new model year vehicles. The new vehicle report also includes new vehicle equipped rates of technologies discussed in the ADAS prevalence reports. By identifying technologies with similar new vehicle adoption rates as adaptive cruise control and lane keep assist, the total fleet equipped rate of adaptive cruise control and lane keep assist can be estimated as a function of the equipped rate of the matching technology.

According to HLDI (2019), approximately 15% of model year 2020 vehicles had adaptive cruise control as a standard feature with another 55% as an optional feature. From the same report, approximately 16% of model year 2018 vehicles had lane departure warning as a standard feature, with another 55% as an optional feature. These rate comparisons are shown in Figure 3.

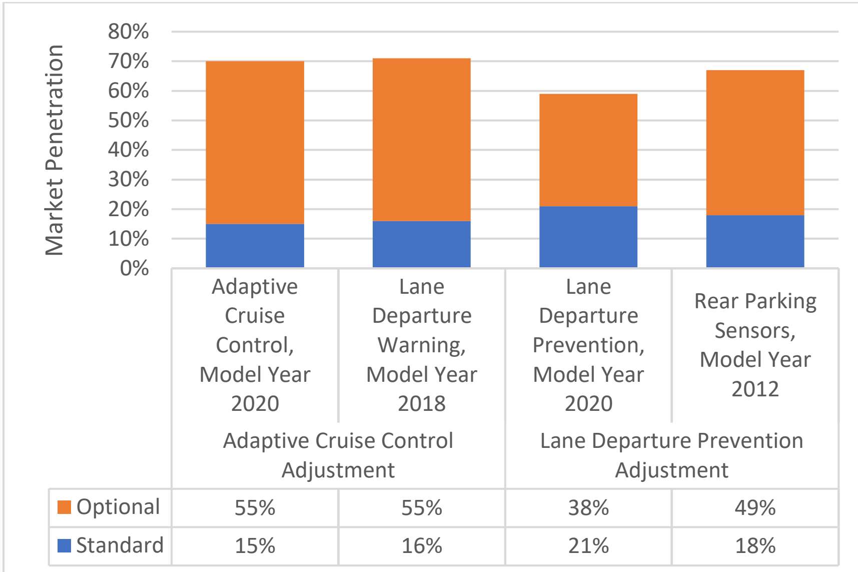

Figure 3. Model Year Standard and Optional Rates for Different ADAS Technologies. ADAS = Advanced Driver Assistance System. Adapted from Highway Loss Data Institute (2019).

If it is assumed that adaptive cruise control continues to enter the market at rates similar to those of lane departure warning, then the total fleet equipped rate for lane departure warning in 2020 is roughly equivalent to the total fleet equipped rate for adaptive cruise control in 2022. The 2020 fleet equipped rate for lane departure warning was 16% (HLDI, 2023). The 2022 equipped rate for adaptive cruise control can therefore be assumed also to be 16%. The adjustment is shown graphically in Figure 4.

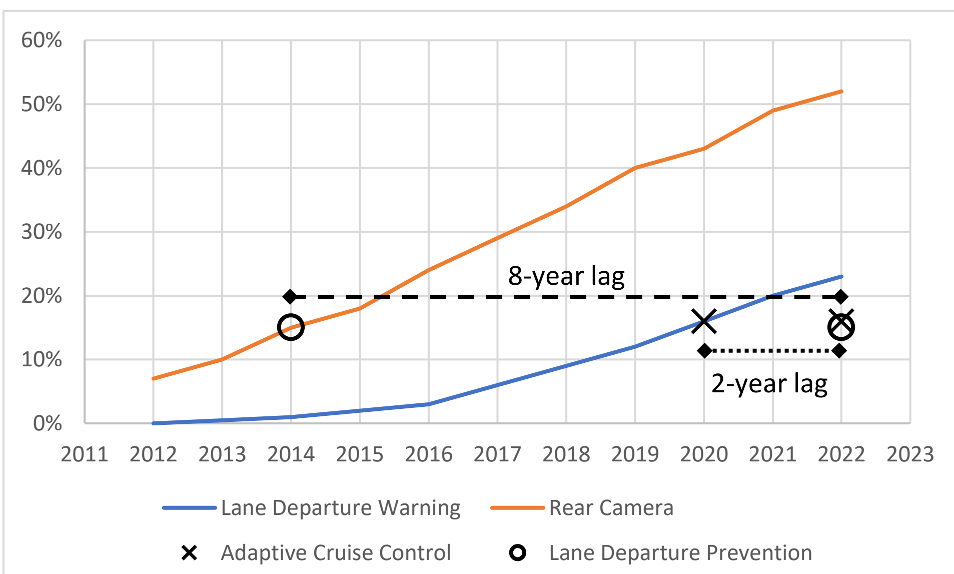

Figure 4. Adjustment of ADAS Features Based on Install Rates of Similar Features in Prior Years. ADAS = Advanced Driver Assistance System. Based on data from Highway Loss Data Institute (2023).

The same method can be used to estimate equipped rates of lane departure prevention systems. For model 2020 vehicles, approximately 21% had lane departure prevention systems as standard features, and 38% had them as optional features (HLDI, 2019). From the same report, approximately 18% of model year 2012 vehicles had rear parking sensors as a standard feature, with another 49% as an optional feature. These rate comparisons are shown in Figure 3. Again, if it is assumed that installation rates are similar moving forward with lane departure prevention lagging by 8 years, then the total fleet equipped rate for rear parking sensors in 2014 is roughly equivalent to the total fleet equipped rate for lane departure prevention in 2022. The 2014 fleet equipped rate for rear parking sensors was 15% (HLDI, 2023). The 2022 equipped rate for lane departure warning can therefore be assumed also to be 15%.

There are limitations with using this methodology. This approach assumes that technologies are adopted at similar rates, which may not occur in reality. Equipped rates of most technologies increase by 2 to 4 percentage points per year (HLDI, 2023), the differences of which can be substantial when compounded over a long time period. In addition, some technologies are more likely to be installed on "optional" models. Front automatic emergency braking, for example, has a much higher percentage of optional installs than rear parking sensors (HLDI, 2023). Finally, some technologies may be subject to government mandates or voluntary agreements that may accelerate adoption compared to technologies not subject to mandates. One example is electronic stability control, which was subject to a mandate first announced in 2007 and effective 2012. Caution should be used when extrapolating equipped rates of technologies over long periods of time and when comparing against technologies with different "optional" installation rates and technologies subject to mandates or voluntary agreements.

Estimating From FARS-vPIC New Vehicle Installation Rates of Similar Technologies

Not all features are included in the HLDI estimates. For example, lane centering assist and pedestrian automatic emergency braking were not included in the HLDI (2019) model year reports, and so estimating the equipped rates of these features requires additional calculation. The equipped rate by model year of these other features can instead be estimated, with limitations discussed here, by analyzing the automation features of vehicles involved in fatal crashes in the FARS dataset. FARS provides VINs for each involved vehicle, which can be decoded in vPIC. The decoded VIN in vPIC returns whether the involved vehicle had various features equipped as either standard or optional. The percentage of model 2021 vehicles equipped with lane centering assist and pedestrian automatic emergency braking involved in fatal 2021 crashes are shown in Figure 5.

The same method can be used to estimate equipped rates of pedestrian automatic emergency braking. From the FARS-vPIC data, 67% of model year 2021 vehicles involved in 2021 fatal crashes had lane centering assist as a standard feature, and 0% as an optional feature. From the HLDI (2019) vehicle model year installation rates, approximately 61% of model year 2008 vehicles had electronic stability control as a standard feature, with another 14% as an optional feature.

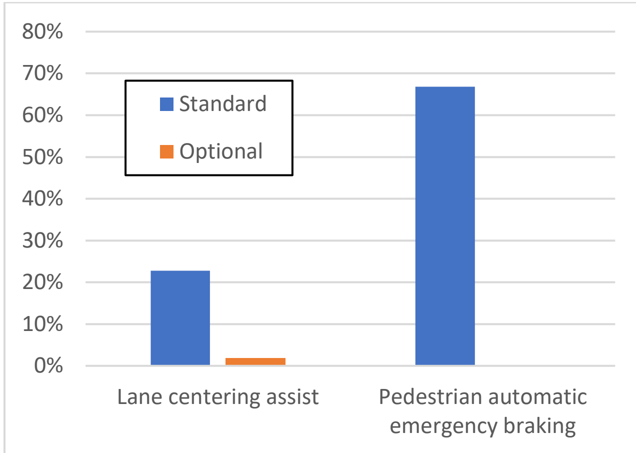

Figure 5. Percentage of Model Year 2021 Vehicles Involved in 2021 Fatal Crashes With Automation Technologies

If it is assumed that pedestrian automatic emergency braking continues to enter the market at rates similar to those of electronic stability control and that fatal crashes provide a representative sample of the entire vehicle fleet, then the total fleet equipped rate for electronic stability control in 2009 is roughly equivalent to the total fleet equipped rate for pedestrian automatic emergency braking in 2022. The 2009 fleet equipped rate for electronic stability control was 25% (HLDI, 2020). The 2022 equipped rate for pedestrian automatic emergency braking can therefore be assumed also to be 25%. These estimates are reported in the first column of Table 5.

Table 5. Estimated 2022 Market Penetration of Vehicle Automation Technologies in the United States

Technology	Vehicles Equipped	Activated When Equipped	Activated of Total Fleet
Adaptive cruise control	16%[a]	57%[b]	9%
Automatic emergency braking	16%[c]	93%[b]	15%
Forward collision prevention	22%[c]	93%[b]	20%
Lane centering assist	8%[d]	57%[e]	5%
Lane departure prevention	15%[a]	65%[b]	10%
Pedestrian automatic emergency braking	25%[d]	93%[e]	23%

[a] Comparing leading adoption rates of similar technologies from model year rates of target technology (Highway Loss Data Institute, 2019).
[b] From observed activation rates at 14 dealership service centers (Reagan et al., 2018).
[c] From Highway Loss Data Institute (2023) equipped vehicle estimates.
[d] Comparing leading adoption rates of similar technologies from model year rates of target technology involved in fatal crashes (Highway Loss Data Institute, 2019; National Center for Statistics and Analysis, 2023; National Highway Traffic Safety Administration, 2023a).
[e] Assumed the same as similar technologies in Reagan et al. (2018).

Connected Vehicles

This approach assumes that installation rates over time were similar for different technologies. Lane centering assist and pedestrian automatic emergency braking have never been mandated or subject to a voluntary agreement among automakers. Electronic stability control, however, became mandatory on new vehicles beginning in 2012 based on Federal Motor

Vehicle Safety Standard (FMVSS) 127, which was announced in 2007. The calculations for lane centering assist rely on electronic stability control equipped rates from 2004 and were probably unaffected by FMVSS 127. The pedestrian automatic emergency braking estimates rely on electronic stability control equipped rates from 2009, which may have been higher than expected due to the FMVSS 127 mandate.

Fatal crashes from all 50 states and the District of Columbia were used to estimate percentages of vehicles equipped with automation technologies. This provided a larger data set than Virginia fatal crashes alone, as there were 4,147 vehicles in the 2021 FARS database that were eligible for additional vehicle automation data (i.e., model years 2017–2022 passenger vehicles from 38 manufacturers), compared to only 70 eligible vehicles in Virginia. The analysis, therefore, assumed that national crashes are representative of Virginia crashes. To test this assumption, fatal crashes from 2017 to 2022 in FARS were analyzed to compare vehicle automation properties of Virginia crashes with those of national crashes.

As NHTSA records automation features only for vehicles of model years 2017 and later, the percentage of model year 2017–2022 vehicles as a function of all model years should be similar in Virginia and nationally. After FARS data were filtered for passenger cars, the percentage of all vehicles that were manufactured between 2017 and 2022 was calculated. The results are shown in Figure 6.

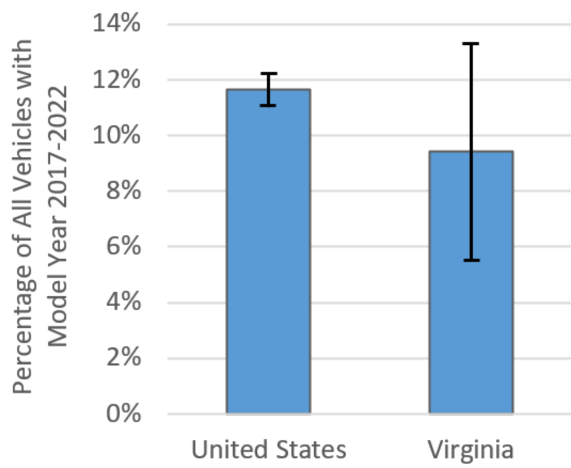

Figure 6. Percentage of All Vehicles Involved in 2017–2021 Fatal Crashes Having Model Year 2017–2022

Error bars were calculated at the 95th percent confidence interval using the central limit theorem and the following equation, where $\hat{p}$ is the mean of the sample and *n* is the sample size. The results showed that the two samples were similar within a margin of error.

$$95\text{CI} = \hat{p} \pm 1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

To determine that technologies were installed at similar rates on model year 2017–2022 vehicles, the rates of lane departure warning systems installed on these vehicles involved in fatal crashes between 2017 and 2021 were compared. Lane departure warning systems were selected as they are the most commonly installed ADAS that are subject to a federal mandate or industry commitments. The rates of vehicles with standard and optional lane departure warning systems were nearly identical in Virginia and nationally. The results are shown in Figure 7.

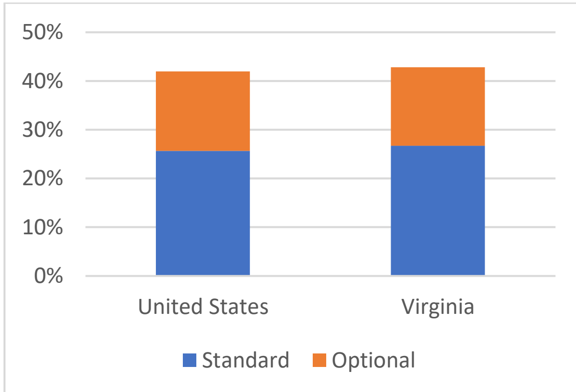

Figure 7. Percentage of Model Year 2017–2022 Vehicles Involved in 2017–2021 Fatal Crashes That Were Equipped With Lane Departure Warning Systems

Activation Rate of Installed Features

To estimate the percentage of those drivers that have the capability to use automation features but leave them deactivated, Reagan et al. (2018) observed vehicles brought in for service at 14 Washington, D.C., metro area dealerships. They found activation rates of 93% for vehicles equipped with automatic emergency braking, 57% for vehicles equipped with adaptive cruise control, and 8% for vehicles equipped with lane departure prevention. The percentage of vehicles both equipped with a technology and not deactivated by the driver (i.e., turned off) is shown in Table 5.

The study by Reagan et al. (2018) is 5 years old and may not reflect current activation rates. Technologies may have become more user-friendly in recent years, leading to higher activation rates. In addition, the study was conducted in the Washington, D.C., metro region, and results may not apply to rural regions. Their findings agree with a General Motors study from 2016 (Flannagan et al., 2016), which found a 91% activation rate for forward collision warning, compared to the activation rate of 93% by Reagan et al. (2018) 2 years later.

To estimate the percentage of the U.S. vehicle fleet where an automation technology was both installed and activated, the "equipped" rate was multiplied by the "activated when equipped" rate. For all registered vehicles in the United States in 2021, 7% were estimated to be running automatic emergency braking, 13% of running adaptive cruise control, and 5% of running lane departure prevention. Actual usage may be far lower, as drivers may elect to have adaptive cruise control "activated" yet not set a desired speed in many situations, effectively not using the technology. These estimates therefore provide an estimated ceiling of usage of AV technologies.

Features Installed and Activated

Estimated market penetration rates of these technologies on all registered vehicles in the United States in 2022 are shown in Table 5. Rates are expressed in three ways. The first column lists the percentage of all vehicles where the technology was estimated to be equipped or installed. Because some technologies are installed but never used, the second column estimates the percentage of equipped vehicles where the technology is not activated, based on observations at 14 dealership service centers in the Washington, D.C., metro region (Reagan et al., 2018). The third column multiples the first and second columns to estimate the percentage of the vehicle fleet where a technology is both installed and activated. Actual usage of the technology may be far below this value, as many drivers with adaptive cruise control activated may still choose not to use it in most scenarios, but it provides a ceiling of potential use rate.

The penetration rate of vehicles with DSRC radios, i.e., connected vehicles, could be estimated from field data. A roadside unit with a DSRC radio could record the transmittal of basic safety messages from vehicles equipped with DSRC. The number of unique basic safety messages received may be compared with vehicle counts from a nearby count station to estimate the percentage of vehicles equipped with DSRC radios. In the absence of a count station, unique DSRC counts could be compared with annual average daily traffic (AADT) to develop an approximate estimate.

The current penetration rate of connected vehicles is negligible. General Motors is the only manufacturer to have sold connected vehicles (U.S. Government Accountability Office, 2022). Between 2017 and 2019, General Motors manufactured approximately 25,000 Cadillacs equipped with DSRC radio but have since ceased due to uncertainty surrounding the use of the DSRC spectrum (U.S. Government Accountability Office, 2022). According to the U.S. Government Accountability Office (2022), Toyota has also delayed plans to equip vehicles with DSRC radios.

The proposed method (i.e., using a roadside unit to detect DSRC-equipped vehicles) to compare unique observed basic safety messages with in-range traffic volumes remains a viable option to estimate connected vehicle penetration rate should production of equipped vehicles resume.

AV Technologies

Many vehicle automation technologies use sensors to detect nearby vehicles, vulnerable road users, and obstacles. This task investigated the feasibility of detecting radar, lidar, and sonar transmissions with these sensors to determine if a given vehicle is equipped with or actively using automation technologies.

Discussions with the Virginia Tech Transportation Institute indicated that this approach was not feasible for several reasons. First, transmissions from several systems running simultaneously create noise, making determination of whether a vehicle is running, for example, blind spot monitoring or adaptive cruise control. Second, some systems transmit when in standby mode and not in use, making determination of actual usage difficult. Third, sensor calibration and positioning are extremely difficult to accomplish in the field. Fourth, many manufacturers are moving to vision-based systems for their automation technologies. As vision-based systems do not transmit light waves but instead read existing light waves, there is no way to detect whether or not they are installed or in use.

Based on these discussions, there appears to be no way to estimate vehicle automation penetration rates using roadside sensors.

Identification of Potential Data Collection Methods

From the analysis in this study, there appear to be three established methods to collect data on automation features in vehicles and one potential method dependent on additional data collection.

vPIC VIN Decoding of Registered Vehicles

VDOT could decode VINs of all registered vehicles in Virginia, or a representative sample of VINs, through the vPIC database to obtain relevant information on optional or standard features for given vehicle makes, models, and years. This strategy is straightforward and requires little effort and would require only a few weeks of processing time to query VINs. One disadvantage of this strategy is that vPIC data on automation features cover only model years 2017 and newer. To estimate the percentages in prior model years, VDOT could leverage HLDI estimates back to 2012 as a proxy for actual vPIC data, thus acquiring a reasonable estimate of market penetration. VDOT could maintain this data as a standalone database, updated annually. Another disadvantage is that the portion of vehicles with optional technologies actually installed is unknown and would need to be estimated using HLDI (2023) rates for similar technologies.

Leverage HLDI Estimates

The HLDI estimates are currently the most sophisticated available. VDOT could use the estimates as published annually and apply those estimates directly. The advantage of this approach is that it requires the lowest effort, as HLDI already publishes these figures. One disadvantage is that the data are not specific to Virginia but rather are presented at a national level. This is not expected to produce significant errors, as the Virginia fleet is not expected to differ from the national fleet in any way that might go beyond errors already used in the assumptions. Another disadvantage is that HLDI does not publish data on several features of interest to Virginia, primarily adaptive cruise control, lane keep assist, and lane centering, and pedestrian automatic emergency braking rates. Adaptive cruise control and lane keep assist installation rates in new vehicles are reported in a different HLDI (2019) report, and these data can be used to estimate fleet penetration rates by comparing new vehicle installation rates of similar technologies with associated total fleet penetration rates. Alternatively, HLDI may be able to share selected data, either specific to Virginia or specific to technologies, e.g., adaptive cruise control, not listed in their total fleet estimations.

VIN Reports by Manufacturer

Estimates could be obtained from manufacturers directly. HLDI currently sends VINs from state crash databases directly to a selection of vehicle manufacturers (Teoh, 2023). The manufacturers are able to provide information on whether certain technologies are installed, eliminating the need to estimate the proportion of vehicles with optional features that are actually installed. HLDI is unable to share their data due to data licensing agreements, but VDOT may be able to negotiate with manufacturers individually, sending the VINs of all or a sample of vehicles registered in Virginia.

This approach has the advantage of providing vehicle-specific installation rates. If the data are comprehensive, they may provide the highest quality estimates. A disadvantage of this approach is generally uncertainty and high levels of effort. It is unclear which manufacturers have these data and are willing to participate, as well as the accuracy of their estimates. The fact that NHTSA must manually collect these data from press releases and vehicle manuals suggests that manufacturers may be unwilling to share vehicle-specific automation installation rates with governments. This approach also requires a significant effort as there are at least 38 separate manufacturers to coordinate with and potentially significant data cleaning required.

Estimates of Actual On-Road Usage

Even though vehicles may have automation features installed, drivers may deactivate systems or leave them activated but rarely use them when driving. Activation rates can be estimated from studies in the literature, of which the current best source is Reagan et al. (2018). Researchers may be able to estimate actual on-road usage rates from future naturalistic driving studies or similar studies.

An alternative approach to estimating actual usage could potentially be to obtain estimates using crash studies. Although not ideal, crashes can serve as a reasonable surrogate for actual driving behavior. In addition, crashes generally warrant extensive investigation of driver behavior and vehicle technologies. If a driver was determined to be using an automation feature immediately prior to a crash, then these crash counts could be compared against those for other crashes with equipped vehicles where the technology was not in use to determine usage rates. For example, Texas recently began reporting vehicle automation use in their state crash database (Texas DOT, 2023). The quality and comprehensiveness of the Texas data are unclear, but were the data to be accurate and comprehensive, then comparing automation feature on-off status in crashes of vehicles equipped with that technology could provide a reasonable estimate of actual usage rates. Findings would need to control for extenuating factors such as lower crash rates on freeways—a vehicle with adaptive cruise control used exclusively on freeways would show up in few crashes despite the heavy use of cruise control.

Yet another approach could leverage information from EDRs. Most new vehicles are voluntarily equipped with EDRs. Vehicles so equipped are required to record certain data at specified intervals in the seconds immediately prior to an activation event *(Federal Register,* 2006). Although current rules do not require EDRs to collect data on vehicle automation status, new rules could require the collection of on/off status of various automation features. Most

Level 2 ADAS vehicles can be described as the integration of separate ADAS functions such as lane keeping, lane centering, adaptive cruise control, and collision avoidance.

Under the FAST Act of 2015, Congress permits the downloading of EDR data for research purposes provided any personally identifiable information and VINs are not disclosed (Davis, 2015). States could require crash investigators to download and record EDR data as part of police investigations into all crashes. Because manufacturers have nonstandard and often complex means to download EDR data, NHTSA could require manufacturers to install simple, uniform methods of data retrieval. A USB port installed under the dash of all new vehicles to download EDR data seamlessly is just one example. In the absence of comprehensive EDR data collection, a large sample of EDR data can be accessed through the Crash Investigative Sampling System (NHTSA, 2023b).

Discussion

The three proposed methods each have unique benefits and challenges. HLDI cannot share vehicle-level data but in discussions has been open to aggregating data at state levels or reporting additional CAV technologies. A consortium of states may be able to negotiate a mechanism by which to fund HLDI's additional effort. This appears to be the approach with the most potential.

Obtaining VIN-level data from manufacturers may be extremely challenging for a state DOT. There are at least 18 core manufacturers, each with policies on data sharing and privacy, any one of which who may not wish to share data with the public sector where the data could become subject to a Freedom of Information Act request. Also, by performing VIN lookups for a single state, then the other 49 states and federal and foreign governments might also submit requests, which could create a substantial burden for manufacturers. As NHTSA has yet to request VIN-level data for vehicles involved in fatal crashes, there are probably significant challenges in obtaining these data.

Obtaining adequate data from crash studies is infeasible with the current level of detail in crash reports and databases. Engagement of ADAS is rarely recorded. Even Level 2 ADAS crashes are reported to NHTSA only on an as-known basis, with most manufacturers having no mechanism to learn of crashes aside from customer reports. EDRs also do not report automation feature use in a consistent way, and without further rulemaking, are unlikely to do so.

CONCLUSIONS

- *Data on active ADAS features used primarily on VDOT-maintained roads are of most value to VDOT.* The automation features of most value to VDOT are those with the highest safety and capacity impacts on VDOT-maintained roads. Penetration rates of features that are predominately used in parking or rearward movement are of lower value to VDOT. Features with active safety components such as lane keep assist have been demonstrated to have greater safety benefits than warning features such as lane departure warning. Penetration rates of active features are of higher value to VDOT.

- *There are currently quality estimates of penetration rates of certain vehicle automation technologies.* HLDI (2023) publishes reasonable estimates of current fleet penetration rates of rear parking sensors, front crash prevention, blind spot monitoring, lane departure warning, front automatic emergency braking, and simultaneous adaptive cruise control and lane centering features. These provide a reasonable estimate of the penetration rate of these technologies in Virginia. HLDI also projects future year equipped rates of these technologies, which have proven to be reliable based on past estimates of current year rates.

- *There are several available methods to estimate rates of other automation technologies.* The HLDI estimates do not estimate penetration rates of certain technologies of interest to VDOT, such as adaptive cruise control, lane keep assist, and lane centering, and pedestrian automatic emergency braking rates. These can be obtained through other methods. VDOT can investigate the rates of standard and optional availability of these features in vehicles involved in fatal crashes by using the FARS database or by using vPIC decoding of all or a sample of registered vehicles in Virginia. The optional and standard availabilities can be used to estimate actual installation rates by comparing them to similar technologies in the HLDI reports.

- *There are no current methods to directly measure automation technology usage rates in on-road driving.* The actual usage of automation technologies in equipped vehicles cannot be directly measured using roadside field equipment. These rates, however, can be somewhat estimated from studies of system activation rates of vehicles brought in for service. These figures can be supplemented by data from naturalistic driving studies and system status in crash reporting as these types of data become available.

RECOMMENDATIONS

1. *VDOT's Connected and Automated Vehicle Program Manager and VTRC should investigate opportunities for data sharing with HLDI.* Currently, the most sophisticated estimates of vehicle automation penetration rates are produced annually by HLDI. Their raw data are protected by data sharing agreements with vehicle manufacturers, but VDOT may be able to access certain aggregated data for high-priority features or data specific to Virginia to improve the quality and scope of their estimates. VDOT should pursue opportunities to leverage HLDI data to develop high-quality penetration rate estimates in Virginia.

2. *VDOT's Connected and Automated Vehicle Program Manager and VTRC should continue to monitor the literature for sources of data on on-road usage rates of vehicle automation technologies.* There are no current methods to directly measure automation technology usage rates in on-road driving. There are a few examples in the literature, however, that can be leveraged to estimate rates based on activation rates of vehicles brought in for service. VDOT should continue to monitor for additional research in the literature regarding activation rates and actual on-road usage rates from naturalistic driving studies, manufacturer reports, AV crash reporting, and other sources.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, within 1 year of the publication of this report VDOT's Connected and Automated Vehicle Program Manager and VTRC will engage in discussions with HLDI regarding data sharing opportunities for fleet-equipped rates for high-priority vehicle automation technologies. VDOT may also engage directly with vehicle manufacturers regarding equipped rates at both the aggregate make/model/year level and at the individual level. Engagement with manufacturers is dependent on a decision of VDOT's Connected and Automated Vehicle Program Manager regarding the benefits of additional data vs. the costs and effort required in obtaining the data. If data on high-value penetration rates cannot be obtained from these engagements, VTRC will attempt to obtain the penetration rates by extrapolating equipped rates of similar technologies at benchmark model years as described in the section "Estimating From Comparable HLDI New Vehicle Installation Rates of Similar Technologies" in this report. Additional analyses will be conducted to verify the accuracy of this approach.

With regard to Recommendation 2, within 6 months of the publication of this report, VDOT's Connected and Automated Vehicle Program Manager and VTRC will begin monitoring research developments in automated driving through participation in the Transportation Research Board, the Connected Vehicle Pooled Fund Study, NCHRP efforts, and a periodic review of the scientific literature. This effort will continue with an emphasis on new developments in methods to estimate on-road usage rates of vehicle automation technologies. This task will be considered complete after 2 years or when reasonable estimates of on-road usage become available, whichever occurs sooner.

Benefits

The benefit of implementing Recommendation 1 is that VDOT may be able to obtain reliable estimates of CAV penetration rates at low cost and effort by leveraging ongoing national-level research. This could eliminate the need for costly expansions to existing registration systems. With high-quality CAV rate estimates, VDOT can improve existing modeling and planning efforts that rely on CAV penetrations as inputs (Heaslip et al., 2020; Miller and Kang, 2019). The CAV Program Manager could utilize these estimates to guide updates to the 2020 VDOT CAV Program Plan.

The benefits of implementing Recommendation 2 are more accurate estimates of on-road usage of CAV technologies, beyond equipped vehicle rates. These estimates would have a direct impact on the performance of already developed models of AV impacts on capacity (Heaslip et al., 2020) and long-range planning (Miller and Kang, 2019). Improved estimates of CAV usage combined with developed models will improve VDOT's ability to predict and forecast the impact of CAVs, allowing for more informed infrastructure planning. An additional benefit of monitoring ongoing research efforts is the cost savings to VDOT by avoiding duplicative research efforts.

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