Independent Statistics & Analysis
U.S. Energy Information Administration

Study of the Potential Energy Consumption Impacts of Connected and Automated Vehicles

March 2017

Independent Statistics & Analysis
www.eia.gov

U.S. Department of Energy
Washington, DC 20585

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Introduction

The U.S. Energy Information Administration (EIA) contracted with Z, INC. to analyze the potential energy consumption implications of connected and automated vehicle technologies on light-, medium-, and heavy-duty on- and off-road vehicles in the United States.

Z, INC. subcontracted with Energetics Incorporated to review the state of automated vehicle technologies and project potential energy effects by:

- Conducting a literature review and interviewing key stakeholders on the current state and projected development of automated vehicles, applicable technologies, and regulations
- Discussing the potential implications of these technologies on future vehicle sales, usage, ownership, and energy consumption
- Developing an Excel-based model to project energy consumption effects of different adoption scenarios based on the *Annual Energy Outlook 2017* Reference case

Recognizing that connected and automated vehicle technologies and regulations are rapidly developing, Energetics recommended further study as more data become available. Suggested further study includes:

- Projection scenarios with all five levels of autonomy and possible ownership models available
- Exploring the effects of human factors on trust, adoption, and usage related to vehicle miles traveled, purchasing, and ownership strategy
- Improving the projections to include vehicle powertrain and fuel type

EIA plans to incorporate into the upcoming *Annual Energy Outlook 2018* a methodology for projecting the effects of connected and automated vehicles on energy consumption, sales, ownership, fuel economy, and related vehicle metrics for light-, medium-, and heavy-duty vehicles. EIA will use this report to help develop inputs and methodology to enable projection scenarios with varying degrees of connected and automated vehicle adoption. Further expansion and refinement will be possible as the technologies evolve and existing and future regulations develop in response to these technologies.

Appendix A

Study of the Potential Energy Consumption Impacts of Connected and Automated Vehicles

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U.S. Energy Information Administration

Prepared by:
Energetics Incorporated
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Under Contract Number DE-EI0002498
Call Order DE-BP0005336

Submitted:
February 22, 2017

Preface

The U.S. Energy Information Administration (EIA) develops energy consumption data and projections (tables and reports) for the United States (U.S.) and the world. These publicly available sources provide extensive information about historical, current, and projected energy consumption (by fuel type) for personal use, industrial, and commercial applications. The transportation sector in the U.S. is a leading energy consumer, and relies primarily on gasoline- and diesel-powered vehicles for on-road travel.

Connected and automated vehicles are under development and testing, and could impact U.S. transportation sector energy use. Autonomous vehicles have the potential to provide opportunities for vehicle manufacturers, users, and policymakers to establish a foundation for improved per-vehicle and transportation infrastructure use while reducing energy use on a mile-of-travel basis. The deployment of these vehicles, as well as their energy impacts, depends on the technologies offered, costs, influence of enabling and/or restrictive policies and legislation, and rate/nature of consumer adoption.

This report considers the impacts of autonomous vehicles through 2050. Because of the early state of the industry and the high level of uncertainty, the 2026–2031 period (10–15 years in the future) was the primary focus for potential impacts.

This report presents results from a comprehensive literature review as well as input from limited expert interviews about the technical, societal, and economic impacts of the deployment of autonomous vehicles. The study focused on determining the potential impacts of these vehicles on energy consumption over time via estimates of potential market penetration.

Acknowledgements

EIA led the conceptual development of this study. EIA would like to recognize the efforts of Z, INC. and Energetics Incorporated staff for conducting the research. Energetics Incorporated would like to acknowledge the industry experts who were interviewed during the research stage for their invaluable input to the project.

Executive Summary

The U.S. Energy Information Administration develops, maintains, and operates the National Energy Modeling System (NEMS), a modular computer simulation model of the U.S. energy system. The Transportation Demand Module component of the NEMS represents energy consumption in the transportation sector dependent on prices, technology, policy, and other relevant factors.

The overarching goal of this project was to estimate the impact of Connected and Automated Vehicles (CAVs) on transportation energy use in the United States through 2050. The project's research examined CAV technology, commercial product availability, consumer/market adoption, driver behavior, and other mechanisms. Because of the early state of the industry and the high level of uncertainty, the focus was primarily on a 15-year horizon. The project results will inform EIA of CAV technology's technical status and the potential impacts on transportation energy use for incorporation into the NEMS model.

CAV technology information was collected through a comprehensive literature review that was augmented by telephone interviews with leading technology developers and researchers. The research results were used to develop this report and data summary spreadsheets and a companion transportation energy use projection model.

Status of Automated Vehicles

Many experts believe connected, automated, and autonomous vehicle technologies may trigger a revolution in personal transportation and mobility. These beliefs are based on the technology's expected societal benefits relating to safety, convenience, reliability, and equity. Automated vehicles control the function of at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) without direct driver input. Autonomous vehicles, also referred to as "fully-automated" vehicles, are a subset of automated vehicles. Autonomous vehicles are capable of self-driving with limited or no connectivity with other vehicles or the infrastructure. The Society of Automotive Engineers International (SAE) categorizes automated driving functionality into distinct levels, summarized below by level of driver involvement during operation:

- **Level 0 (Driver Only)** – No automation; the human driver is responsible for all driving tasks.
- **Level 1 (Assisted)** – The automated system on the vehicle can assist the human driver within the defined use cases (i.e., operating environments and conditions) of the driving task.
- **Level 2 (Partial Automation)** – The automated system on the vehicle conducts multiple parts of the driving task. The human continues to monitor the driving environment and perform the remaining driving tasks.
- **Level 3 (Conditional Automation)** – The automated system conducts multiple parts of the driving task and monitors the driving environment within the defined use cases. The human driver must always be ready to take back control when the automated system requests.
- **Level 4 (High Automation)** – The automated system conducts the driving task and monitors the driving environment within the defined use cases. The human need not take back control when operating in these defined use cases. The human driver assumes control outside of the defined use cases.
- **Level 5 (Full Automation)** – The automated system performs all driving tasks within all use cases that a human driver could perform them.

CAVs require a cooperative system of cameras, sensors (e.g., radar, LiDAR, and sonar), communications technologies (e.g., 5.9 gigahertz dedicated short-range radio communication), automotive technology (e.g., drive-by-wire systems), controllers, and advanced information capabilities (e.g., neural networks, machine learning, and artificial intelligence).

Federal and State Policies

The federal government is involved in this space via the National Highway Traffic Safety Administration (NHTSA), the Federal Highway Administration, and the Federal Motor Carrier Safety Administration, all of which are part of the U.S. Department of Transportation. There are currently no specific federal policies or regulations in place that govern (or restrict) the use, operation, or deployment of automated technologies for light-duty vehicles (LDV) or heavy-duty vehicles (HDV). In 2016 NHTSA issued a Notice of Proposed Rulemaking that would mandate vehicle-to-vehicle connectivity, a related technology, on all new LDVs. NHTSA adopted SAE's automated driving level definitions in late 2016.

States are working to better understand how highly-automated vehicles should be monitored and regulated. At the time of this report, seven states and Washington, DC, had passed policies pertaining to the testing, development, operation, and liability of automated and autonomous vehicles: California, Florida, Michigan, Nevada, North Dakota, Tennessee, and Utah. These policies primarily encourage the testing and future deployment of CAV technology. Most of the remaining states have pending legislation pertinent to CAV technology, or are testing CAV technologies prior to developing regulations.

Scope of Development/Commercialization

Most LDV manufacturers, automotive technology suppliers, and others (e.g., Waymo [previously Google's self-driving car project] and Uber) are active in developing CAVs, with different commercialization timelines. CAV technology is applicable to all vehicle types and is currently available on sedans (compact, midsize, and large), compact hatchbacks, midsize crossover utility vehicles, and minivans. Some manufacturers are opting to progress through all of the automation levels. There is some disagreement within the industry on the path to full autonomy, especially regarding partial autonomy (Level 3) and whether it should be adopted or not. In general, most manufacturers expect to have Level 2 technologies available on product offerings by 2017. Companies who are targeting Level 3 technologies are projecting market availability by 2020. Level 4/5 systems are projected to be introduced into the market between model years 2017-2030. LDV consumer adoption studies typically use surveys to collect data on consumer knowledge and preferences for CAV technology. Numerous studies and press releases have confirmed that LDV consumers are interested in automated vehicles from a technological perspective and because of their perceived benefits and utility, but at varying degrees of trust with incremental automation levels. One survey determined that LDV consumers were willing to pay up to an incremental cost of $3,000, $5,000, and $7,500 for Level 2, 3, and 4 automated driving features, respectively.

Three medium-duty and heavy-duty commercial vehicle applications were identified as probable targets for future automated vehicle development: long-haul freight delivery, local delivery, and transit bus. Most of the development and testing has been for long-haul trucking. Several vehicle manufacturers and technology providers (Volvo Trucks North America, Peterbilt Motors, and Peloton Technology) are initially targeting Level 1 platooning functionality. Others (e.g., Freightliner Trucks and OTTO) are targeting Level 3 and higher automated driving. Urban-operated vehicles, such as delivery and transit applications, will likely see more limited deployment than long-haul/highway vehicles. These urban vehicles will likely have little, or no, benefit from low-level automated vehicle technology, so automation efforts there will likely focus on Level 4 and Level 5 for optimized operation.

Impacts on Safety and Energy

Automated vehicles have the potential to improve vehicle safety and to shift the transportation system's energy use. NHTSA attributes 94% of crashes to human error. High market penetration of automated vehicles could potentially reduce accident rates by eliminating or lowering the causative effects of human error. Reducing the number of accidents has the potential to change the landscape for insurance and liability because of new vehicle policies and services for drivers, vehicle manufacturers, and fleet operators. Even so, insurance industry companies do not anticipate automated vehicles to have a large impact on the vehicle insurance landscape over the next decade. However, various factors (e.g., insurance discounts) may influence the deployment rate and thus the insurance industry's pace of addressing CAVs.

Vehicle energy consumption strongly depends on three interdependent variables: vehicle miles traveled, vehicle efficiency, and the travel cost (basis for consumer adoption). Automated vehicles provide functionality and services that could both increase or decrease energy consumption. The CAV-enabled factors that could have the greatest impact on decreasing energy consumption include: 1) vehicle lightweighting and rightsizing, 2) powertrain electrification, 3) platooning, and 4) eco-driving. Conversely, CAV-enabled factors that could have the greatest impact on increasing energy consumption are: 1) reduced travel cost, 2) higher highway speeds, 3) longer commute distances, and 4) inclusion of previously unserved/underserved user groups (e.g., elderly, disabled, and young people).

Path Forward

The study determined that there are five main challenges that must be addressed to facilitate the expansion of CAV market penetration: 1) technology capability, cost, and cybersecurity, 2) consumer opinion, acceptance, and use, 3) policy and regulation, 4) insurance and liability, and 5) energy and economic impact uncertainties. Despite the challenges, increasing stakeholder investment, research and market penetration support projections that automated vehicles will continue to impact the future transportation landscape.

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List of Acronyms, Abbreviations, and Initializations

3D	three-dimensional
ADAS	Advanced Driver Assistance Systems
ATC	Autonomous Tractor Corporation
BMW	Bavarian Motor Works
CAV	Connected and Automated Vehicle
CMU	Carnegie Mellon University
DARPA	Defense Advanced Research Projects Agency
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIA	U.S. Energy Information Administration
ESC	Electric Stability Control
EV	electric vehicle
GM	General Motors
GPS	Global Positioning System
HD	heavy-duty
HDV	heavy-duty vehicle
HLDI	Highway Loss Data Institute
IIHS	Insurance Institute for Highway Safety
LB	lower bound
LDV	light-duty vehicle
LiDAR	light detecting and ranging
MaaS	Mobility-as-a-Service
MD	medium-duty
MDV	medium-duty vehicle
mph	miles per hour
NEMS	National Energy Modeling System
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
OEM	(vehicle) original equipment manufacturer
PATH	Partners for Advanced Transportation Technology
R&D	research and development
SAE	Society of Automotive Engineers
UB	upper bound
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VMT	vehicle miles traveled

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1. Study Structure

The U.S. Energy Information Administration (EIA) develops, maintains, and operates the National Energy Modeling System (NEMS), a modular computer simulation model of the United States (U.S.) energy system. The Transportation Demand Module is a component of the NEMS that is designed to represent energy consumption in the transportation sector dependent on prices, technology, policy, and other relevant factors. NEMS operates in a national scope and on a regional level of aggregation.

The representation of energy system elements, in the transportation sector and throughout the energy system, depends on assumptions regarding the cost and performance of specific technologies, processes, and the associated behavioral options available to the owners and operators of energy-using equipment. The research results discussed in this report will assist EIA staff in developing or refining Connected and Automated Vehicle (CAV) NEMS modeling assumptions for the United States.

The goal of the project was to research and analyze the current state of development for vehicle connectivity and automation/autonomous technologies and provide estimates of current and future cost, market penetration potential, and impacts on travel demand and vehicle efficiency. Research was conducted to examine CAV technology, market adoption, driver behavior, and other mechanisms that could affect the energy impacts of automated vehicles in the United States through the year 2050. Because of the early state of the industry and the high level of uncertainty, the 2026–2031 (10–15 years in the future) period was of primary interest. All vehicle classes (light-duty [LD], medium-duty [MD], and heavy-duty [HD]) were included in the investigation.

A comprehensive literature review (technical journal articles, trade news, manufacturer press releases, technical conference proceedings, etc.) was performed to identify the state of technology performance, risks, and the potential range of impacts on energy consumption. The literature review was augmented with telephone interviews with several leading technology developers, researchers, and industries affected by automated vehicles (such as insurance and legislative industries). Certain aspects of the research (e.g., insurance and policy/legislation) were conducted to determine the extent that they could alter the energy use projections developed in the project.

A simulation model was also developed for this project with EIA energy use and vehicle population data, assumptions, and projections as inputs to the baseline case. The model uses the data (energy impact, consumer adoption, vehicle categories, commercialization timeline statements, etc.) and assumptions collected in this project as inputs to predict the potential impacts of CAV technology on transportation energy use.

This report summarizes the model development and the modeling results. Topics that apply to both the LDV and MDV/HDV vehicle categories are discussed first, followed by LDV-specific and MDV/HDV-specific data and findings. Project findings are fully documented in several related files: (1) this report, (2) two companion Microsoft Excel spreadsheets cataloging the collected data (one for LDVs and one for MDVs/HDVs), and (3) a companion Microsoft Excel-based simulation model. Full details of the model are included in the model file. The simulation was developed as a stand-alone model, but could be modified and improved to be integrated into the overall NEMS modeling structure.

The project findings and projections will be used to further EIA's understanding of how CAVs could affect transportation energy use in the U.S. This will inform future application of automated vehicle technology representation and adoption in the NEMS transportation model.

2. Automated Vehicle Technology Introduction

Many experts predict that automated vehicle technology will enable a shift in the future of personal transportation, mobility, and freight transportation. This view is primarily fueled by automated vehicles' potential social benefits, namely improved safety, convenience, reliability, and equity. Many industry, government, and academia researchers insist that automated systems will be safer than human drivers and that robust driverless hardware and software systems will be available and affordable for the average consumer sooner than the expectations established just a few years ago; in fact, several automated features are already being integrated into production vehicles.

The U.S. Department of Transportation (DOT) defines automated vehicles as "those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, and/or braking) occur without direct driver input."[1] Autonomous vehicles are a subset of automated vehicles in which self-driving is possible with limited or no connectivity with other vehicles or infrastructure. Much of the industry has adopted the term "Connected and Automated Vehicle" to describe vehicles with any level of connectivity and/or automation capability. "Connected" implies communication between a vehicle and an outside entity. This connection includes Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and any other connectivity (Vehicle-to-Everything [V2X]). Connectivity can provide efficiency and safety benefits independent of, and in conjunction with, automation.

DOT's National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers International (SAE) each divide automated functionality into distinct levels. NHTSA's work focused on vehicle capabilities, while SAE categorized the technology by level of driver intervention and/or attentiveness required for operation. In 2016, NHTSA agreed to adopt the SAE Level definitions to avoid redundancy and confusion. NHTSA's summary of this classification system[2] is below, followed by a reference diagram (see Figure 1).[3]

- **Level 0 (Driver Only)** – No automation; the human driver is responsible for all driving tasks.
- **Level 1 (Assisted)** – The automated system on the vehicle can assist the human driver within the defined use cases (i.e., operating environments and conditions) of the driving task.
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- **Level 5 (Full Automation)** – The automated system performs all driving tasks within all use cases that a human driver could perform them.

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[1] U.S. Department of Transportation, "Automated Vehicles," accessed January 13, 2017.

[2] National Highway Traffic Safety Administration, *Federal Automated Vehicles Policy*, accessed September 26, 2016.

[3] TRW Automotive, "Autonomous Cars Must Progress through these 6 Levels of Automation," accessed November 8, 2016.

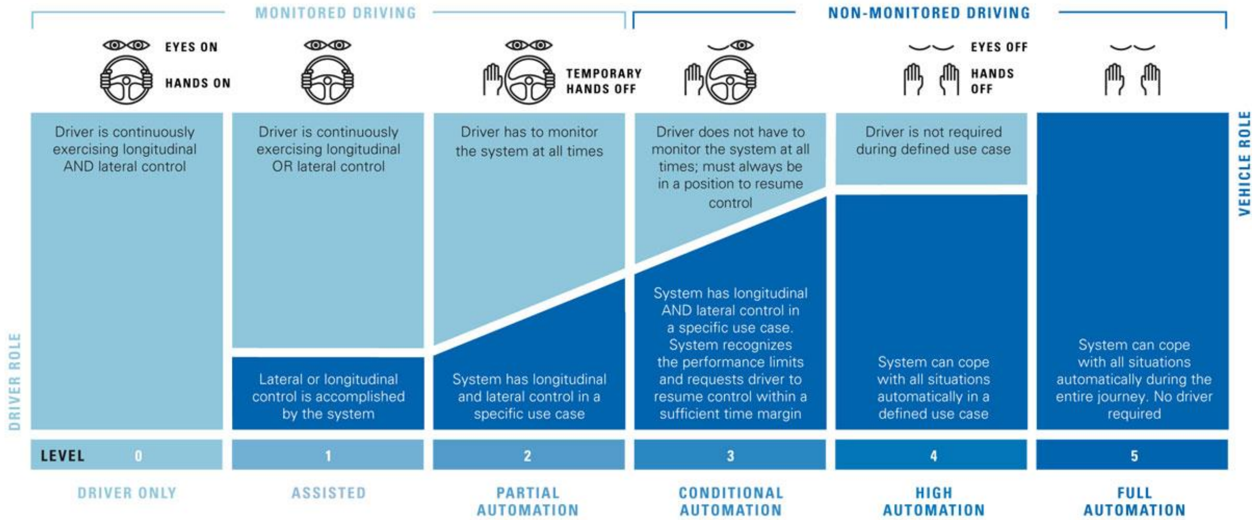

Figure 1: Description and comparison of automated vehicle functionality levels[4]

[4] TRW Automotive, "Autonomous Cars Must Progress through these 6 Levels of Automation," accessed November 8, 2016.

3. Automated Vehicle Policy, Legislation, and Regulations

A wide range of potential impacts on the testing and deployment of CAVs was investigated to determine whether/how they could affect vehicle energy use, including policy and legislation. The focus was relatively narrow, i.e., to determine whether strong evidence exists that current or likely future CAV-related policies/legislation could alter energy use projections. This section is not intended to be a comprehensive investigation into CAV policy and legislation.

The government regulation of this technology is divided between state and federal responsibilities. Typically, federal regulations oversee vehicle design and safety while state regulations are limited to licensing.[1]

Automated vehicle technology can be deployed in states without new federal regulations. However, it has been stated that national regulatory consistency would be helpful. A patchwork of separate regulations by states would likely complicate automated vehicle use for interstate travel. This could prevent the legal operation of certain automated vehicle technologies across state lines and would likely reduce automated vehicle use.

Note that government–industry partnerships (federal or state) could also influence the rollout of new vehicle technologies to ensure their effectiveness and safety while on the roadways. Stakeholder partnerships are often quite complex and may address high-level engineering specifications, safety standards, manufacturer compliance, end users' needs, and enforcement.

3.1 Federal regulation

The federal level of involvement in vehicle systems includes specific performance for new technology. The federal agencies with oversight responsibility for automated-related factors on the nation's highways include NHTSA, the Federal Highway Administration, and the Federal Motor Carrier Safety Administration (FMCSA). NHTSA has the broad responsibility of reducing deaths, injuries, and financial losses due to vehicle accidents. FMCSA serves a similar purpose for large trucks and buses. These organizations' primary strategies to improve commercial vehicle safety include developing and enforcing regulations; using information systems to target safety regulations; educating carriers (i.e., vehicle owners), drivers, and the public; and partnering with stakeholders to reduce truck and bus accidents.

There are no specific federal policies or regulations in place that govern (or restrict) the use, operation, or deployment of automated technologies for LDVs, MDVs, or HDVs. NHTSA has stated that many vehicle technologies are deployed without regulation being in place that allows their use. However, NHTSA makes it clear that technologies cannot pose an "unreasonable risk to safety."[2] Because of this, many technologies see significant market penetration before standards are developed. One factor leading to this situation is that there is typically a five- to eight-year timeframe for regulation development and activation.[3]

NHTSA released a best-practices policy guidance document on fully autonomous vehicles on September 20, 2016. This guidance may encourage consistency on automated vehicle policy among the states

[1] Anderson, B., "Safety Perspectives of Connected and Automated Vehicles," presentation at I-95 Corridor Coalition Connected and Automated Vehicles Conference: What States Need to Know, 2016.

[2] Ibid.

[3] Ibid.

without setting pre-emptive federal policy. This document recognizes that the development of this technology is inevitable, looks to establish early guidance to enhance safety aspects, and maintains flexibility. This flexibility demonstrates that NHTSA is aware that the technology and applications for automated vehicles will evolve over time. The open language allows alterations based on input from industry leaders and the public. The purpose of this policy is to accelerate the use of automated vehicle technology and act as a guidance document rather than a strict rule. This approach helps guide industry stakeholders to safe and effective design, development, testing, and deployment of this technology.[4]

The DOT (including NHTSA and the Federal Highway Administration) also studies connectivity policy and guidance, a key enabler for automated vehicle technology. In December 2016, NHTSA released a proposal for mandatory V2V connectivity capability on cars and light trucks, citing significant potential safety benefits.[5] The document states that the Federal Highway Administration will follow up with guidelines to states for V2I communications. Further federal action through a regulation or mandate could rapidly accelerate both partial and fully autonomous technology deployment timelines. The Insurance Institute for Highway Safety (IIHS) stated that a federal mandate for 2016 model vehicles could increase penetration of automated safety technologies by as much as six years.[6]

3.2 State regulation

State policymakers are working to understand how automated vehicles should be monitored and regulated. Because this is a relatively new technology, there are insufficient on-the-road test data to establish comprehensive regulations at this time (outside of Google/Waymo's work in California). Avoiding a patchwork of incongruous policies and regulations is critical. Consumers might be dissuaded from purchasing automated vehicles if the level of autonomy has to be adjusted every time they cross state lines. The Council of State Governments recently followed NHTSA's 2016 automated vehicle policy guidance with its Resolution on State and Federal Regulation of Autonomous Vehicles.[7] This resolution asserted that states should enact legislation to allow for the testing and deployment of automated vehicles in line with NHTSA's guidance. Two industry lobbying groups, the Alliance of Automobile Manufacturers and Global Automakers, stated that there is a strong need for a consistent, nationwide approach to automated vehicle technology policy and regulation.[8,9]

Additional complications exist for manufacturers to test CAV technologies on the road. One recent (December 2016) example was in San Francisco, California, where Uber implemented an autonomous Volvo Cars XC90 test fleet. The company assumed a permit was not needed because an engineer was in the vehicle. However, the California Department of Motor Vehicles sent Uber a letter the day after testing began insisting that Uber stop its testing immediately and obtain permits for the vehicles before

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[4] National Highway Traffic Safety Administration, *Federal Automated Vehicles Policy*, accessed September 26, 2016.

[5] National Highway Traffic Safety Administration, "U.S. DOT Advances Deployment of Connected Vehicle Technology to Prevent Hundreds of Thousands of Crashes," December 13, 2016.

[6] Highway Loss Data Institute, "Predicted Availability of Safety Features on Registered Vehicles – A 2015 Update," *HLDI Bulletin*, 32 no. 16 (2015), accessed November 29, 2016.

[7] The Council of State Governments, *Resolution on State and Federal Regulation of Autonomous Vehicles*, 2016.

[8] Alliance of Automotive Manufacturers, "Auto Alliance Response to Guidance on Autonomous Vehicles," September 20, 2016.

[9] Global Automakers, *A Path Toward Consistent Automated Vehicle Policy*, accessed January 17, 2017.

continuing. California eventually revoked the registrations for Uber's test fleet, and the company ended testing until further notice.[10]

To provide helpful and consistent policy decisions, states will need to work with the private sector to grasp the technology's implications for economy, safety, and efficiency as quickly as possible.

3.2.1 Enacted state policies

Seven states (California, Florida, Michigan, Nevada, North Dakota, Tennessee, and Utah) and Washington, DC, have passed policies pertaining to the testing, development, operation, and liability of automated vehicles. Of these, only Nevada requires a Certificate of Compliance for specific technical requirements for CAVs and special endorsements for Department of Motor Vehicles and state drivers.[11] Arizona's governor issued an executive order that requires the state government to take the necessary steps toward testing and deployment of automated vehicles on public roads,[12] and Louisiana enacted a law that defines "autonomous technology" but does not offer guidance or regulation on testing and deployment.[13]

Table 1 indicates the currently enacted state-level CAV policies.[14] Each policy addresses one or more of the following aspects of CAVs:

- **Definition**. Most current state policy does not have specific language available to describe automated vehicles and their operation, so states add it to the current regulations for future use.
- **Testing**. This includes permitting manufacturer vehicle testing on public roads and any other restrictions/allowances associated with these efforts. Additionally, some states have commissioned DOT or other agencies to study automated vehicle technology and its impacts.
- **Operation**. Several states have started to develop regulations for drivers who operate and/or monitor autonomous vehicles, e.g., allowing cell phone use when the car is operating in fully autonomous mode. Many also explicitly note that there are no existing prohibitions of automated driving or that local governments are not authorized to create such prohibitions.
- **Liability**. Many of the states below address liability in the case of a vehicle original equipment manufacturer (OEM)-produced vehicle that has been modified with a third-party automated driving system, generally stating that the vehicle OEM is not liable for any damages (unless the original, non-automated vehicle was flawed in some way).

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[10] Mele, Christopher, "In a Retreat, Uber Ends Its Self-Driving Car Experiment in San Francisco," *New York Times*, December 21, 2016.

[11] Anderson et al., *Autonomous Vehicle Technology: A Guide for Policymakers*, RAND Corporation (Santa Monica, California, 2016).

[12] Office of the Governor Doug Ducey, "Self-Driving Vehicle Testing and Piloting in the State of Arizona; Self-Driving," Executive Order: 2015-09.

[13] Louisan State Legislature, "HB1143 by Representative Julie Stokes," accessed January 13, 2017.

Table 1: Currently enacted state-level policies pertaining to automated vehicles

State	Bill	Introduced, Last Action	Scope of Coverage
California	AB 1592	1/6/2016, 9/29/2016	Testing
	SB 1298	2/23/2012, 9/25/2012	Definition, testing, and operation
District of Columbia	B19-0931	9/19/2012, 1/23/2013	Definition, testing, operation, and liability
Florida	HB 7027	12/2/2015, 4/4/2016	Definition, testing, and operation
	HB 7061	1/12/2016, 4/14/2016	
	CS/HB 1207 CS/HB 1207	1/4/2012, 4/16/2012	
	SB 52	11/19/2012, 5/29/2013	Operation
Louisiana	HB 1143	3/1/2016, 6/2/2016	Definition
Michigan	SB 0169	2/7/2013, 12/26/2013	Definition and testing
	SB 0663	11/6/2013, 12/27/2013	Liability
Nevada	AB 511	3/28/2011, 6/17/2011	Definition, testing, and operation
	SB 140	2/10/2011, 6/17/2011	Operation
	SB 313	3/20/2013, 6/2/2013	Liability and operation
North Dakota	HB1065	1/6/2015, 3/26/2015	Testing
Tennessee	SB 1561	1/12/2016, 2/1/2016	Operation
	HB 1564		
	HB 616	2/10/2015, 5/6/2015	
	SB 598		
Utah	HB 280	2/3/2016, 3/23/2016	Testing
	HB 373	2/20/2015, 3/27/2015	

3.2.2 Pending state policies

Most of the states not mentioned in the previous section have pending legislation pertinent to automated vehicle technology, or are testing automated vehicle technologies prior to developing regulations.[14] As an example of the latter, Pennsylvania is working to implement automated vehicle regulation in line with the recent NHTSA guidance through its Autonomous Vehicles Testing Policy Task Force.[15] Pennsylvania has allowed Uber and Volvo to test autonomous vehicles on the road in Pittsburgh before this legislation is enacted. Pennsylvania did not develop regulations as a first step, because the regulatory process would

[14] Weiner, Gabriel, and Bryant Walker Smith, "Automated Driving: Legislative and Regulatory Action," December 23, 2016.

[15] Saksa, Jim, "As PennDOT Prepares for Driverless Vehicles, Other State Agencies Stall," *PlanPhilly*, September 20, 2016.

slow the progress of these technologies. Instead, the state will develop a guiding automated vehicle testing policy.[16]

Table 2 summarizes a sampling of the CAV-related state policies and legislation that are under development as of this writing.[17]

Table 2: Sampling of state-level policies related to automated vehicles under development

State	Policy/Policies	Date Introduced	Status
Arizona	HB 2167	January 2013	Introduced
Colorado	SB 13-016	January 2013	Postponed indefinitely
Hawaii	HB 1461	January 2013	Committee
Massachusetts	HB 3369	January 2013	Committee
Michigan	SB 0169	February 2013	Passed March 2014
New Hampshire	HB 444	January 2013	Inexpedient to legislate
New Jersey	A2757	May 2012	Committee
New York	S4912	May 2013	Committee
Oklahoma	HB 3007	January 2012	Committee
Oregon	HB 2428	January 2013	Committee
South Carolina	HB 4015	April 2013	Committee
Texas	HB 2932	March 2013	Committee
Washington	HB 1649	January 2013	Reintroduced
Wisconsin	SB 80	March 2013	Conducted fiscal estimates

[16] Kopko, M., "Pennsylvania's Program," presentation at the I-95 Corridor Coalition Connected and Automated Vehicles Conference, 2016.

[17] Anderson et al., *Autonomous Vehicle Technology: A Guide for Policymakers*, RAND Corporation (Santa Monica, California, 2016).

4. Insurance and Liability

As part of its effort to assess the potential energy impacts of CAVs, the project investigated how CAVs are insured to determine whether/how insurance policy may affect CAV adoption and energy use. The goal was to ascertain whether there is strong evidence that insurance policy regarding CAVs at this early stage could impact market adoption and use of CAVs. This section is not intended to be a comprehensive investigation of insurance and CAVs.

A 2015 McKinsey & Company report estimated that driverless cars could reduce traffic accidents by 90%.[1] The study indicated that this would have public health benefits and would change the automotive insurance landscape, which took in nearly $200 billion in premiums in 2014.[2] The insurance industry is engaged in the transformation that automated vehicle technologies are projected to have on vehicle safety and operation. In December 2015, an article in the *Delaware Business Times* reported that "self-driving cars could turn insurance industry on its head."[3] Similar stories have been reported by the *Wall Street Journal*, *Los Angeles Times*, and *Bloomberg*. Each news source has portrayed driverless cars as an imminent threat that insurers are "scrambling to figure out" to survive.[4,5,6] The insurance industry is aware of the development of automated vehicle technologies. Although most insurers have been slow to take action, some have been making strategic investments to prepare themselves for a transition in the industry.

Insurance companies are long-time leaders in the development of technologies, policies, and strategies to reduce losses (e.g., deaths, injuries, and property damage) from crashes on the nation's roads. State Farm and other insurers helped found the IIHS in 1959. In 2015, insurers funded a $30 million expansion of the IIHS's crash-testing facility.[7] Automotive insurers also support the Highway Loss Data Institute (HLDI), which shares and supports the IIHS mission through scientific studies of insurance data representing the human and economic losses resulting from the ownership and operation of vehicles.[8] IIHS and HDLI are working toward a vision of a "zero crash future." These organizations' members cover 85% of the U.S. private passenger insurance market.[9]

As shown in Figure 2, crash deaths per billion vehicle miles have steadily declined since 1950 with vehicle deaths totaling 32,675 in 2014.[10] IIHS President Adrian Lund noted that although automated

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[1] Bertoncello, Michele, and Donminic Wee, "Ten Ways Autonomous Driving Could Redefine the Automotive World," McKinsey & Company, June 2015.

[2] Insurance Information Institute, "Private Passenger Cars Insured in the Shared and Voluntary Markets, 2014," accessed November 29, 2016.

[3] Canavan, K., "Self-Driving Cars Could Turn Insurance Industry on Its Head," *Delaware Business Times*, December 9, 2015.

[4] Scism, Leslie, "Driverless Cars Threaten to Crash Insurers' Earnings," *The Wall Street Journal*, July 26, 2016.

[5] Peltz, James. "Self-Driving Cars Could Flip the Auto Insurance Industry on Its Head," *Los Angeles Times*, June 20, 2016.

[6] Buhayar, Noah, and Peter Robison, "Can the Insurance Industry Survive Driverless Cars?," *Bloomberg*, July 30, 2015.

[7] Scism, Leslie, "State Farm Plans for a Driverless Future," *The Wall Street Journal*, July 27, 2016.

[8] Insurance Institute for Highway Safety, Highway Loss Data Institute, "About the Institute," accessed November 29, 2016.

[9] Zuby, David, "Do Smart Cars Equal Safer Roads?," presented at the Property Casualty Insurers Association of America Capital Engagement Series, Washington, DC, July 29, 2014.

[10] Lund, Adrian, "Highway Safety: Past, Present and Future," presented at the Lifesavers Conference, Long Beach, California, April 3, 2016.

vehicles may be instrumental in achieving a "zero crash future," the technology is still decades away. Mr. Lund also noted that there are basic actions applicable to all vehicles (conventional and automated) that could save thousands of lives without the need for advanced technologies.

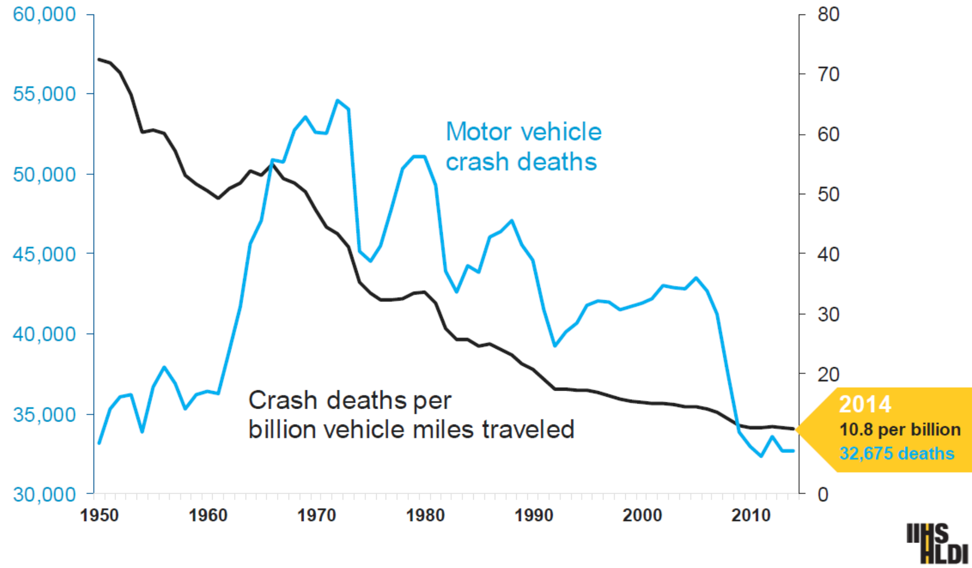

Figure 2: Motor vehicle crash deaths and deaths per billion vehicle miles traveled[11]

NHTSA found that in 2013 10% of fatal crashes and 18% of injury crashes were reported as distraction-affected crashes.[12] While automated features such as front collision warning can help mitigate some of the risks of distracted driving, additional risks may stem from inappropriate use of automated features. In particular, Level 3 automation presents an inherent risk in that drivers are given permission to turn their attention elsewhere at some times but must be ready to take control at a moment's notice. David Kidd, Senior Research Scientist at the IIHS Vehicle Research Center, indicated that "these [lane-keeping assistance] systems are immature. They can't improvise or adapt to normal changes in the driving environment like humans can."[13] From their experience, IIHS feels that anything less than fully automated driving will introduce new challenges for the people who use them, because drivers could fail to notice when the systems reach their limits and will have trouble resuming control of the vehicle.[14]

Regardless of the current technology maturity level and risks associated with automated vehicle technologies, several crash avoidance and mitigation systems (such as front crash prevention, adaptive headlights, land departure warnings, and blind spot assist) are already available, and some are becoming standard features on new car models. HLDI tracks automated vehicle technology deployment data, claims

[11] Lund, Adrian, "Highway Safety: Past, Present and Future," presented at the Lifesavers Conference, Long Beach, California, April 3, 2016.

[12] National Highway Traffic Safety Administration, *Traffic Safety Facts: Distracted Driving 2013* DOT HS 812 132, April 2015.

[13] Insurance Institute for Highway Safety, Highway Loss Data Institute, "IIHS-HLDI Test Drives Uncover Driver Assistance System Quirks," *Status Report,* 51 no. 8. (2016), Special Issue: Autonomous Vehicles.

[14] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Robot Cars Won't Retire Crash-Test Dummies Anytime Soon," *Status Report*, 51 no. 8 (2016), Special Issue: Autonomous Vehicles.

reduction statistics, and the predicted availability of safety features on registered vehicles for years and makes the data publicly available on its website.[15] Initial evaluations of automated safety technologies have shown reductions in liability claim frequencies—up to 39% for bodily injury liability claims for forward collision warning systems and up to 35% for automated braking systems (see Figure 3).[16]

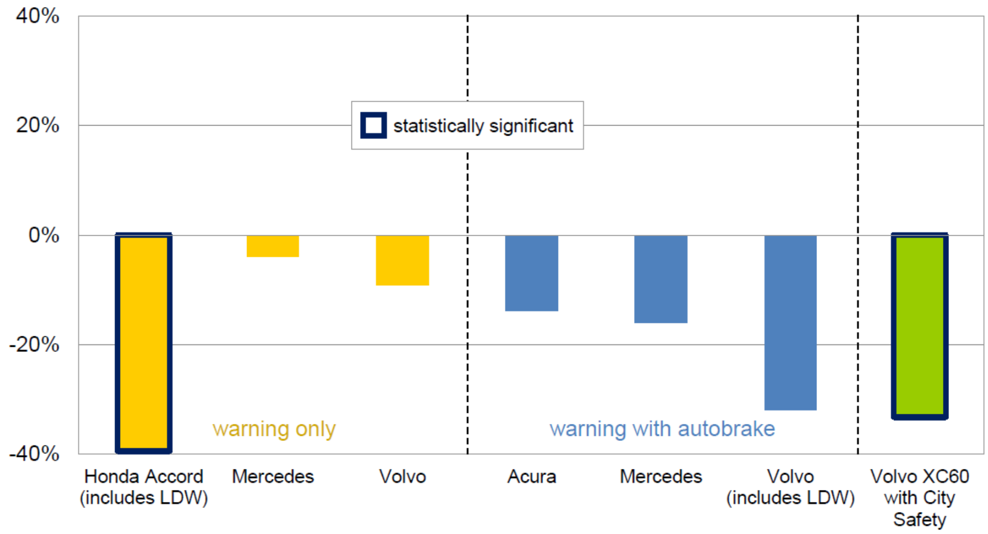

Figure 3: Effect of front crash prevention on bodily injury liability claim frequency[17]

The introduction of these technologies and their potential to lower claim frequency should not come as a surprise to insurers. Neither should the long timeframes that accompany fleet penetration of new technologies. For example, Figure 4 shows the predicted percentage of registered vehicles with available Electric Stability Control (ESC), which was introduced in 1995. ESC was required on all new LDVs beginning in 2011 (16 years after its commercial introduction). It is predicted that ESC will not be installed on 95% of registered vehicles until 2032, which is 37 years after its introduction and 21 years after it became a required feature.[6] Similar timeframes are exhibited for other crash avoidance systems, and fully automated systems could follow a similar trajectory. According to Matt Moore, HLDI vice president, "Even if the U.S. government were to require all new vehicles sold to be autonomous tomorrow, it would take at least 25 years until nearly 95% of the vehicles on the road would have the capability."[18]

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[15] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Automation and Crash Avoidance," accessed November 29, 2016.

[16] Zuby, David, "Do Smart Cars Equal Safer Roads?," presented at the Property Casualty Insurers Association of America Capital Engagement Series, Washington, DC, July 29, 2014.

[17] Ibid.

[18] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Robot Cars Won't Retire Crash-Test Dummies Anytime Soon," *Status Report,* 51 no. 8 (2016), Special Issue: Autonomous Vehicles.

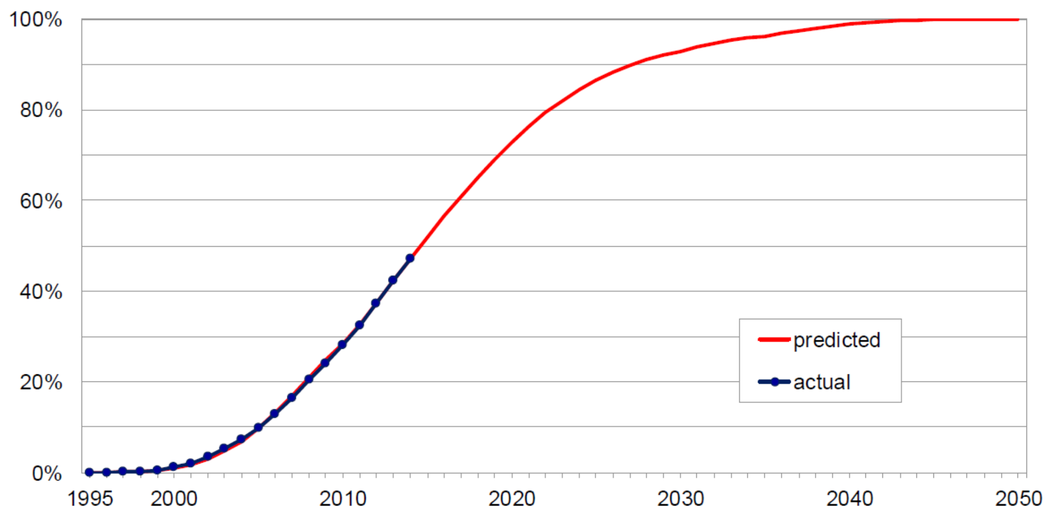

Figure 4: Percentage of registered vehicles with available ESC (actual and predicted)[19]

Insurance industry executives' responses to a 2016 KPMG survey indicate they believe the effects of self-driving cars will not have a significant impact on their business over the next decade. However, after more than 11 years, 35% of participants expect a somewhat significant impact, and 49% of participants expect a significant or extremely significant impact. Another finding was that 94% of respondents expect liability to change, while 52% expect property damage coverage to change. Additionally, 84% of respondents expect insurance claim frequency to decrease, and 71% expect premium per policy to decrease because of driverless vehicles.[20] Decreased claim frequency is expected considering HLDI insurance research on automated safety features to date.[21] However, cars with automated safety features are not yet the majority of vehicles on the road. According to California Insurance Commissioner Dave Jones, there have not been significant enough changes in claims or experience to warrant changes in customer rates.[22]

Despite an apparently clear awareness that a significant impact on the insurance business is looming and that automated driving safety features are indeed helping to reduce insurance claims, the majority of KPMG survey respondents do not plan to address the impact of driverless vehicles over the next 12–18 months.[23]

Some insurers, however, are preparing for decreased accident frequency and premium rates. In 2014, State Farm Insurance became a founding member at the University of Michigan's Mobility Transformation Center and actively collaborates with industry stakeholders to understand what is needed to tailor policies for automated vehicles or make arrangements with automotive and equipment

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[19] Lund, Adrian, "Highway Safety: Past, Present and Future," presented at the Lifesavers Conference, Long Beach, California, April 3, 2016.

[20] Albright et al., *Automobile Insurance in the Era of Autonomous Vehicles: Survey Results*, KPMG, June 2015.

[21] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Automation and Crash Avoidance," accessed November 29, 2016.

[22] Peltz, James, "Self-Driving Cars Could Flip the Auto Insurance Industry on Its Head," *Los Angeles Times*, June 20, 2016.

[23] Albright et al., *Automobile Insurance in the Era of Autonomous Vehicles: Survey Results*, KPMG, June 2015.

developers.[24] Allstate Insurance Company is studying CAVs. The company is also considering other new revenue streams, such as selling coverage for mobile phones or monetizing existing data from tracked driving behavior, to compensate for possible drops in rates due to proliferation of CAV technology.[25] The concept of diversifying insurance revenue streams is in-line with predictions from Deloitte that the insurance industry will need to adapt its business model to a new mobility ecosystem. As shown in Figure 5, future insurance coverage could involve a variety of stakeholders and new types of coverage, including a shrinking share of traditional policies, car- and ride-sharing policies, stop-loss and other catastrophic coverage policies for vehicle original equipment manufacturers and fleet operators, self-driving vehicle policies, and other services.[26]

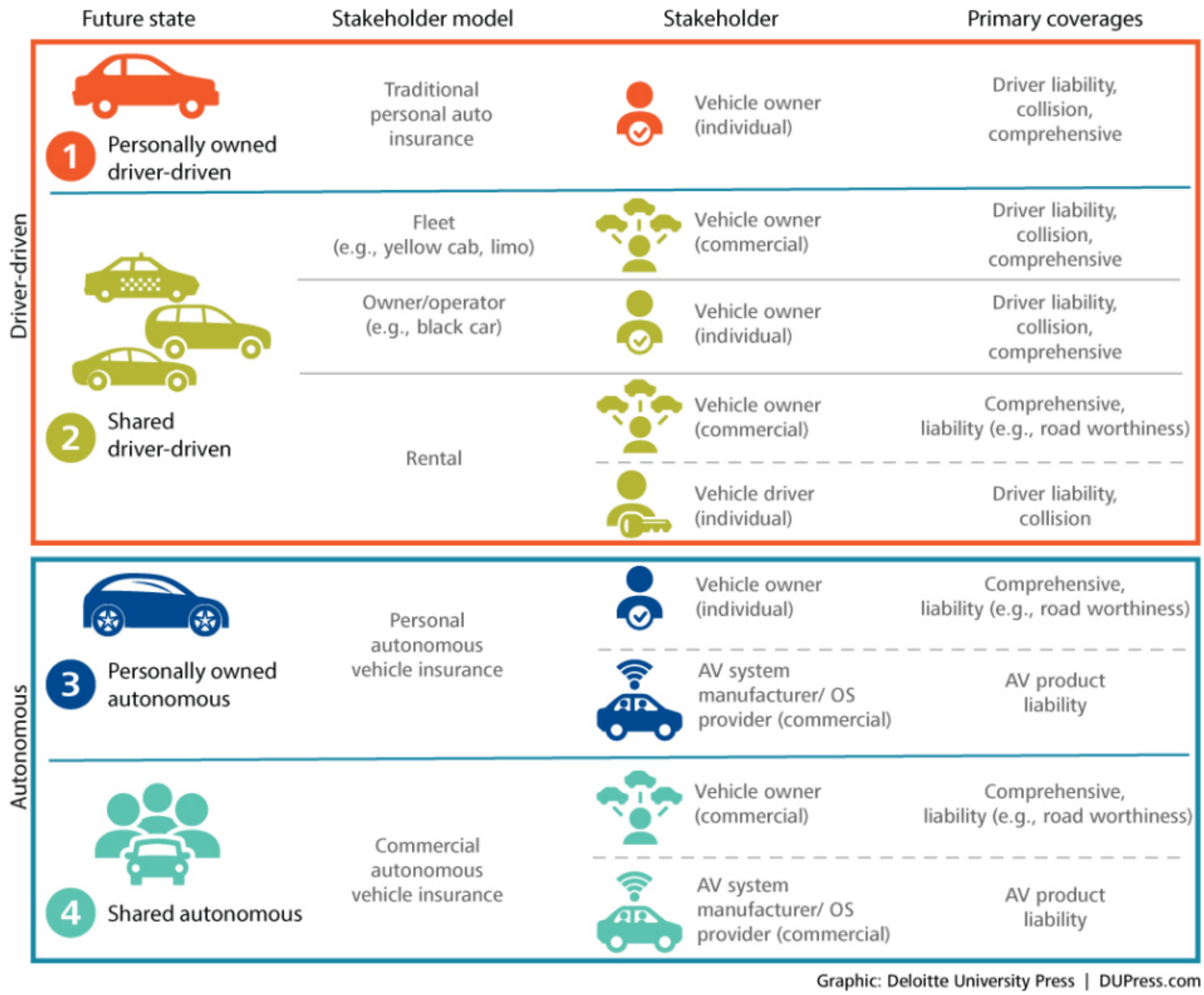

Figure 5: Stakeholders and insurance products in the future of mobility

[24] Scism, Leslie, "State Farm Plans for a Driverless Future," *The Wall Street Journal*, July 27, 2016.

[25] Buhayar, Noah, and Peter Robison, "Can the Insurance Industry Survive Driverless Cars?," *Bloomberg*, July 30, 2015.

[26] Deloitte University Press, "Insuring the Future of Mobility: The Insurance Industry's Role in the Evolving Transportation Ecosystem," June 27, 2016.

Insurers have been and are still committed to the development of safer vehicles and roadways, and they will collectively remain committed to whatever technologies and/or policies can help move the needle toward a zero-crash future, despite the financial implications on the traditional automotive insurance market. While self-driving cars are not expected to have an impact on insurance over the next decade, various factors may influence the rate of deployment and thus the insurance market. Insurance discounts for vehicles with automated driving safety features may help accelerate technology adoption, but ultimately it is the consumers and state/federal regulators that will most greatly influence the rate of automated vehicle deployment (as stated previously, estimates indicate that federal mandates could accelerate automated vehicle technology penetration by as much as six years).[27] Regardless of the rate of deployment, insurers may need to diversify and rethink their offerings to meet the demands of new mobility modes.

[27] Highway Loss Data Institute, "Predicted Availability of Safety Features on Registered Vehicles – A 2015 Update," *HLDI Bulletin*, 32 no. 16 (2015), accessed November 29, 2016.

5. Automated Vehicle System Technology

Connected and Automated Vehicles require a cooperative system of sensors, communications technologies (e.g., 5.9 gigahertz Dedicated Short Range Communications), automotive technology (e.g., drive-by-wire systems), controllers, and advanced information capabilities (e.g., neural networks, machine learning, and artificial intelligence). While highly- or fully-automated (Level 4 and Level 5) vehicles are the end goal of this technological confluence, lower level (e.g., Levels 1 and Level 2) capabilities are being commercialized along the way as stepping-stones. These technologies help the driver with vehicle control and are labelled as Advanced Driver Assistance Systems (ADAS). Figure 6 provides an example of a full ADAS technology suite, along with the different devices that enable their function.

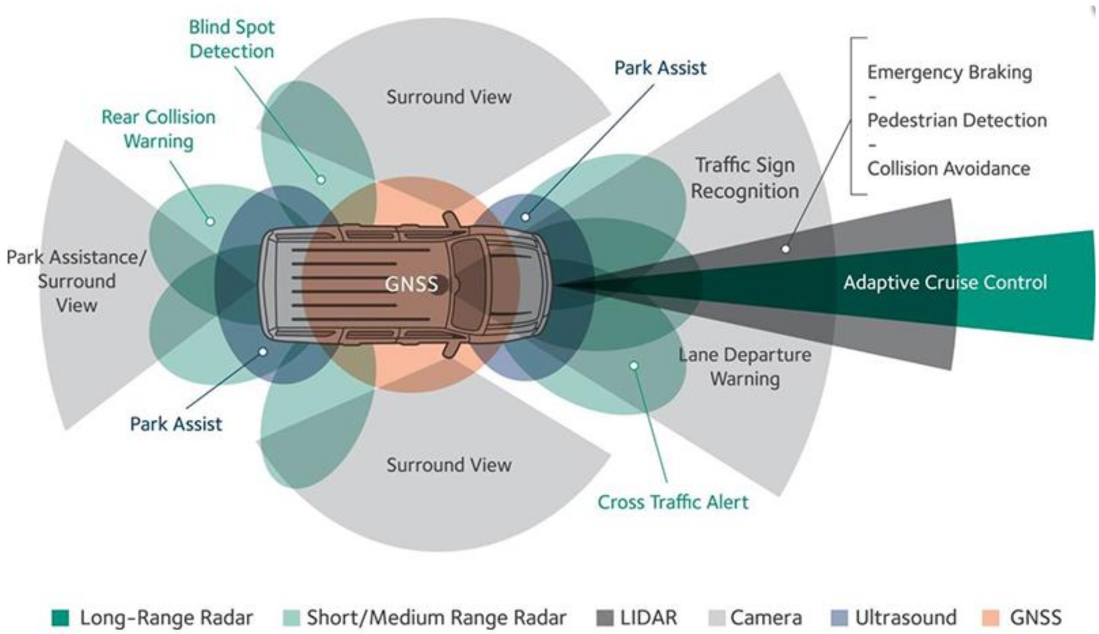

Figure 6: Summary of typical automated vehicle hardware and function[1]

5.1 Mapping and localization

Automated vehicles must be able to perceive and comprehend both passive and active elements surrounding them. The vehicles must be capable of mapping (perceiving and processing) their full three-dimensional (3D) environment in real-time. Global Positioning Systems (GPSs) are accurate to a 1-meter resolution. This has generally been sufficient for in-vehicle navigation systems; however, this resolution is insufficient for safe vehicle autonomy. An accuracy of 10–15 centimeters is required to accurately perceive the vehicle's environment and provide the high-resolution localization data needed for safe vehicle autonomy. To achieve this, manufacturers depend on sensor arrays.[2,3]

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[1] NovAtel, "High-Precision GPS for Autonomous Vehicles," accessed December 5, 2016.

[2] Green Car Congress, "Delphi & Mobileye to Showcase Centralized Sensing Localization and Planning (CSLP) Autonomous Driving System in Public Demo at CES 2017," November 30, 2016.

[3] TomTom, *HAD Map*, 2015.

5.1.1 Relative localization

Radar sensing uses radio waves to determine the physics (distance, angle, and velocity) of vehicles. The radar sends out pulses of radio waves and measures the time required for the reflected signal to return. These data are calculated to provide a direct measurement of the distance, angle, and velocity. Radar technology is particularly applicable for mid- and long-range automated functions of a vehicle. Radar systems have been used for forward collision warning, adaptive cruise control, and other safety technologies in production vehicles for some time. Radar systems are used on the front and rear bumpers of many automated test vehicles for range finding.

Light detecting and ranging (LiDAR) is another important sensing technology applicable to automated vehicles. LiDAR devices send out pulses of light and measure the time required for the reflected signals to return, which provides a direct measurement of distance. Constant redirection of this signal allows LiDAR to create a 3D map of its close-range surroundings. LiDAR technology is similar to radar, but has a much higher resolution because the wavelength of light is 100,000 times smaller than radio. To date, the sensors have generally been very expensive because they need to be rotated and/or oscillated by a mechanical system during operation.[4] (For example, Waymo claims to have reduced the sensor package price by 90%, down to $7,500, while Velodyne's Puck™ [Model VLP-16] costs $7,999.) More recently, a few companies[5] have announced the upcoming availability of affordable solid-state LiDAR sensors, ranging from $10-$250 each.[6,7,8]

Many in the industry see LiDAR as an essential piece of the automated vehicle system and are working to make the sensors less expensive, more reliable, and more efficient. Companies such as Waymo, HERE, TomTom, and Zenrin use LiDAR-equipped vehicles to map geographic regions for future CAV deployment. Analysis estimates the automotive LiDAR market will be worth $223.2 million by 2024 as a result of automated vehicle functionalities.[9]

Ultrasonic sonar sensors have been used in vehicle applications for several years, specifically for backup warning and park-assist systems. These sensors are also used to provide redundancy in vehicle navigation and collision avoidance functionalities. Sonar uses sensors to detect sound waves moving within its environment, enabling the vehicle to visually detect obstacles.[10]

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[4] Poulton, Christopher, and Michael R. Watts, "MIT and DARPA Pack Lidar Sensor onto Single Chip," August 4, 2016.

[5] Massachusetts Institute of Technology, Innoluce, Innoviz Technologies, LeddarTech, Quanergy, and Velodyne

[6] Ackerman, Evan, "Ford and Baidu Invest $150 Million in Velodyne for Affordable Lidar for Self-Driving Cars," August 17, 2016.

[7] Etherington, Darrell, "Velodyne's Latest Solid-State LiDAR Design Keeps Costs Low for Production at Scale." *TechCrunch*, December 13, 2016.

[8] LeddarTech, "LeddarTech Showcases 2D and 3D Solid-State LiDARs for Mass-Market Autonomous Driving Deployments," December 15, 2016.

[9] Grand View Research, "Automotive LiDAR Market Size Worth USD 223.2 Million by 2024: Grand View Research, Inc.," *PRNewswire*, December 12, 2016.

[10] Langer, Dirk, and Charles Thorpe, "Sonar Based Outdoor Vehicle Navigation and Collision Avoidance," accessed December 5, 2016.

5.1.2 Cameras

Cameras are the least expensive and most reliable technology on the market today for automated vehicles.[11] Cameras are able to detect colors with programmable software algorithms that provide necessary information to the vehicle, including traffic signals, road markings, road signs, pedestrians, cyclists, and more. LiDAR and radar systems cannot do this. Most current ADAS systems depend heavily on reading camera inputs and use computer vision and machine learning to interpret the vehicle's surrounding environment from the live video. LiDAR, radar, and cameras are all proven technologies, but cameras remain the production leader for automated vehicles because of their lower costs and higher availability.[12] Mobileye, a leading ADAS- and CAV-technology supplier, is currently developing mapping software that uses a series of eight cameras, without LiDAR, to create highly detailed and constantly updated road maps from in-use vehicles.[13]

5.1.3 Absolute localization

Radar, LiDAR, and sonar ("time of flight range" sensors) provide high-definition relative localization down to 10–15 cm. GPS provides an absolute localization and enables automated vehicles to be tracked via satellite to determine the progressive approach toward a destination for a given itinerary. GPS utilizes high-precision global navigation satellite systems to provide accurate and reliable measurements for any travel itinerary.[1] This is accomplished using multi-frequency sensors to mitigate atmospheric signal delays, as well as multi-constellations to track the vehicle in highly obstructed urban environments.[1]

5.2 V2V/V2I communication

Advanced communications systems are beneficial to automated vehicles. The most common communication methods are vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). V2V communication involves one vehicle being able to inform other vehicles within a given proximity of important decisions it makes. For example, should a vehicle have to brake suddenly, that vehicle must alert the vehicles nearby as well as their respective drivers. V2I communications involve sending information to, and accepting information from, traffic infrastructure, such as a traffic signal informing a vehicle of a red light. This communication will enable the vehicle to react to the change in traffic flow patterns without compromising safety.[14]

Two wireless technologies are currently being considered for production automated vehicles. The first is Dedicated Short Range Communications, which uses a reserved spectrum for closer range communications. This technology provides close-range V2V and V2I communication, and is the focus of the V2V mandate NHTSA proposed in December 2016. The second technology is high-bandwidth cloud connectivity, which allows vehicles and infrastructure to upload traffic, roadwork, road condition, map updates, and other data to a cloud-hosted database via an Internet connection. These databases will be capable of relaying information to all other relevant vehicles and infrastructure devices.

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[11] Santo, David, "Autonomous Cars' Pick: Camera, Radar, Lidar?," *EE Times*, July 7, 2016.

[12] Ibid.

[13] Interview with Mobileye representative, December 5, 2016.

[14] Mooney, Janine, "Autonomous Vehicle Trials Demonstrate V2V and V2I Communications," *Manufacturing.net*, October 25, 2016.

A wide variety of information will be accessible to V2I-equipped vehicles, such as traveler routes, work zones, road weather, pavement markings and infrastructure assets, incident management, traffic signals, and operational restrictions information.[15]

5.3 Drive-by-wire technology

Drive-by-wire technology allows the vehicle to maintain control of the main safety features such as steering, throttle, and braking. Automated vehicle steering is controlled via an electric steer-by-wire steering system that is powered by an electric motor coupled to the steering column or rack. The control system monitors the applied torque to the steering wheel as well as other safety features. The vehicle's braking system is controlled by a brake-by-wire system that uses electronic signals from multiple sensors that convert those signals from brake pedal displacement. Throttle-by-wire systems control the throttle position functions by sending analogous voltage signals to the throttle to increase or decrease the vehicle acceleration rates.[16]

5.4 Control system

From a general perspective, the control system of automated vehicles is primarily vision-based. The three main sub-systems are sensors, image processors, and vehicle controllers. The sensor array, typically a combination of camera, radar, LiDAR, and sonar, provides the vehicle with all the visual information about a given driving scenario, such as lane markings, traffic signals and signage, pedestrians, other vehicles, and roadside incidents. The processor fuses all of these inputs together, taking the real-time visual data from the camera and sequentially determining the corresponding environment based on texture and shape and supplemented by more concrete localization from radar, LiDAR, and sonar. Several companies (e.g., Mobileye, SAIPS, and Cruise Automation) are working on machine learning and artificial intelligence, which will provide cognitive reasoning to assist with vehicle decision-making based on image and pattern recognition. The processor sends its determination to the vehicle controller, which operates the drive- and steer-by-wire systems to direct the vehicle.

There are many types of vehicle-controlling mechanisms, including method control input, controller design method, and controller implementation structure. The method control input utilizes either two-wheel steering, four-wheel steering, or direct yaw control to keep the vehicle on track. Controller design methods, such as neural networks and input scaling, require extensive V2V and V2I communication systems and infrastructures to determine a vehicle's appropriate travel itinerary. A controller implementation structure utilizes combinations of feed-forward and feedback information to control the vehicle's physics.[17]

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[15] Peters, Joseph, "Accelerating Road Vehicle Automation," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 25–35.

[16] Kalinowski, Jordan, Thomas Drage, and Thomas Braunl, "Drive-By-Wire for Autonomous Formula SAE Car," Presentation at the 19th World Congress, The International Federation of Automatic Control, Cape Town, South Africa, August 24–29, 2014.

[17] Isa, Khalid Bin, and Adzan Bin Jantan, "An Autonomous Vehicle Driving Control System," *Int. J. Engng Ed.*, 21 no. 5 (2005), pp. 855–866.

6. Light-Duty Automated Vehicles

Light-duty automated vehicle technology is not new in the United States. There has been talk and speculation since General Motor's (GM's) Futurama exhibit/ride at the 1939 New York World's Fair. Serious technical work occurred through the 1960s, concentrated in the partnership between GM and RCA. Most of the research between 1960 and 1980 occurred at the Ohio State University. The University of California, Berkeley, Partners for Advanced Transportation Technology (PATH) program began in 1986.[1]

The DOT maintained a large and active on-road vehicle automation program throughout most of the 1990s through the National Automated Highway Systems Consortium. Work was stopped after the final demonstration of Level 2 highway autonomy in 1998 because of budget constraints.[2] Carnegie Mellon University (CMU) performed a parallel demonstration, autonomously driving a vehicle from Pittsburgh to Los Angeles with 98.2% lateral control using camera and laser vision systems combined with a neural network concept.[3]

Demonstration efforts were revitalized when Congress authorized the Defense Advanced Research Projects Agency's (DARPA) "challenges" in 2004, 2005, and 2007, which combined industry and academia teams competed to build vehicles to autonomously navigate desert or urban courses.[4] Many of the active university automated vehicle research programs participated in these challenges, including CMU, Massachusetts Institute of Technology, Stanford University, and the Virginia Tech Transportation Institute. These competitions demonstrated that automated vehicle technologies (e.g., computing/ processing, sensing, networking, and connectivity) had advanced to the point of commercial feasibility. The competitions success marked a milestone where CAV research began to become a major focus for industry.

6.1 Research, development, and demonstration

As technology has progressed, public and private interest in and funding of CAV research has increased tremendously. Most of the work focuses on the validation of reliability and safety and the analysis of system behavior. There has not been a strong focus on testing to quantify the energy impacts. The acceleration of CAV research indicates strong interest in quickly deploying automated vehicles.

In addition to (and a signifier of) more available funding, a number of technical conferences dedicated to the study of automated vehicles have been founded, including the Autonomous Vehicle Symposium (co-sponsored by the Transportation Research Board and Association for Unmanned Vehicle Systems International), Institute of Electrical and Electronics Engineers' International Conference on Connected Vehicles and Expo, and the Autonomous Vehicle Test and Development Symposium. In addition, several established conferences have dedicated portions of their agenda for CAV technology. These include the Consumer Electronics Show, Intelligent Transport Systems World Congress, Congress on Automotive Electronic Systems, and SAE Convergence. These conferences and gatherings provide a platform to

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[1] California Partners for Advanced Transportation Technology, "PATH," accessed January 13, 2017.

[2] Shladover, Steven E, Jane Lappin, Robert P. Denaro, and Bryant Walker Smith, "Introduction: The Transportation Research Board's 2013 Workshop on Road Vehicle Automation," *Road Vehicle Automation*, Springer International Publishing (2014).

[3] Carnegie Mellon University, "No Hands across America," accessed December 8, 2016.

[4] Defense Advanced Research Projects Agency, "DARPA Urban Challenge," accessed December 8, 2016.

present research and development (R&D) results and highly publicized "reveals" of new CAV technology to the public.

6.1.1 Government

The federal government supports automated vehicle technology development and demonstration in multiple ways. The Obama Administration unveiled a plan in January 2016 that allotted nearly $4 billion over 10 years to accelerate the deployment of self-driving cars.[5]

The U.S. Department of Energy (DOE) established the Systems and Modeling for Accelerated Research in Transportation Mobility consortium "to examine the nexus of energy and mobility for future transportation systems."[6] CAV is one of the five primary pillars of this research. The DOE Advanced Research Projects Agency – Energy's "Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation" program awarded over $15 million to projects on connected vehicle technologies that reduce energy consumption.[7] The program's the more recent "Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles" project awarded $32 million to projects that specifically target increasing energy efficiency from combined connectivity and automation in vehicle applications.[8]

The DOT and its Federal Highway Administration believe that V2I will be a key enabler for automated vehicle technology by making it more attractive to future buyers; however, the agency aims to accelerate the deployment of both V2V and V2I.[9] The DOT has funded research on V2V and V2I, independent of automated driving technology, on in-use vehicles since the late 1980s to determine the safety benefits and effectiveness of the systems.[10,11,12] The resulting analysis led NHTSA to propose a rule to mandate V2V communication on LDVs in an effort to reduce crashes on U.S. roadways.[13]

DOE and DOT recently announced a collaboration to "accelerate research, development, demonstration, and deployment of innovative smart transportation systems and alternative fuel technologies."[14] This collaboration is linked to DOT's SmartCity Challenge, which awarded $50 million to Columbus, Ohio, to implement innovative technologies, including CAVs. Additionally, two major transportation research

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[5] Wagstaff, Keith, "Obama Administration Unveils $4B Plan to Jump-Start Self-Driving Cars," *NBC News*, January 14, 2016.

[6] Argonne National Laboratory, *The Complex Systems Landscape of Future Urban Transport*, accessed January 13, 2017.

[7] Advanced Research Projects Agency-Energy, *Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET)*, July 28, 2016.

[8] Advanced Research Projects Agency-Energy, *Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles (NEXTCAR)*, accessed January 13, 2017.

[9] Peters, Joseph, "Accelerating Road Vehicle Automation," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 25–35.

[10] Anderson, Blair, "NHTSA V2V NPRM Update," presentation at ITS America, June 12, 2016.

[11] National Highway Traffic Safety Administration, "Vehicle-to-Vehicle Communications," December 13, 2016.

[12] Harding et al., *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application* DOT HS 812 014, (Washington, DC, August 2014).

[13] National Highway Traffic Safety Administration, "U.S. DOT Advances Deployment of Connected Vehicle Technology to Prevent Hundreds of Thousands of Crashes," December 13, 2016.

[14] U.S. Department of Energy, "DOE and the Department of Transportation Announce Collaboration to Support Smart Transportation Systems and Alternative Fuel Technologies," April 29, 2016.

groups, the American Association of State Highway and Transportation Officials and the Transportation Research Board, recently released research needs to enable CAV development and deployment.[15,16]

6.1.2 Academia

Several universities are leading research and engineering in the automated driving technology space. The following discussion is not exhaustive but covers several universities with notable involvement in CAV R&D.

- **University of California, Berkeley,** has a long history of CAV R&D and testing through the PATH program, primarily working toward fully automated highway systems. PATH's most recent research is on adaptive cruise control, advanced traffic signal controls for V2I, and heavy-duty truck platooning.[17]
- **Carnegie Mellon University (CMU)**, another longtime participant in CAV technology, has partnered with multiple industry players (including the GM Collaborative Research Lab and Uber's Advanced Technology Center) to investigate a wide range of automated vehicle technology. Several of CMU's CAV-focused staff moved to both Delphi Automotive (through CMU spin-off company Ottomatika) and Uber, and CMU is currently focused on computer vision and decision-making.
- The **University of Michigan's Transportation Research Institute** has a large research program in its Mobility Transformation Center that covers development and testing of CAV technologies.[18] The institute houses MCity, an open-access 32-acre real-world simulation of an urban and suburban environment for testing CAVs.[19]Additionally, several industry stakeholders (including nine vehicle OEMs and Tier 1 suppliers) committed $1 million to fund the center, and dozens of other major stakeholders committed $150,000 to the center's work.[20] The university is also helping create the American Center for Mobility, a testing and product development facility to validate CAV technology and create voluntary standards.[21]
- **The Center for Automotive Research at Stanford University** was established in response to the university's participation in DARPA's challenges (see discussion in Section 6).[22] The center is a community of industry and academia focused on addressing future challenges in personal mobility; it contains experts in engineering, humanities, law, policy, and environment. The center has completed numerous multi-disciplinary projects on CAVs (i.e., on computer and machine learning algorithms, vehicle control at handling limits, and using professional drivers to control the car to improve control algorithms), and it continues to provide connections between industry,

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[15] Shladover, Steven E., and Douglas Gettman, *Connected/Automated Vehicle Research Roadmap for American Association of State Highway and Transportation Officials*, National Cooperative Highway Research Program, accessed October 13, 2015.

[16] Transportation Research Board, "Research Needs Statements," accessed January 17, 2017.

[17] California Partners for Advanced Transportation Technology, "Automated and Connected Vehicles," accessed January 17, 2017.

[18] University of Michigan, Mobility Transformation Center, "Research," accessed January 17, 2017.

[19] University of Michigan, Mobility Transformation Center, "Mcity," accessed January 17, 2017.

[20] University of Michigan, Mobility Transformation Center, "Industry," accessed January 17, 2017.

[21] American Center for Mobility, "What is the American Center for Mobility?," American Center for Mobility. Accessed January 17, 2017.

[22] Center for Automotive Research at Stanford, "CARS," accessed January 17, 2017.

government, and academia. A recent example is its hosting of NHTSA's open forum on Guidelines for the Safe Deployment of Automated Vehicle Safety Techniques in April 2016.[23]

- The **Virginia Tech Transportation Institute** has focused on the safety side of CAV research. The institute recently focused on human-machine interface design and how to optimize drivers' interaction with partially automated driving systems that require their passive attention and capability to resume control of the vehicle when needed.[24] The Institute also operates the Virginia Automated Corridors initiative, which provides an environment for government and industry to test and certify their CAV systems.[25]
- The **Massachusetts Institute of Technology** houses the Computer Science and Artificial Intelligence Laboratory and has conducted research on a range of CAV-related topics, including technology development (i.e., LiDAR, radar, and GPS), consumer adoption, autonomous vehicle Mobility-as-a-Service (MaaS) concepts,[26] and ethical considerations.[27]

Other active CAV U.S.-based university programs include Texas A&M's Transportation Institute,[28] University of Arizona (Uber partnership on optics),[29] Princeton University (Princeton Autonomous Vehicle Engineering team and involvement in DARPA challenges),[30] Pennsylvania State University (signal processing and control software),[31] University of Minnesota (legal and policy),[32] University of Texas Austin, Cornell University, and University of California, Davis.

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[23] National Highway Traffic Safety Administration, "NHTSA Events," accessed January 17, 2017.

[24] Blanco et al., "Automated Vehicles: Take-Over Request and System Prompt Evaluation," *Road Automation 3*, Springer International Publishing (2016), pp. 111–119.

[25] Virginia Tech Transportation Institute, "Virginia Automated Corridors," accessed January 17, 2017.

[26] Spieser et al., "Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore," *Road Vehicle Automation*, Springer International Publishing (2014), p. 229.

[27] Moral Machine, "Moral Machine," accessed January 17, 2017.

[28] Texas A&M Transportation Institute, "Connected and Automated Transportation," accessed November 19, 2016.

[29] Brandom, Russel, "Uber Will Partner with University of Arizona for Self-Driving Car Research," *The Verge*, August 25, 2015.

[30] Princeton Autonomous Vehicle Engineering, "About Us," accessed January 17, 2017.

[31] Penn State Applied Research Laboratory, "Advanced Technology (AT)," accessed January 17, 2017.

[32] Lari, Adeel, Frank Douma, and Ify Onyiah, "Self-Driving Vehicles and Policy Implications: Current Status of Autonomous Vehicle Development and Minnesota Policy Implications," *Minnesota Journal of Law, Science & Technology*, 16 no. 2 (2015), pp. 737–768.

6.1.3 Technology and vehicle developers

The pace of automated vehicle technology R&D in the passenger vehicle industry has accelerated over the past few years. The DARPA challenges discussed earlier were followed by the rise of Silicon Valley as a major hub for automated vehicle R&D. For example, Google has tested its fully automated vehicle technology since 2009 and has accumulated over 2 million miles on modified Lexus RX sport utility vehicles and other prototype vehicles.[33] Google parent company, Alphabet, spun off its CAV division in early December 2016 to form Waymo.[34] Most of the major automotive OEMs developed technology centers in Silicon Valley soon after the U.S. economic recession ended in 2010. The map shown in Figure 7 illustrates Silicon Valley facilities by company.[35]

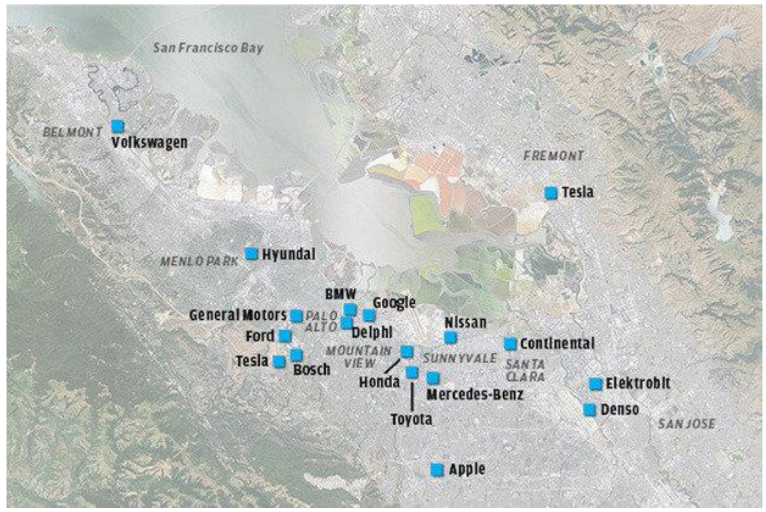

Figure 7: Proliferation of automotive OEM presence in Silicon Valley

Source: Mearian, Lucas, "Why Detroit is Moving to Silicon Valley," *ComputerWorld,* December 30, 2015.

All of the major automotive OEMs are involved in CAV research. Some are developing most of the technology in house. Others (e.g., Honda, Toyota, and Volvo Car Corporation [Volvo Cars]) are collaborating to use standard suppliers. Some vehicle OEMs (e.g., Bavarian Motor Works [BMW], Ford, and GM) are acquiring and/or partnering with automated vehicle development startup companies. Transportation network companies such as Uber, Lyft, Didi, and Gett have also displayed strong interest in automated vehicle technology. These companies generally partner with vehicle OEMs or Tier 1 suppliers to provide the needed automotive expertise. BMW, Ford, Nissan, and Tesla announced that they are transitioning from describing themselves as vehicle manufacturers to mobility providers (i.e., transportation network companies). This change reflects the disruption CAVs have made in the transportation industry.

Table 3 shows a sampling of recent and ongoing industry CAV demonstrations to provide an understanding of the industry-wide focus. None of the systems shown are Level 5. The testing for all the systems to date has been limited to certain operational domains (i.e., Google's testing only occurs where the company has completed a thorough mapping regime). In addition, California has authorized 12 vehicle OEMs, Tier 1 suppliers, and other startups to test autonomous vehicles in the state.[36]

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[33] Google, "Waymo," accessed January 17, 2017.

[34] Etherington, Darrell, and Lora Kolodny, "Google's Self-Driving Car Unit Becomes Waymo," *TechCrunch,* December 13, 2016.

[35] Mearian, Lucas, "Why Detroit is moving to Silicon Valley," *Computer World,* December 30, 2015.

[36] State of California Department of Motor Vehicles, "Testing of Autonomous Vehicles," accessed January 17, 2017.

Table 3: Sampling of recent and ongoing industry CAV demonstrations

Company	***Demonstration/Testing Description***
Audi	**Level 3**: 50,000 miles of testing. Accomplished 500-mile Level 4 drive from Palo Alto to Las Vegas
Bosch	**Level 3**: 6,000 miles of testing in Germany, U.S., and Japan
Daimler	**Level 4**: Drove 100 km route in Germany on a Mercedes-Benz S500 prototype
Delphi Automotive	**Level 4**: Cross-country U.S. trip (Delphi Automotive system installed on a Audi SQ5)
Fiat-Chrysler	**Level 4**: Testing Google technology in 100 Chrysler Pacifica minivans
Ford	**Level 4**: Testing 30 Ford Fusion midsize sedans in California, Arizona, and Michigan, in snow and night without headlights
GM	**Level 4**: Chevy Bolts in Arizona and California. Deploying Chevrolet Volts for employees on Detroit campus in 2017
Google/Waymo	**Level 4**: Over 2 million test miles on fleet of Lexus RX SUVs and prototypes
Honda/Acura	**Level 4**: Demonstrated at Intelligent Transportation Systems World Congress 2013. Testing at GoMentum Station
Hyundai/Kia	**Level 4**: Plan to run tests at American Center for Mobility facility in Willow Run
Nissan	**Level 4**: Testing zero emission vehicle fleet at the National Aeronautics and Space Administration Ames Research Center
Uber	**Level 4**: Ford Fusion (purchased off dealer lot and instrumented) and Volvo XC90 (partnership with Volvo) taxis in Pittsburgh
Volvo Cars	**Level 4**: See Uber testing. Also placing vehicles into use by real drivers for testing on-road; 100 in China and 100 in Sweden

6.1.4 Technology deployment timeline and cost

A number of automotive OEMs and suppliers have announced timelines for commercial CAV deployment. Table 4 provides a high-level summary of the major CAV rollout timeline announcements. Level 1 is not included because these technologies (e.g., adaptive cruise control) are widely-available in the passenger vehicle market.[37] Unless otherwise noted, the table includes the dates when each CAV level will be available in the majority of the manufacturers' vehicles for the public. This table does not include the suppliers who only provide the production-ready technology to the OEMs without specifying the market.

[37] Wayland, Michael, "Adaptive Cruise Control Goes Mainstream," *The Detroit News*, March 3, 2015.

Table 4: Light-duty vehicle industry announcements of CAV deployment timelines

Vehicle OEM or Developer	**Level 2**	**Level 3**	**Level 4/5***
Audi[38]	2016[a]	2021[a]	n/a
Bosch[39]	n/a	n/a	2020[b]
BMW[40]	2016	n/a	2021, 2025[c]
Continental[41]	2016	2020	2021
Daimler[42]	2017	n/a	2020
Delphi Automotive[43]	n/a	n/a	2019
Denso[44]	n/a	n/a	2030
Fiat-Chrysler	2016	n/a	n/a
Ford[45]	2016	n/a	2021, 2025[d]
GM[46]	2017[e]	2020	2025[f]
Google/Waymo[47]	n/a	n/a	2019
Honda/Acura[48]	2016	2020	n/a
Hyundai/Kia[49]	2016	2020[g]	2030[g]
Nissan/Renault[50]	2016[h]	2018[i]	2020
Tesla[51]	2014[j]		2018
Toyota/Lexus[52]	2016	n/a	2020/2021
Uber[53]	n/a	n/a	2030
Volkswagen[54]	2016	n/a	2021[k]
Volvo[55]	2016	n/a	2017[l]

* Most manufacturers do not distinguish between Levels 4/5, but rather indicate "full autonomy."
[a] Level 2 system is for <40 miles per hour (mph). Audi plans to release a speed-limited Level 3 system in the A8 in 2017.
[b] Bosch plans to also release fully automated parking in 2018.
[c] 2021: Ride-sharing application. 2025: Available to consumers
[d] 2021: Ride-sharing, 100,000k units per year. No steering wheel or pedals. 2025: Available to consumers
[e] Only in Cadillac CT6 vehicles, for use on highways GM has mapped out with LiDAR
[f] Will be deployed on electric vehicles in the Lyft ride-sharing service
[g] Vice Chairman Kwon Moon-Sik: "highly autonomous driving by 2020 and fully autonomous by 2030"
[h] Single-lane highway-only
[i] Highway only
[j] There is some disagreement, because the driver is not required to keep their hands on the wheel.[56]
[k] Commercial ride-sharing application
[l] Putting vehicles in customer hands for real-time testing (100 in Sweden, 100 in China)

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[38] Pachal, Pete, "Despite Tesla's Setbacks, Audi is Racing Fast toward Self-Driving Cars," *Mashable*, July 16, 2016.

[39] Gordon-Bloomfield, Nikki, "Bosch: We'll Have Fully Autonomous, Connected Vehicles in Four Years' Time," *Transport Evolved,* January 5, 2016.

[40] Kacher, Georg, "BMW Doubles Down on EVs," *Automobile Magazine*, August 9, 2016.

[41] Continental, "Pioneering Automated and Autonomous Driving: Continental Accepts the Challenges," March 31, 2016.

[42] Campbell, Matt, "Mercedes-Benz Autonomous Vehicles Due on the Road between 2020 and 2025," *CarAdvice,* January 7, 2017.

[43] Mobileye, "Press Releases," accessed November 18, 2016.

[44] Automotive News, "Denso Sees 15-Year Wait for Self-Driving Car," *Automotive News,* June 23, 2015.

[45] Naughton, Keith, "Ford to Sell Driverless Cars to Public by 2025, CEO Says," *Bloomberg*, September 12, 2016.

As indicated in Table 4, there is some disagreement within industry on the path to full autonomy, especially on whether or not partial autonomy (Level 3) should be skipped entirely. Tesla considers it "morally wrong to withhold functionalities that improve safety" in reference to Level 3 technology.[57] Audi[58] and BMW[59] explicitly included Level 3 in their implementation plans, while others such as Ford,[60] Google,[60] Toyota,[52] and Volvo Cars[60] state that partial autonomy is unsafe because of the uncertainty that drivers will have the awareness to resume control when needed. In a recent paper summarizing a session at the Automated Vehicle Symposium 2015, Volvo Cars discussed the complex nature of monitoring and ensuring driver awareness ("human factors challenges"). They concluded that either (1) manufacturers could design a Level 3 system as best as possible within the SAE definition or (2) manufacturers could avoid Level 3 systems and ensure that two clearly defined and communicated CAV driving modes are available: either the driver holds full responsibility while the automated driving system assists, or the vehicle is fully autonomous and needs no attention from the driver.[61] The human factors issue has become prominent enough to warrant full breakout sessions in each of the past Automated Vehicle Symposiums.

Regardless of manufacturer-estimated timelines, the future and progression of CAV technology is highly uncertain. Two longtime CAV-research academia participants, Steven Shladover from PATH and Alain Kornhauser from Princeton, believe that many of these timeline predictions are due to over-hype of the technology, and that the predicted rollout will likely be extremely limited both technologically and geographically.[62] Automated vehicles appeared in the past five years of the Gartner Hype Cycle for Emerging Technologies curve. This curve, published annually since 1995, graphically portrays the technology maturity and anticipated adoption timelines for emerging technologies and applications based on the company's adoption model results. The approach assigns each technology or application into one

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[46] Thompson, Cadie, "GM Will Use Lyft to Launch its First Self-Driving Car," *Business Insider*, July 18, 2016.

[47] Driverlessuser, "Sergey Brin on Driverless Car Future," *Driverless Car Market Watch*, October 2, 2012.

[48] Sage, Alexandria, "Honda Shows Off Self-Driving Cars at New Calif Testing Facility," *Reuters*, June 2, 2016.

[49] Kin-hai, Park, "Hyundai Motor to Make Fully Autonomous Car by 2030," *The Korea Times*, November 18, 2015.

[50] NissanNews.com, "Infographic: ProPILOT, Nissan's Single-Lane Autonomous Driving Technology," August 26, 2016.

[51] Thompson, Cadie, "Elon Musk says Tesla's Fully Autonomous Cars Will Hit the Road in 3 Years," *Business Insider*, September 25, 2015.

[52] Interview with representative from Toyota Research Institute, November 11, 2016.

[53] Kalankick, Travis, Twitter post, February 7, 2015.

[54] Cremer, Andreas, and Jan Schwartz, "VW Eyes Transportation Deals to Boost Self-Driving Car Plans," *Reuters*, August 19, 2016.

[55] Muoio, Danielle, "Volvo is about to Go through the Most Ambitious Self-Driving Car Experiment Ever," *Business Insider*, April 6, 2016.

[56] Oremus, Will, "Is Autopilot a Bad Idea?," *Slate*, July 6, 2016.

[57] Lambert, Fred, "Elon Musk Defends Level 3 Autonomy against Google & Volvo, Says 'Morally Wrong to Withhold Functionalities that Improve Safety,'" *Electrek*, September 13, 2016.

[58] Audi USA, "Piloted Driving," 2016.

[59] Mobileye, "BMW Group, Intel and Mobileye Team Up to Bring Fully Autonomous Driving to Streets by 2021," July 1, 2016.

[60] Oremus, Will, "Is Autopilot a Bad Idea?," *Slate*, July 6, 2016.

[61] Seppelt, Bobbie D., and Trent W. Victor, "Potential Solutions to Human Factors Challenges in Road Vehicle Automation," *Road Vehicle Automation 3,* Springer International Publishing (2016), pp. 131–148.

[62] Simonite, Tom, "Prepare to be underwhelmed by 2021's Autonomous Cars," *MIT Technology Review*, August 23, 2016.

of five key phases: 1) emergence (Technology Trigger), 2) excessive enthusiasm (Peak of Inflated Expectations), 3) excessive disappointment (Trough of Disillusionment), 4) gradual practical adoption (Slope of Enlightenment), and 5) slower gradual practical adoption (Plateau of Productivity). The 2016 Hype Cycle for Emerging Technologies curve (Figure 8) places autonomous vehicles at the downhill side of the "Peak of Inflated Expectations." The results also indicate that Gartner anticipates that autonomous vehicles are more than 10 years away from mainstream adoption.

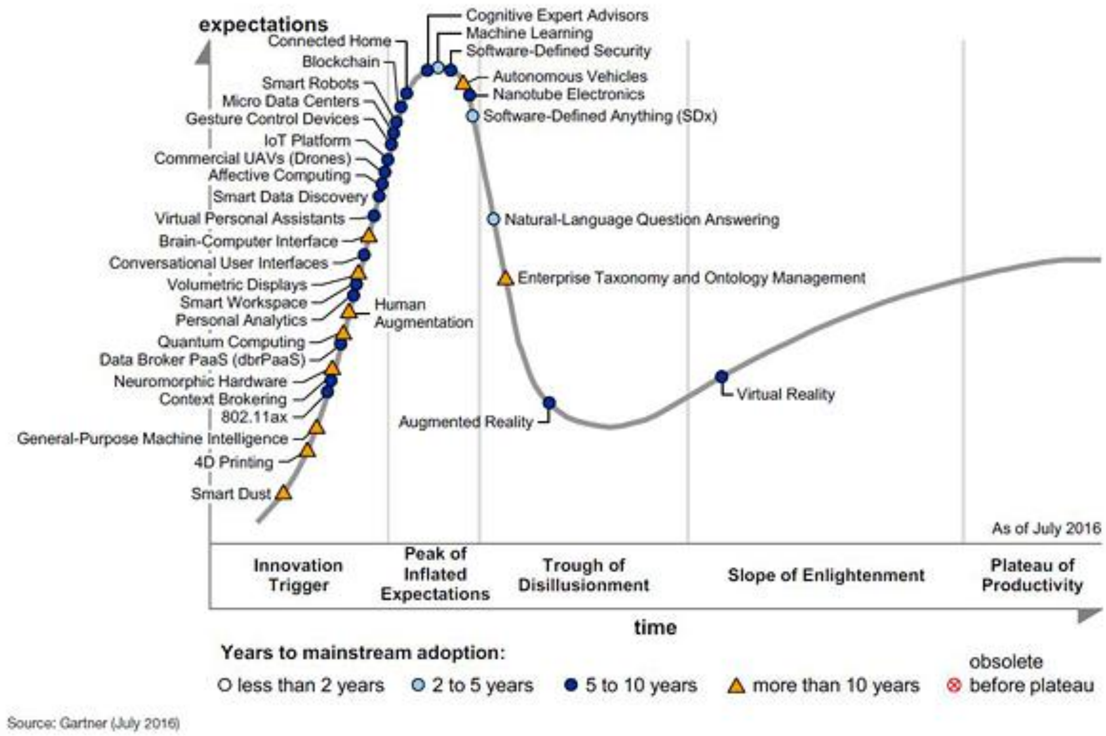

Figure 8: Hype cycle for emerging technologies, 2016[63]

The accuracy of the Gartner curve with real-world technology adoption varies. It accurately predicted the rise, fall, and proliferation of tablet computers, but underestimated the impact of Big Data. Even so, the curve is a frequently used resource for tracking emerging high-tech industry technologies.

Many of the large international technical consulting firms have issued reports on the future LD automated vehicle market, overall indicating a very high uncertainty due to the unpredictable nature of consumer adoption and decision-making. This is in line with a 2014 California Air Resources Board study that concluded "the adoption pattern for [automated vehicles] is evolving and uncertain."[64] Some of the major predictions are listed below, with more discussion in the following section.

[63] Garter, "Gartner's 2016 Hype Cycle for Emerging Technologies Identifies Three Key Trends that Organizations Must Track to Gain Competitive Advantage," August 16, 2016.

[64] Barcham, Raphael, *Climate and Energy Impacts of Automated Vehicles*, California Air Resources Board (June 2014).

- **ABI Research** has projected that while OEMs are targeting automated vehicle commercialization by 2021, Level 2 and Level 3 systems (i.e., ADAS) will account for 86% of global automated vehicle sales through 2026. The company predicts that sales of vehicles at higher automation levels (Levels 4 and Level 5) will only approach 1/3 of automated vehicle sales by 2030.[65]
- **Deloitte**, through hundreds of conversations with key stakeholders, concluded that "a fundamental shift is driving a move away from personally-owned, driver-driven vehicles and toward a future mobility system centered around (but not exclusively composed of) driverless vehicles and shared mobility" and suggests that this transition could occur much more quickly than anticipated. Deloitte forecasts CAVs will account for 80% of total U.S. sales by 2040.[66]
- **Goldman Sachs** predicts that automated vehicle technologies will achieve 100% market penetration by 2025, with Levels 1 and 2 included on 85% of the total new sales at that time, and Levels 3 and 4 on the remaining 15%. It anticipates 100% market penetration of Levels 3 and 4 on new vehicle sales by 2045.[67]
- **IHS Automotive** forecasts U.S. sales of several thousand Level 4 and Level 5 automated vehicles in 2020, growing to nearly 3.5 million sold in 2035.[68]
- **Juniper Research** predicts an accelerating market share of automated vehicle sales driven by increasingly stringent safety and environmental regulations coupled with further development in enabling technologies. This will amount to widespread driverless vehicles in 2020–2025 (global production of 14.5 million, installed capacity of over 22 million). However, it will generally be limited to certain urban city centers or other specific operational domains because of a need for V2X infrastructure.[69,70]
- **McKinsey & Company** estimates that up to 15% of new cars sold globally in 2030 could be fully autonomous.[71]

6.1.4.1 Technology development/deployment challenges

To meet all of the goals discussed above with safe and reliable CAVs, myriad technological challenges will need to be addressed:

- **Mapping and localization technology**. Developing cognitive software that sees and comprehends the world like a human driver does is difficult using input from sensor arrays.[72] This is especially important for inclement weather (rain and snow) and emergency situations. Additionally, accelerated manual mapping efforts are needed to expand the geographical domain for certain CAV designs.

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[65] Allied Business Intelligence Research, "Car OEMs Target 2021 for Rollout of SAE Levels 4 and 5 of Autonomous Driving," November 17, 2016.

[66] Corwin et al., "The Future of Mobility: What's Next?," Deloitte University Press, September 14, 2016.

[67] Goldman Sachs, "Monetizing the rise of Autonomous Vehicles," *Cars 2025* 3 (September 17, 2015).

[68] IHS, "Self-Driving Cars Moving into the Industry's Driver's Seat," January 2, 2014.

[69] Own, Gareth, *Autonomous Vehicles & ADAS*, Juniper Research (November 2016).

[70] Juniper Research, *On Track with Self-Driving Vehicles 2.0*, Juniper Research (2016).

[71] McKinsey, and Stanford University. "Automotive Revolution & Perspective towards 2030," *Springer India-New Delhi Auto Tech Rev* 5 (2016), pp. 1–20.

[72] Rousseau, John, and Brad Crane, "The Human Transition to Autonomous Vehicles," Artefact, accessed December 13, 2016.

- **Accurate positioning**. GPS is not accurate enough to be used for safety-critical applications. Upgrades are needed in both precision (currently in the +/- meter range) and frequency in order to facilitate mass-market usage of this technology.
- **Fail-safe and fault-tolerant design**. There is a growing need for robust backup systems that can safely stop the vehicle during failure, either due to the human driver being unable to take over or due to a hardware/software malfunction. Pervasive redundancies will be required for such operation.
- **Human factors**. As mentioned, most manufacturers agree that safe and reliable partially automated systems (Level 3) will be very difficult to design and implement because of the uncertainty from human factors. Many ADAS technologies have started to measure driver attentiveness using vehicle inputs (e.g, Mercedes' Attention Assist[73] and Nissan's Driver Attention Alert[74]), but interior sensor-based systems that directly monitor the driver will be needed (e.g., Gaze Region Estimation[75]) as driver input is removed. The systems will also need to be able to communicate this information to the driver, requiring an exceedingly effective human-machine interface.
- **Sensor cost**. Manufacturers need sensor arrays that do not price CAVs out of consumer budgets. This is especially important for LiDAR sensors; either LiDAR prices need to be cut drastically or systems need to operate reliably without LiDAR integration.
- **Interoperability**. As the CAV rollout begins, different manufacturers' systems will need to be able to operate within a vehicle fleet that includes CAVs from other manufacturers and conventional vehicles.
- **Cybersecurity**. Because V2V and V2I communication is required for operational CAVs, messaging requirements and network defense are needed. The messages must be transmitted from trusted sources without compromising authenticity, fabrication, and privacy protection.[76] The introduction of cybersecurity threats will require additional local, state, and federal guidelines and standards, as exemplified by NHTSA's existing work.[77] The safety benefits of this technology will be realized when every vehicle remains secure and resilient against cyberattacks.[78]

6.1.5 Consumer adoption

The project investigated the potential impacts of how and when consumers will adopt CAVs to determine how they could affect energy use. The goal of this effort was to determine whether there was strong evidence of consumer adoption barriers/motivators at the early stage that could alter the energy use projections developed in the project. Therefore, this section is not intended to be a comprehensive investigation into consumer and CAVs.

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[73] Mercedes-Benz, "Safety," accessed December 14, 2016.

[74] NissanNews.com, "Nissan's 'Driver Attention Alert' Helps Detect Erratic Driving Caused by Drowsiness and Inattention," April 1, 2015.

[75] Fridman et al., "Driver Gaze Region Estimation without Use of Eye Movement," *IEEE Intelligent Systems*, 31 no. 3 (May–June 2016), pp. 49–56.

[76] Anderson, Blair, "NHTSA V2V NPRM Update," presentation at ITS America, June 12, 2016.

[77] IHS, "Correcting and Replacing IHS Clarifies Autonomous Vehicle Sales Forecast – Expects 21 Million Sales Globally in the Year 2035 and Nearly 76 Million Sold Globally Through 2035," June 9, 2016.

[78] Abuelsamid, Sam, "Cyber Security Is Imperative Before Deploying Autonomous Vehicles," Navigant Research. September 1, 2016.

As with all new advanced technologies, there is not a straight line between initial product commercialization and mass-market adoption and use. Consumers must be interested in the new functionality because of its perceived benefits and utility. Numerous studies and press releases have confirmed that consumers have general interest in automated vehicles from a technological perspective[79] but at varying degrees of trust with incremental automation levels.[80]

Consumer adoption models have indicated variable rates of automated vehicle technology acceptance. KPMG breaks this into three scenarios. The aggressive scenario, albeit unpractical, indicates that fast adoption depends on technological breakthrough in V2X connectivity and immediate consumer benefits. In addition, it requires considerable trust with the technology across demographic and geographic variables. The base-case scenario includes time required for gradual customer acceptance, NHTSA involvement for V2V and V2X connectivity, and market volatility. The conservative scenario indicates slow progression in consumer trust and adoption of these technologies as well as subsequent improvements. Figure 9 shows different adoption scenarios of CAV technologies, as estimated by KPMG.

[79] J.D. Power, "Consumer Interest Builds for 'Gateway' Automated Vehicle Technologies, Says J.D. Power Study," *PR Newswire*, April 28, 2016.

[80] Deloitte, *2014 Global Automotive Consumer Study: Exploring Consumers' Mobility Choices and Transportation Decisions*, 2014.

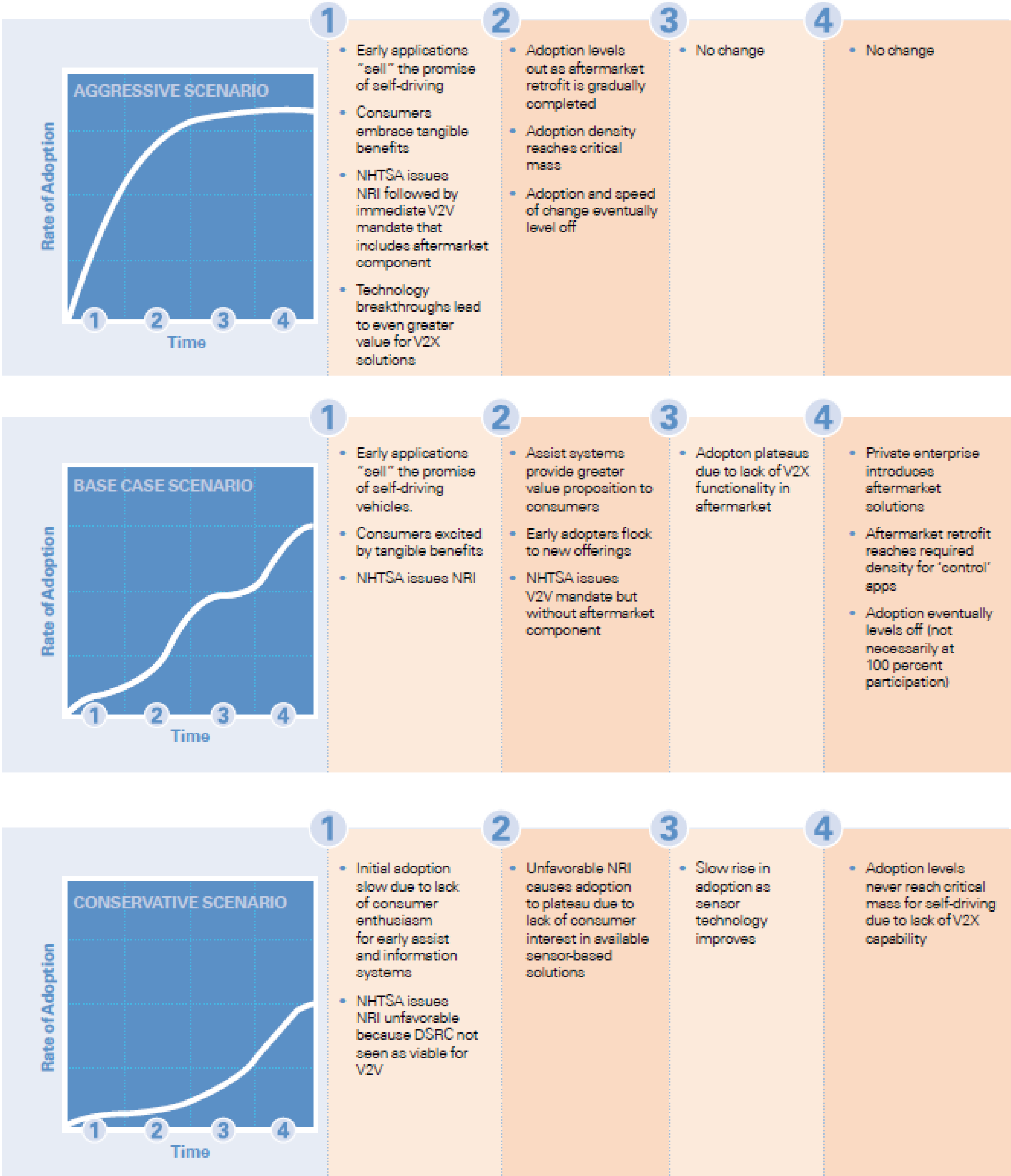

Figure 9: Adoption rates of automated vehicles for different adoption scenarios[81]

Consumer preferences on different levels of vehicle automation were determined via previously completed surveys. The results for these surveys were summarized for these general questions:[82]

1. Are consumers satisfied with technology that is already in their vehicle?
2. How do consumers learn about in-vehicle technologies? How would they prefer to learn about them?

3. Are consumers willing to use various alternatives to driving? Do they currently use them?
4. Are consumers willing to use automation in vehicles?
5. Are older adults willing to use autonomous vehicles and/or alternatives to driving in order to increase their mobility?

According to a study conducted by the Automobile Association of America (AAA) based on 1,832 interviews of drivers over 18 years of age, 75% of AAA members report feeling afraid to ride in self-driving vehicles; despite that, drivers who own vehicles with semi-autonomous features trust self-driving technologies 75% more than drivers who do not.[83] It is possible that consumers who drive premium-level vehicles are much more receptive to the technologies, which could change over time given gradual, smart innovating and investing in an evolving automotive market.

Consumers may also quickly trust a technology soon after trying it. According to a study conducted by Abraham, 63% and 58% of surveyed consumers were able to learn more about CAV technology by the vehicle manual, and trial-and-error, respectively.[84] Figure 10 indicates the current and preferred methods for consumers learning CAV technology.

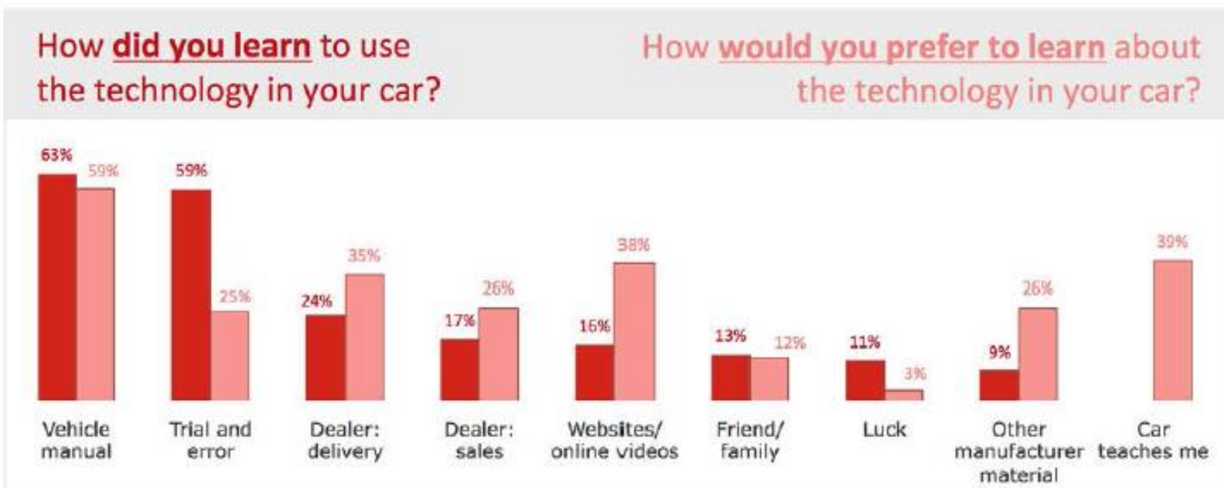

Figure 10: Current and preferred methods of learning CAV technologies[85]

Survey responses from Abraham et al. (2016) also indicated a difference in preferred learning methods based on age differences.[86] Figure 11 provides a breakdown of survey responses by age group about preferred methods of learning how to use in-vehicle technologies.

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[81] KPMG, and Center for Automotive Research, *Self-Driving Cars: The Next Revolution*, 2012.

[82] Abraham et al., *Autonomous Vehicles, Trust, and Driving Alternatives: A Survey of Consumer Preferences*, Massachusetts Institute for Technology, AgeLab (May 30, 2016).

[83] Stepp, Erin, "Three-Quarters of Americans 'Afraid' to Ride in a Self-Driving Vehicle," *AAA NewsRoom*, March 1, 2016.

[84] Abraham et al., *Autonomous Vehicles, Trust, and Driving Alternatives: A Survey of Consumer Preferences*, Massachusetts Institute for Technology, AgeLab (May 30, 2016).

[85] Ibid.

[86] Ibid.

Preferred Method	Age						
	16-24	25-34	35-44	45-54	55-64	65-74	75+
A friend or family member*	23.8%	12.9%	11.5%	8.4%	11.4%	13.5%	9.7%
Websites or on-line videos*	30.2%	42.4%	43.8%	42.8%	36.6%	36.3%	29.8%
Dealer while interacting with sales staff*	21.3%	22.1%	18.4%	25.7%	25.5%	32.6%	35.1%
Dealer during delivery*	18.8%	28.4%	27.2%	29.5%	39.5%	46.5%	39.9%
Vehicle manual*	53.5%	54.7%	54.7%	55.2%	60.1%	65.6%	67.5%
Other material provided by manufacturer	20.3%	23.7%	24.8%	26.2%	27.7%	28.5%	29.4%
Trial and error*	38.1%	39.4%	32.9%	23.9%	17.3%	15.6%	14.9%
By luck*	5.9%	5.4%	5.4%	2.3%	2.3%	1.9%	1.8%
The car teaches me	34.2%	42.9%	36.6%	39.2%	41.3%	37.6%	31.6%

*: Age differences significant at α=0.05

Figure 11: Differences in preferred methods of learning new in-vehicle technologies broken down by age group[87]

These differences in learning CAV technologies help determine future involvement of manufacturers and dealerships. This potential evolution in the vehicle market requires new policies for automakers and dealerships. AAA's study provides a roadmap for automakers on liability and regulations for CAV technologies, particularly for equipment failure and data security.[88] Introducing these barriers to CAV technology deployment also introduces risk for customers willing to pay for the technology. Approximately 77%, 67%, and 41% of surveyed consumers indicated a willingness to pay an incremental $3,000, $5,000, and $7,500 for Level 2, 3, and 4 automated driving features, respectively.[89,90]

6.1.5.1 Level 2 technologies

Level 2 technologies are features available on many current vehicles. This indicates there is customer interest and acceptance to warrant manufacturers to offer them. The drivers still maintain control of these Level 2 system-equipped vehicles. Maintaining control is more readily accepted than full vehicle autonomy by consumers because of their familiarity and comfort with the technologies. A 2016 study surveying 618 licensed drivers at least 18 years old revealed that the most frequent preference for vehicle

[87] Abraham et al., *Autonomous Vehicles, Trust, and Driving Alternatives: A Survey of Consumer Preferences*, Massachusetts Institute for Technology, AgeLab (May 30, 2016).

[88] Naughton, Keith, "Mercedes, Infiniti Owners Most Likely to Let Car Do Driving," *Bloomberg*, August 27, 2016.

[89] Bansal, Prateek, and Kara M. Kockelman, "Are Americans Ready to Embrace Connected and Self-Driving Vehicles? A Case Study of Texans," under review for publication in *Transportation* (April 2016), accessed November 10, 2016.

[90] Mosquet et al., "Revolution in the Driver's Seat: The Road to Autonomous Vehicles," *BCG Perspectives*, The Boston Consulting Group (April 21, 2015).

automation continues is for no self-driving capability (Level 2, 45.8%), followed by partially self-driving vehicles (Level 3, 38.7%), with completely self-driving vehicles being the least preferred choice (Level 4 and Level 5, 15.5%).[91]

6.1.5.2 Level 3 technologies

Level 3 technologies have limited functionality compared to fully autonomous vehicles. Level 3 automated driving systems perform all critical vehicle operation functions under certain traffic and environmental conditions, but they require the driver to be available to assume control over the vehicle if the system encounters a situation or scenario that it cannot handle independently.[92]

A 2016 survey of University of South Florida students and faculty indicated a 46% likelihood that consumers would use automated vehicles when they become commercially available and provide the appropriate benefits.[93] The same survey indicated that 46%, 65%, and 67% of surveyed consumers would be more likely to purchase an automated vehicle if consumers benefit from lower insurance rates, increased fuel efficiencies, and less stressful driving experiences, respectively.[93] These perceived benefits of Level 3 technologies enable consumers to obtain more knowledge about these vehicles as more are introduced to the market. By lowering insurance rates, consumers will consider these vehicles as viable alternatives to conventional vehicles. With increased knowledge of the benefits and decreased costs of automation technologies, consumer adoption of Level 3 CAVs is projected to increase.

6.1.5.3 Level 4 and Level 5 technologies

Level 4 automated driving systems operate similarly to Level 3 systems, but they will be expected to perform all critical vehicle operation functions under certain predefined route, traffic, and environmental conditions. Unlike Level 3 systems, Level 4 systems will be expected to be fully capable of operating the vehicle when operating in the design use case (e.g., limited-access highway or pre-mapped urban centers), and Level 5 (fully autonomous) systems will be expected to be capable of operating the vehicle in any situation.

Consumers play a vital role in general market projections for self-driving vehicles. A 2014 market study conducted by IHS Automotive forecasts that the United States will account for 29% of worldwide sales of self-driving cars with human controls (level 4) and self-driving-only cars (level 5) in 2035, or nearly 3.5 million vehicles.[94] General survey responses from SAE International indicate that Level 4 autonomy is considered a "sweet-spot," given that 80% of respondents believe that people should always have the option to drive themselves, and 64% prefer to be in control of their vehicles.[95] This indicates that consumers who want Level 4 automated driving features still want the option to drive themselves. In addition, the increased implementation cost of Level 4 technologies may reduce consumer acceptance of

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[91] Schoettle, Brandom, and Michael Sivak, *Motorists' Preferences for Different Levels of Vehicle Automation: 2016* SWT-2016-8, University of Michigan (May 2016).

[92] Nordhoff, Sina, *Mobility 4.0: Are Consumers Ready to Adopt Google's Self-Driving Car?*, University of Twente, (August 2014).

[93] Menon, Nikhil, "Consumer Perception and Intended Adoption of Autonomous Vehicle Technology – Findings from a University Population Survey," *Graduate Thesis and Dissertations*, November 2015.

[94] IHS, "Self-Driving Vehicles Moving into the Industry's Driver's Seat," January 2, 2014.

[95] SAE International, "KBB Survey: Most Consumers Would Accept SAE Level 4 Autonomy, but Think Safety Diminishes," September 28, 2016.

the technology. A 2012 study by J.D. Power and Associates indicated that 37% of drivers were interested in purchasing fully autonomous cars, but only 20% were interested with the introduction of added costs.[96]

6.1.6 Cost

Most major vehicle OEMs currently offer ADAS systems (Level 1 or Level 2) on a range of vehicles in different classes. Table 5 offers a sampling of the systems, available vehicles, and their incremental cost range as shown on the manufacturers' websites. Most of the prices also include other lower-level ADAS features, such as blind-spot monitoring, lane-departure warning, and emergency braking, but only the key active automated driving technologies are listed. The cost range presented is not entirely accurate because of feature packaging (e.g., Ford only offers Lane Keep Assist on the Edge as part of a multi-thousand dollar equipment suite that includes other features). This table provides a general idea of the system pricing as of December 2016, but is not meant to be a comprehensive listing.

Table 5: Summary of system pricing by vehicle manufacturer (December 2016)

Company	Technologies Included	SAE Automation Level	Vehicle Model	Cost
Daimler	Adaptive Cruise Control Steering Assist Active Lane Change Assist	2	CLA	$1,500
Fiat-Chrysler US	Adaptive Cruise Lane Keep Assist Automated Parking	2	Jeep Cherokee	$1,495
Ford	Adaptive Cruise Control Lane Keep Assist	2	Taurus	$1,995
	Lane Keep Assist	1	Mid-size sedan and sport utility vehicle	$1,625–$5,050
	Adaptive Cruise Control	1	Mid-size sedan and SUV	$1,200–$1,800
Honda/ Acura	Adaptive Cruise Control Lane Keep Assist	2		$1,000
Hyundai/ Kia	Adaptive Cruise Control Lane Keep Assist	2		$1,900
Subaru	Adaptive Cruise Control Lane Keep Assist	2	All except BRZ	$1,395–$2,945
Tesla	Near-full autonomy on the highway	2, 3	All vehicles	$2,500 new, $3,000 retrofit

Highly-automated test vehicles are not affordable or available to the average consumer. Most Level 4 systems use LiDAR. Most manufacturers have used the Velodyne Puck™ (Model VLP-16) on their test vehicles. These systems currently cost $7,999 per unit.[97] Velodyne recently announced a future unit that will cost $500. As mentioned earlier, less expensive ($10-$250) solid-state LiDAR devices are being developed by the Massachusetts Institute of Technology, Innoluce, Innoviz Technologies, and Quanergy.[6]

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[96] Howard, Daniel, and Danielle Dai, "Public Perceptions of Self-Driving Cars: The Case of Berkeley, California," prepared for the 93rd Annual Meeting of the Transportation Research Board, 2013.

[97] Velodyne LiDAR, "Pluck," accessed December 9, 2016.

Other manufacturers, such as Mobileye and Tesla, plan to forego LiDAR entirely and use cameras and radar to enable full autonomy. Mobileye predicted that the Level 4 system it is developing with Delphi Automotive (for release in 2019) will add $5,000 to the cost of a new vehicle.[98]

6.1.7 Light-duty vehicle technology status conclusions

As indicated by the above discussion, LD CAV research and development activity has risen in the past decade and has accelerated in the past one to two years. Industry, academia, and government are all actively involved in propagating further advancements and validation of the technology as well as understanding the corresponding consumer behavior and adoption response. Level 1 and Level 2 CAV technology is already on the road and in users' hands. Vehicles with higher levels of automation are projected to be more widely available in the U.S. transportation market around 2020. However, actual market penetration will depend on many factors including the evolution of consumer opinion from the current skepticism and the level of regulatory involvement.

[98] Interview with Mobileye representative, December 5, 2016.

7. Medium- and Heavy-Duty Automated Vehicle Technology

Commercial and industrial applications are anticipated to be ideal applications for early adoption of automated driving technology because of the potential for operating-cost savings and increased safety. The higher capital cost of these vehicles results in the incremental cost of the automated vehicle technology being a lower percentage of the total vehicle cost. The potential energy, safety, and cost impacts on society are often much greater per vehicle than for LDV applications.[1]

While MDVs and HDVs are used for a wide variety of applications (mostly commercial) on U.S. roadways, three applications were identified as probable targets for automated vehicle development: long-haul freight delivery, local delivery, and transit bus. Other applications may be viable in the future.

7.1 Research, development, and demonstration – technology and vehicle developers

Most major medium-duty (MD) and heavy-duty (HD) truck OEMs are developing automated vehicle technology in some capacity. The disruptive nature of the technology has also attracted many startup companies that have partnered with larger organizations to develop the necessary hardware, software, and control logic required to operate advanced automated vehicles on existing roadways. Automated vehicle technology for DOT Class 8 long-haul, semi-truck applications has been the focal point of many development efforts because of the potential for market impact and potential for cost, safety, and environmental benefits.

Much of the automated truck technology development focus is on platooning two or more vehicles. Platooning is when two or more vehicles (typically 2 or 3) follow each other in close proximity for the primary purpose of reducing aerodynamic drag. Platooning reduces the aerodynamic drag for all vehicles in the platoon, although following trucks see a larger benefit. Aerodynamic drag scales with the square of vehicle speed, so platooning has the largest fuel use impact at highway speeds. Because of this, truck platooning is expected to be used primarily on highways, with limited-access highways as the preferred highway type because of the less frequent instances of vehicle entry/exit and no traffic stoppages. Current truck platooning applications do not require infrastructure changes to current highways. Fuel consumption savings vary based on vehicle speed, vehicle aerodynamics, vehicle load, following distance, and other factors. In one representative platooning test, two semi-trucks trucks were platooned at a constant 64 mph at a 36 foot following distance. This configuration resulted in an average fuel consumption saving of 4.5% for the lead truck and 10% for the following truck. (The overall "team" savings were 7.25%.[2])

Automated platooning applications use V2V communication between all vehicles in the platoon, a sensor array on each vehicle in the platoon, and drive-by-wire, brake-by-wire, and steer-by-wire systems (on Level 2+) to enable the close following distances to be safely achieved because the following vehicles react at the same time as the lead vehicle.

Automation level descriptions for platooning are consistent with the automation levels discussed throughout this report. Most platooning applications currently being developed have either Level 1 or Level 2 functionality. Level 1 platooning systems control the longitudinal position of the following trucks via acceleration and brake control. (Some describe Level 1 platooning as cooperative adaptive cruise control.) Level 2 platooning expands the following vehicle control to include lateral control (i.e., steering)

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[1] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.
[2] North American Council for Freight Efficiency, "Confidence Report: Two-Truck Platooning," September 2016.

for lane positioning and lane changes. Like other vehicle automation systems, platooning is also anticipated to reduce the mental demands on the drivers of the following trucks.

The broader category of automated trucks includes both independent single truck operation and multiple trucks as part of a platoon.

Development efforts are also ongoing for delivery and transit applications, but have seen less focus because they require higher-level automation and more challenging deployments than long-haul vehicles (due to the urban operation of these vehicles).

Daimler Trucks has been developing their "Highway Pilot" system in Europe for several years. This system allows the driver to accomplish other tasks, although he or she must remain near the controls to take over vehicle control when required. The Highway Pilot system uses an array of sensors, cameras, and V2V communication to monitor the truck's surroundings and maintain control of the vehicle. Daimler Trucks released the Highway Pilot system in 2014. Mercedes-Benz has recently adapted this technology for transit bus applications and has conducted testing on a 20-kilometer transit route in Schalkwijk (near Amsterdam).[3] The technology was adapted to allow the bus to "see" traffic lights, maneuver through intersections, avoid pedestrians and other obstacles, and automatically approach and stop at bus stops. This bus (see Figure 12) completes all driving tasks autonomously in the majority of situations. A human driver is onboard to schedule stops and to resume control of the bus in case of an emergency.[4]

Figure 12: Mercedes-Benz CityPilot bus

Freightliner (a Daimler Trucks North America company) uses the Highway Pilot system developed by parent company Daimler Trucks. It recently tested the technology on the prototype Freightliner Inspiration Truck (see Figure 13). The truck was approved for operation in Nevada for testing purposes. Drivers are still required for non-highway operation, but the long-distance drives on limited access highways can be completed with no human input after the Highway Pilot system is engaged.[5]

[3] Thomas, Peter, "The Long-Haul Truck of the Future," accessed December 9, 2016.

[4] Daimler, "The Mercedes-Benz Future Bus," accessed December 9, 2016.

[5] Daimler, "Driving Autonomously through Nevada," accessed December 12, 2016.

Figure 13: Freightliner Cascadia truck equipped with Highway Pilot

Volvo Trucks North America's automated vehicle work is focused on HD truck platooning on highways. In Europe, Volvo Trucks has extensive experience with two- and three-truck platoons using Level 2 automation technology. Volvo Trucks has also been involved in several Level 1 automation platooning efforts in the United States with technology partner Peloton Technology.[6]

Peterbilt Motor's (a PACCAR company) automated truck activity has been focused on low-level automation and driver assistance systems. In 2014 the company unveiled the Peterbilt 579 concept truck, which included adaptive cruise control and lane departure warning systems.[7] Much of Peterbilt's ongoing automated truck efforts are focused on Level 1 platooning efforts through partnerships with Peloton Technology.[6]

Navistar (parent company of International Trucks) has expressed interest in automated vehicle technologies but has provided limited information about ongoing work and future technologies. The company has stated that a new line of trucks will include predictive cruise control that will evaluate the terrain of the road in front of the trucks and automatically optimize vehicle speed and gear selection to increase fuel efficiency. This system will also reportedly allow for two-truck platooning operations.[8]

Tesla Motors announced company plans to release an automated tractor-trailer truck within the next two to three years but has not released any detailed information about the project. Elon Musk, Tesla Motors' Chief Executive Officer, has stated, "It'll be a few years after trucks can self-drive before regulators have seen enough data to feel comfortable not having a driver in the car. I think the role of [the] driver will sort of translate to fleet manager. I think that's a more interesting job than driving one."[9]

Peloton Technology has been involved in the majority of platooning demonstration efforts in the United States and provides the required hardware, software, and cloud-based communication and control for Level 1 truck platooning. Cooperative adaptive cruise control coupled with V2V communication and cloud control allow the vehicles to be "always aware" of changing weather, traffic, and other conditions to enable safe Level 1 platooning without any infrastructure requirements. Peloton Technology has demonstrated its system (shown in Figure 14) with a number of HD truck OEMs, including Peterbilt and Volvo Trucks.

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[6] Lockwood, Rolf, "Truck Platooning, Past, Present, and Future," *Truckinginfo*, April 2016.

[7] Peterbilt, "Peterbilt Showcases Autonomous Assist Driving Technology," September 9, 2014.

[8] Hawes, Clarissa, "Navistar Exec Bets Big on Autonomous Trucks and Platooning," *Trucks.com*, October 3, 2016.

[9] Lambert, Fred, "Tesla Semi: Truck Drivers Will Still be Needed for 'a Few Years', Says CEO Elon Musk," *Electrek*, November 7, 2016.

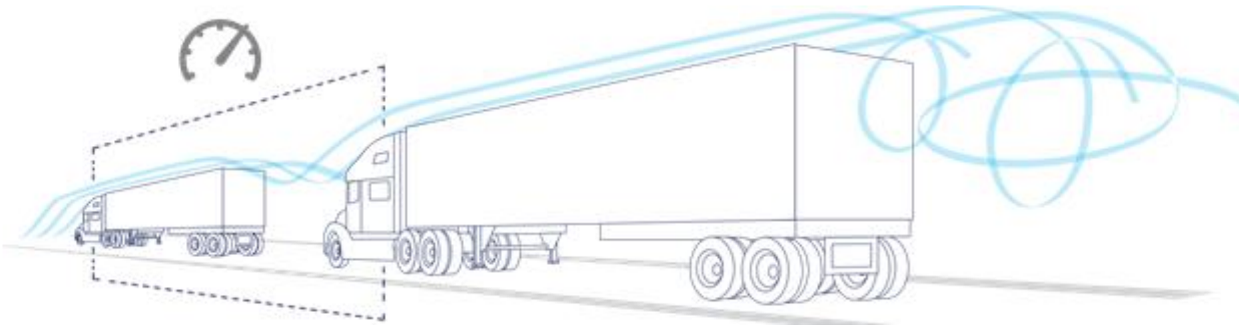

Figure 14: Peloton Technology platooning truck configuration

The **OTTO** Interstate Autopilot system provides self-driving capabilities for HD long-haul freight trucks for extended lengths of highway driving. A truck using the system hauled the first commercial cargo in October 2016 when it delivered 52,000 cans of beer on a trip that included over 120 miles of on-highway driving in Colorado (as shown in Figure 15). A human is onboard and always operates the truck when not on the highway. The driver also assumes the driving during the on-highway portion of the trip if needed, but was not required.[10]

Figure 15: OTTO self-driving truck in Colorado

Local Motors is developing a fully autonomous rapid transit mini-bus concept for urban environments. This all-electric small pod-like bus (being designed to carry up to 12 passengers) is designed to replace traditional transit bus operations in heavily populated areas. The vehicle is still early in the development stage, so limited information is available. The prototype vehicle is shown in Figure 16.[11]

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[10] O'Brien, Chris, "Otto Hauls Budweiser in First Commercial Use of Self-Driving Truck," *Trucks.com*, October 25, 2016.

[11] Local Motors, "Local Motors Debuts "Olli"", June 16, 2016.

Figure 16: Local Motor Olli concept

Waymo is reportedly working on an "autonomous delivery platform" and has recently been awarded a patent for the concept. Little is known about the concept, however the patent indicates that the truck would use a locker system that could unlock by using a PIN code or credit card to allow recipients secure access to their purchases.[12]

7.2 Medium- and heavy-duty technology status conclusions

Automated vehicle technology for MDV and HDV applications varies somewhat depending on the specific application and the required duties of the vehicles. However, the system requirements and vehicle dynamics can be loosely categorized as long-haul/highway vehicles and urban vehicles.

HD long-haul trucks that primarily travel on limited-access highway systems are expected to be the first adopters of this technology because of more restricted traffic patterns and simpler maneuvering requirements. Truck platooning provides most of the energy savings benefits that are projected to be possible with automated driving technology for this application. Since platooning can be accomplished with as low as Level 1 technology, these will be deployed earlier than higher-level automation technology. The driver cost reduction benefits provided by Level 4 and Level 5 systems may drive development of this technology if driver shortages and cost issues increase. The potential payback for long-haul vehicles is favorable because of the high annual mileage (>100,000 miles per year).

Urban operated vehicles, such as package delivery and transit applications, are expected to see limited deployment until fully automated systems are developed. These vehicles are projected to experience little, or no, energy effect from low automation levels, so are expected to focus on Level 4 and Level 5 automation. Even higher-level automation systems have limited potential to reduce fuel use and are targeted more toward congestion reduction and safety benefits. However, the adoption of automation technologies may open the door for vehicle concepts that are different from existing solutions. Transit concepts involving automated vehicle technology may focus more on rapid transit and shared mobility

[12] Murphy, Mike, "Google Wants to Deliver Packages from Self-Driving Trucks," *Quartz*, February 9, 2016.

with smaller, more versatile vehicles. Delivery vehicles could follow a similar trend with more responsive vehicles that allow for same-day delivery or even drone (wheeled or aerial) technology.

8. Energy and Safety Impacts

The widespread use of CAV technology has the potential to impact the energy consumption and safety of the U.S. transportation system. The potential energy impacts are uncertain, because of the high level of non-linear dependence between different aspects of an automated transportation system operating with conventional vehicles. The variability in potential consumer adoption and use of the technology is also a variable. Studying the potential CAV safety benefits was a secondary focus of this study. These benefits, however, may provide regulators with additional arguments to support CAV technology mandates and policies. This section briefly reviews the technology's safety implications, followed by a discussion of the existing research on the potential energy effects.

8.1 Light-duty vehicle impacts

8.1.1 Safety

Motor vehicle crashes are the cause of nearly 33,000 deaths and $871 billion of damages to society each year; avoiding these incidents is a priority for DOT and NHTSA.[1] Over 90% of these accidents are due to human error. As such, safety in the form of accident reduction is one of the most important factors when considering proliferation of automated vehicles. Incrementally removing the driver from the equation, especially in Level 3, 4, and 5 automation levels, could help avoid human driving errors and has the potential to decrease accidents.[2,3,4] There is not enough real-time vehicle usage data to quantify the safety impacts of automated vehicle technology, but according to NHTSA's 2016 report on Tesla's Level 2 Autopilot (which includes an Autosteer feature) "the data show that the Tesla vehicles crash rate dropped by almost 40 percent after Autosteer installation."[5]

8.1.2 Energy

The energy impacts on LDVs depend on three interdependent variables: vehicle miles traveled (VMT), vehicle efficiency, and consumer travel cost (basis for consumer adoption). There are a number of features and trends that either enable or complement CAV technology, the combination of which could either increase or decrease overall energy consumption through changes in these three variables. Several features and trends have the potential to decrease energy usage:

- Eco-driving
- Crash avoidance and smoother traffic flow (roadway throughput)
- Platooning
- Vehicle lightweighting and right-sizing
- Powertrain electrification
- Priority shift to de-emphasize performance in exchange for vehicle comfort and productivity
- Reduced time spent locating parking; potentially eliminating the need
- Ride-sharing

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[1] Anderson, Blair, "NHTSA V2V NPRM Update," presentation at ITS America, June 12, 2016.
[2] Ibid.
[3] Meyer, Gereon, and Stefan Deix, "Research and Innovation for European Association of Automotive Suppliers," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 72–73.
[4] Center for Sustainable Systems, University of Michigan, *Autonomous Vehicles Factsheet* CSS16-18, August 2016.
[5] Lambert, Fred, "Tesla's Crash Rate Was Reduced by 40% after Introduction of Autopilot Based on Data Reviewed by NHTSA," *Electrek*, January 19, 2017.

Others features and trends have the potential to increase energy use:

- Increased traffic congestion
- Increased highway speeds
- Increased feature content (more productivity and comfort in vehicles)
- Willingness to live further from work (longer distance commute)
- Reduced travel costs (may result in willingness to travel more miles)
- New previously unserved/underserved (e.g., mobility impacts for elderly and disabled) user groups
- Increased demand for delivery services

As suggested, there is a strong degree of inter-dependence between VMT, vehicle efficiency, and consumer travel cost impacts from these factors. The following sections describe each factor. A cumulative analysis and projection of their interactions and impact on the U.S. on-road transportation sector energy usage is provided below.

8.1.2.1 Eco-driving

Eco-driving, in particular, has a major impact on fuel economy for automated vehicles. Several recent studies have analyzed the effects of providing real-time "eco-coaching" to human drivers, indicating improvements anywhere between 10%–20%.[6,7,8,9] Automated vehicles could be programmed to follow all of the eco-driving best practices, resulting in consistent achievement of the highest possible fuel economy for each vehicle. Examples of automated driving functionality that could affect fuel economy through eco-driving include adaptive cruise control, V2I communication (e.g., coordination with traffic lights, instant notification of upcoming traffic incidents, and route optimization), and V2V communication (e.g., platooning).[10] A direct result from these functions is reduced braking. Braking is a direct waste of energy, so any reduction in braking increases energy efficiency.

Fuel consumption reductions could plateau due to congestion caused by the slower driving speeds and smoother accelerations inherent to eco-driving practices, especially as the technology is widely incorporated into the national vehicle fleet.[11]

8.1.2.2 Roadway throughput

Roadway throughput is an important metric that measures the distance between an origin and destination point on a section of roadway. As travel levels approach the roadway design capacity, congestion occurs

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[6] Barth, M., and K. Boriboonsomsin. "Energy and Emissions Impacts of a Freeway-Based Dynamic Eco-Driving System." *Transport. Res. Part D: Transport Environ*, 14 no. 6 (2009), pp. 400–410.

[7] Berry, I. M., "The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of US Light-Duty Vehicles," (Master's thesis, Massachusetts Institute of Technology), 2010.

[8] Degraeuwe, B., and B. Beusen, "Corrigendum on the Paper Using On-Board Data Logging Devices to Study the Longer-Term Impact of an Eco-Driving Course." *Transport. Res. Part D: Transport Environ.*, 2013.

[9] Wu, C., G. Zhao, and B. Ou, "A Fuel Economy Optimization System with Applications in Vehicles with Human Drivers and Autonomous Vehicles." *Transport. Res. Part D: Transport Environ*, 16 no. 7 (2011), pp. 515–524.

[10] Anderson et al., *Autonomous Vehicle Technology: A Guide for Policymakers*. RAND Corporation (Santa Monica, California, 2016).

[11] Wadud, Zia, Don MacKenzie, and Paul Leiby, "Help or Hindrance? The Travel, Energy and Carbon Impact of Highly Automated Vehicles," *Transportation Research Part A*, 86 (2016), pp. 1–18.

and throughput declines. Intuitively, CAV technologies could enable higher throughput during peak travel times via decreased accidents, smoother driving techniques, and communication with infrastructure and other vehicles.[12] INRIX reported that inefficiencies that occur because of roadway throughput limitations cost the U.S. economy approximately $124 billion in 2013, and this figure is projected to increase to $186 billion by 2030.[13] A European Association of Automotive Suppliers study indicated that mitigating congestion through traffic flow management and automated time-efficient driving could increase roadway throughput in the U.S. and worldwide.[14] A CAV energy impacts study indicated that adaptive cruise control, if used by a majority of vehicles, could increase lane capacity by up to 80%.[15] Even decreasing the number of accidents could reduce congestion, because up to 25% of congestion is caused by traffic incidents.[16] Lower-level automated vehicles (Level 1 and Level 2) could achieve these benefits if their market penetration is high enough.

These positive effects on roadway throughput and congestion mitigation are dependent on a limited increase in both number of vehicles on the road and annual VMT per vehicle. If the number of vehicles and/or the annual per vehicle VMT drastically increases, congestion could worsen rather than improve. Several of the factors that could cause this are discussed below. A few influencers include reduced perceived travel costs, increased mobility access for underserved groups (discussed in the next section), and passenger-less travel (e.g., a vehicle driving around while waiting for its owner/passenger to return).

8.1.2.3 Increased mobility for underserved groups

Level 4 and Level 5 automated vehicles will increase mobility options for more citizens. People who previously had limited or no commuting options (e.g., elderly, handicapped, and young people) will have increased mobility options, which could increase travel. This is a direct repercussion of increased access to transportation and population growth, especially as the U.S. population ages. Over the next 25 years, Deloitte projects VMT increases as high as 25% due to population growth and the extension of transportation to previously immobile citizens.[17] Carnegie Mellon University estimates that expanding the current driving population to include people who cannot obtain a driver's license (non-drivers, elderly, and those with travel-restrictive medical conditions) could increase VMT by 14%, which adds 295 billion miles of driving annually.[18] One additional consideration, addressed in a case study by Chong et al.,[19] is the possibility of increased public transportation use because of increased accessibility to train and transit

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[12] Alexander-Kearns, Myriam, Miranda Peterson, and Alison Cassady, "The Impact of Vehicle Automation on Carbon Emissions: Where Uncertainty Lies," Center for American Progress, November 18, 2016.

[13] INRIX, *The Future Economic and Environmental Costs of Gridlock in 2030*, Centre for Economics and Business Research, August 2014.

[14] Meyer, Gereon, and Stefan Deix, "Research and Innovation for European Association of Automotive Suppliers," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 72–73.

[15] Fagnant, Daniel, and Kara Kockelman, *Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations*, Eno Center for Transportation (Washington, DC, October 2013).

[16] Anderson et al., *Autonomous Vehicle Technology: A Guide for Policymakers*. RAND Corporation (Santa Monica, California, 2016).

[17] Corwin, Scott, Nick Jameson, Derek M. Pankratz, and Philipp Willigmann, "The Future of Mobility: What's Next?," Deloitte University Press, September 14, 2016.

[18] Grabar, Henry, "How Will Self-Driving Cars Change Cities? It Depends on Who Owns Them," *Slate*, October 25, 2016.

[19] Chong et al., "Autonomous Personal Vehicle for the First- and Last-Mile Transportation Services," proceedings of the 2011 IEEE 5th International Conference on Cybernetics and Intelligent Systems, CIS (2011), pp. 253–260.

stations provided by fully autonomous taxis for the first- and last-mile assistance. As with the other metrics, the cumulative VMT effect is difficult to ascertain.

8.1.2.4 Vehicle lightweighting

Reduced crash rates could enable vehicle OEMs to produce lighter vehicles if satisfying safety regulations enabled using less safety equipment. In this case, the responsibility for ensuring safety would shift from the vehicle chassis and structure to the autonomous system. This would only be possible if federal vehicle safety regulations were modified to reflect the effect CAVs had on safety improvements. Additionally, for Level 5 automation, manufacturers could remove steering wheels, foot pedals, transmission control (shifters), and other user-operated driving-related equipment. Worthwhile lightweighting from these sources would likely only occur if/when there was an extremely high population of highly-automated vehicles, which is not estimated to happen for many years.

Conversely, it is possible that vehicle weight could increase from integrating additional comfort and entertainment features into the vehicle as passengers trust in automated vehicles increases enough to take them on more frequent and potentially longer trips. The impact of this is not yet quantifiable.

8.1.2.5 Powertrain Electrification

Powertrain electrification and CAVs are viewed by many as mutually beneficial technologies. Hybrid-electric vehicles and full electric vehicles' (EVs) precise power control is beneficial for implementing eco-driving approaches. EVs are typically configured for drive- and brake-by-wire, which are enabling systems for automated driving. Replacing mechanical linkages with these systems can reduce weight and introduce additional design options for vehicle manufacturers.[20] The perceived cost and inconvenience of charging EVs could be reduced or eliminated by the vehicles autonomously driving to a charging station when not in use.

Other CAV-enabled trends such as vehicle lightweighting and car sharing are expected to greatly improve the utility of EVs. These trends support the development of shared autonomous vehicle Mobility-as-a-Service (MaaS) business models, which are expected to initially be deployed in dense urban markets (see Section 8.1.2.7). Car sharing and MaaS enables amortization of the high EV battery costs over a larger consumer base. Vehicles used in MaaS systems would likely be owned by transportation-network companies, fleet operators, or other companies rather than individual users. This shift in ownership model would signify an important shift in personal mobility priorities, from performance and style to lowering the cost per mile to attract more customers with lower rates. Delphi Automotive estimates that vehicles in these future fleets will travel between 70,000–80,000 miles per year, compared to the average 12,000 – 15,000 miles per year for personally-owned vehicles.[21] For additional comparison, taxis in New York City drive an average of 70,000 miles per year.[22] EVs are less mechanically complex and are extremely reliable.[23] Electricity is much less expensive per unit of energy than liquid fuels. Consequently, EVs could gain increased operating cost advantage as the annual miles driven per year increases because of the combined lower energy and maintenance costs compared to traditional internal combustion engine-based vehicles. Other factors that could run parallel with the introduction of vehicle autonomy and affect manufacturer and fleet vehicle type choices include: implementation of low-emission zones in U.S. urban

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[20] Gardner, Greg, "The Self-Driving Revolution Will Be Mostly Electric," *Detroit Free Press*, September 21, 2016.
[21] Ibid.
[22] New York City Taxi & Limousine Commission, 2014 Taxicab Factbook, 2014.
[23] Idaho National Laboratory, How Do Gasoline & Electric Vehicles Compare, accessed February 7, 2017.

areas (such as those seen in Europe[24]), vehicle OEM difficulty in meeting greenhouse gas and Corporate Average Fuel Economy standards, and uncertain challenges with charging/refueling (i.e., rapid battery charging infrastructure versus automated gasoline pumps).

However, whether or not electric vehicles have the potential to be widely used in CAVS will depend on battery pack cost reduction, which could come from reduced driving range per charge requirements and/or reduced pack manufacturing costs. Electrification will not proliferate if the technology does not provide a vehicle that is less expensive, more reliable, and more efficient for the public than an equivalent conventional powertrain, or without infrastructure sufficient to support such EVs

8.1.2.6 De-emphasized performance

Modern drivers continue to demand consistently greater performance, generally signified by increased acceleration. However, research indicates that a 1% increase in 0–60 mph time equates to a 0.44% decrease in fuel consumption per mile (when other vehicle attributes are held constant).[25] Stabilizing the vehicle acceleration increases could decrease future energy intensity by about 5%, while reverting vehicle acceleration capabilities to 1982 levels (0-60 mph times between 14-15 seconds) and maintaining highway speed capabilities could reduce fuel consumption by 23%.[26] Increased highway speeds (see Section 8.1.2.10) could offset this fuel savings potential due to higher performance requirements.

8.1.2.7 Productivity and comfort in highly-automated vehicles

Highly-automated vehicles have the opportunity for increased “hands-off” driving. Automated vehicles could increase driver productivity and comfort by relieving them of the responsibility to pay full and constant attention to the driving task. Lower stress and higher productivity are attractive value propositions for highly-automated vehicles, and would likely be responsible for a large portion (30-40%) of the overall CAV-enabled travel cost reduction.[27]

Increased productivity is not guaranteed. A University of Michigan Transportation Research Institute study indicated that “for 62% of Americans, self-driving vehicles currently are not likely to result in an improvement of productivity.”[28] This is primarily because many consumers would be apprehensive when riding in self-driving cars and would not take their eyes off the road. Additionally, many riders may struggle with motion sickness,[29] and light-duty vehicle trips average approximately 19 minutes, which is not enough time for sustained productivity or sleep. Many OEs are implementing CAVs through a ride-sharing service first before selling them directly to consumers. This may be a way to gain rider trust and reduce adverse perspectives. Overall, improved productivity and comfort lean toward increased energy usage due to potentially higher use of vehicles (i.e., increased VMT) and heavier vehicles (see Section 8.1.2.4).

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[24] European Commission, Urban Access Regulations, “Home,” accessed January 20, 2017.

[25] MacKenzie, D., “Fuel Economy Regulations and Efficiency Technology Improvements in U.S. Cars Since 1975,” (Doctoral dissertation, Massachusetts Institute of Technology), 2013.

[26] Wadud, Zia, Don Mackenzie, and Paul Leiby, “Help or Hindrance? The Travel, Energy and Carbon Impact of Highly Automated Vehicles,” *Transportation Research Part A: Policy and Practice*, 86 (April 2016), pp. 1–18.

[27] Ibid.

[28] Sivak, Michael, and Brandon Schoettle, “Would Self-Driving Vehicles Increase Occupant Productivity?,” The University of Michigan, Transportation Research Institute, 2016.

[29] Diels et al., “Motion Sickness in Automated Vehicles: The Elephant in the Room,” *Road Vehicle Automation 3*, Springer International Publishing (2016), pp. 121–129.

8.1.2.8 Reduced parking and ride-sharing

Vehicle use and ownership models will likely be affected as more automated vehicles enter the vehicle population. Four main CAV ownership models are being evaluated: 1) full ownership, 2) partial ownership, 3) "own and share", and 4) fleet ownership. The partial or fractional ownership model is in the early stage of development. One example is the Ford Credit Link program, which allows 3-6 customers to share a single Ford vehicle lease. Another example is the Audi Unite program, which allows up to 5 customers to share the lease of an Audi car. The Unite service also includes other services such as cleaning and pickup and delivery for maintenance. The potential diversity of CAV owners and how they will use the vehicles presents additional challenges. For example, CAVs are not projected to change the established model of full vehicle ownership for luxury car owners, who are more willing to pay a premium for a personal car.[30] Conversely, the larger population is more likely to take advantage of the potentially lower travel costs associated with the own-and-share and/or partial ownership models. Increased ride-sharing and/or partial ownership model utilization in this latter group, including the addition of new riders and owners due to CAV technology (see Section 8.1.2.3), could increase total traffic volume and annual fleetwide VMT.

The popularity of ride-sharing services is rapidly growing as transportation network companies such as Uber and Lyft expand their geographic coverage. Figure 17 is a map of ride-sharing network coverage in the United States at the time of this writing.[31] The current business models for transportation network companies rely on using human drivers, but autonomous vehicles are targeted to be phased in. This change could revolutionize the ride-hailing/sharing industry by reducing costs, and increasing vehicle energy efficiency. Initial estimates indicate that the per-mile vehicle operating cost for Uber could be reduced by over 80% with autonomous vehicles. (The analysis included the removal of the driver and the added cost of CAV technology.) If achieved, this would undercut the per-mile operating cost of personal vehicle ownership by 50%.[32,33] Rocky Mountain Institute analysis predicts that fully autonomous taxi transportation will reach near cost parity with personal vehicle ownership and operation by 2018 (see Figure 18).[34] The National Renewable Energy Laboratory's (NREL) 2016 study on CAVs indicates that, in a fully autonomous ridesharing scenario, travelers could realize a 60% decrease in cost per passenger mile (accounting for cost of travel time as well).[35] ARK Investment's research estimated that when Uber lowered its San Francisco prices by 60% between 2013 and 2014, annual VMT for Uber's San Francisco vehicles increased eightfold (from 17 million miles to 140 million miles)[36], while the number of drivers available increased by a factor of four[37]. The average number of standard taxi trips per month declined from 700 to 504, and the share of MaaS offerings (e.g., taxi cab, Uber, and Lyft) increased from 0.4% to

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[30] Jaynes, Nick, "How Driverless Cars Will Change Car Ownership Forever," *Mashable*, May 30, 2016.

[31] UP HAIL, "Taxi & Rideshare Services in the United States," accessed December 13, 2016.

[32] Burns, Lawrence D., William C. Jordan, and Bonnie A. Scarborough, *Transforming Personal Mobility*, The Earth Institute, Columbia University, January 27, 2013.

[33] Kenney, Tasha, "Shared Autonomous Vehicles Will Make Ride Services 30 Times More Attractive," ARK Investment Research, September 15, 2016.

[34] Johnson, Charlie, and Jonathan Walker, *Peak Car Ownership: The Market Opportunity of Electric Automated Mobility Services*, Rocky Mountain Institute, 2016.

[35] Stevens, et. al., *Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles*, National Renewable Energy Laboratory, 2016

[36] Kenney, Tasha, "Shared Autonomous Vehicles Will Make Ride Services 30 Times More Attractive," ARK Investment Research, September 15, 2016.

[37] Hall, Jonathan, and Alan Krueger, *An Analysis of the Labor Market for Uber's Driver-Partners in the United States*, January 22, 2015.

0.6% of total San Francisco VMT between 2013 and 2014. Additionally, the average Uber total fare during this period remained constant. This analysis indicates that customers were utilizing Uber's services more frequently and for longer distances, partially due to the lower per mile cost.

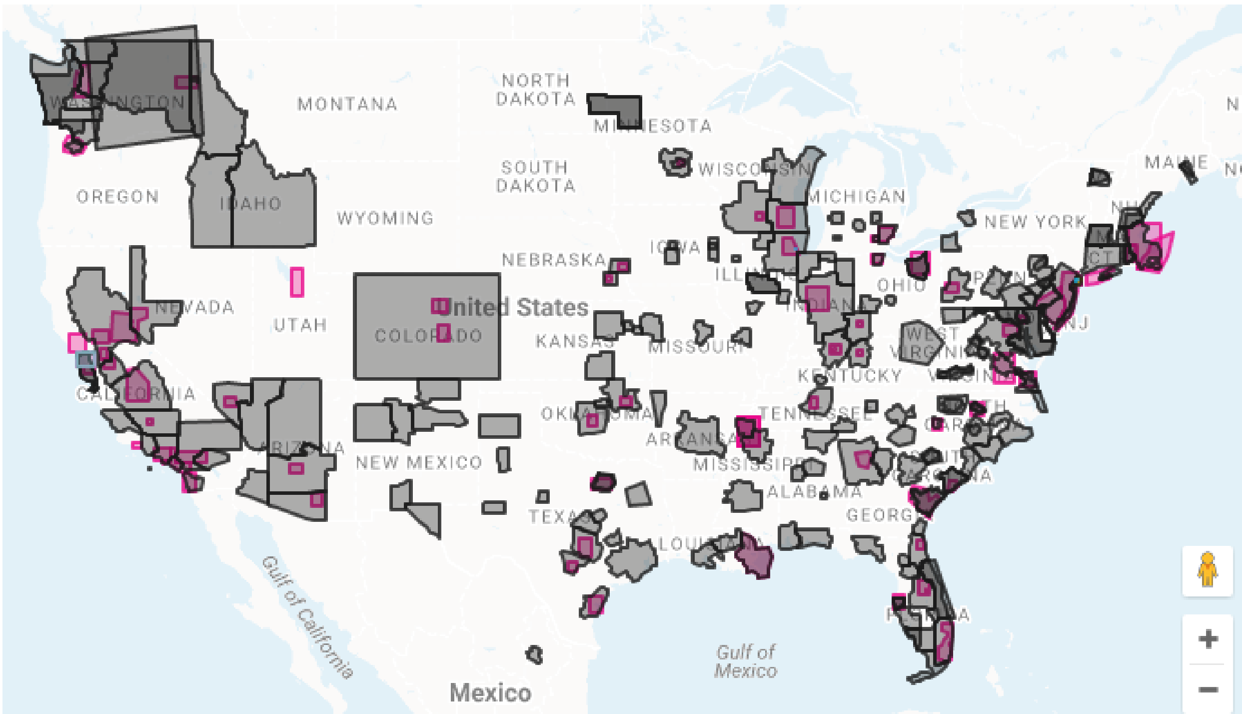

Figure 17: Ridesharing coverage of the United States

Note: Uber: gray; Lyft: pink

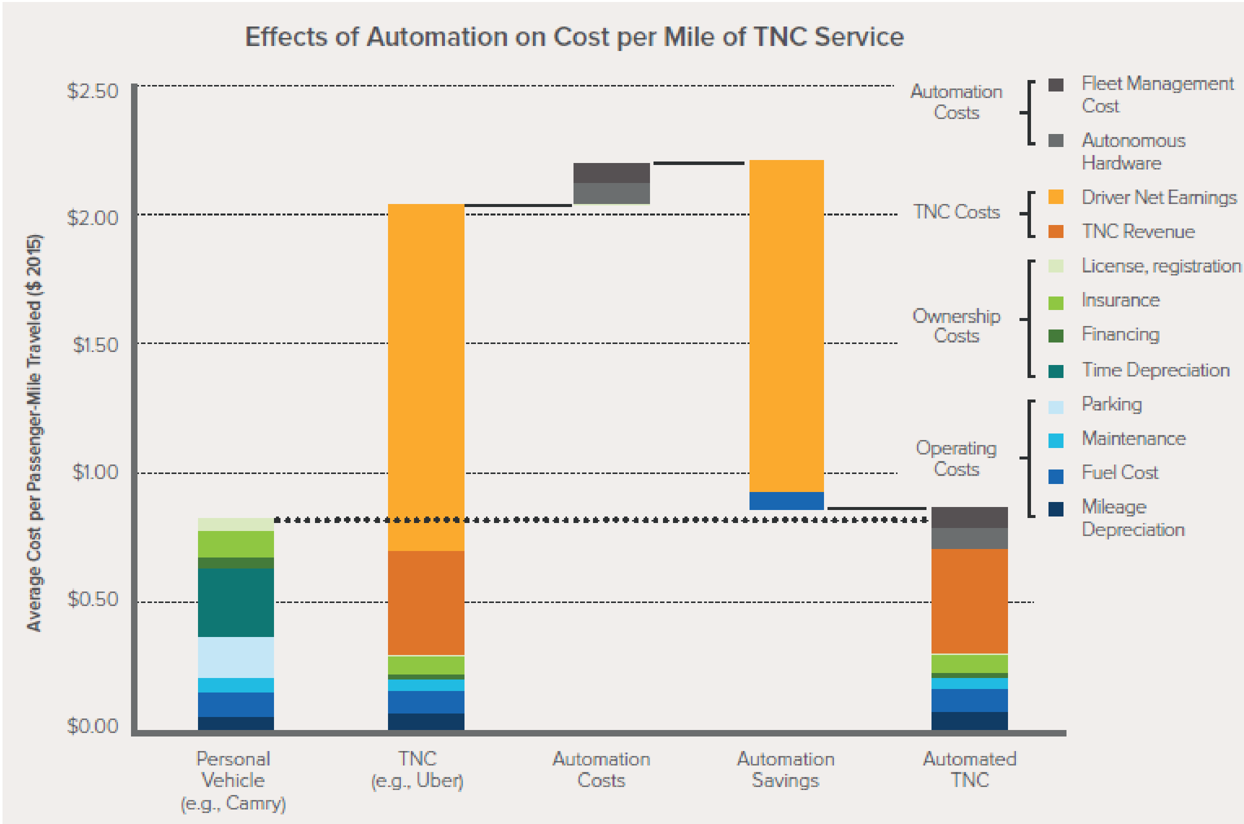

Figure 18: Effects of automation on cost-per-mile of transportation network company service[38]

Pooling multiple passenger trips into a single vehicle could increase the efficiency of travel, offsetting some of the energy usage gains caused by affordable autonomous taxis; more riders per car means less energy used per person-mile. Lyft's pooling service, LyftLine, is available in 15 cities at the time of this writing, and 40% of passenger rides in those cities requested LyftLine.[39] Uber's ride-pooling service UberPOOL is also available in some global markets, and is demonstrating and evaluating how this type of system could work. Consumers may not see a financial benefit from ride-pooling if the projected travel cost reductions are achieved.

An average car spends 95% of its lifetime idle and parked.[40] Proliferation of CAVs could enable networks of shared vehicles (automated taxis) that can pick people up on demand. The resulting increased vehicle utilization could result in reductions in parking requirements. In this scenario, passengers spend less time and fuel searching for parking. This shift could also dramatically change urban land-use patterns.

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[38] Johnson, Charlie, and Jonathan Walker, *Peak Car Ownership: The Market Opportunity of Electric Automated Mobility Services*, Rocky Mountain Institute, 2016.

[39] Interview with Lyft representative, December 14, 2016.

[40] Barter, Paul, "'Cars Are Parked 95% of the Time.' Let's Check!," Reinventing Parking, February 22, 2013.

A case study of Singapore found that shared vehicles could reduce the country's vehicle fleet by two-thirds.[41] A 2014 study by Fagnant and Kockelman found that a single shared vehicle could replace between 9 and 13 urban vehicles.[42] Car sharing and reduced vehicle ownership of highly automated vehicles provide opportunities to decrease VMT.[43] However, considering other metrics under discussion (e.g., increased mobility to underserved groups and increased productivity and convenience), it is possible that this phenomenon could increase VMT.

McKinsey & Company and Stanford University predict that new business models based on shared mobility and connectivity services could expand automotive revenue pools by close to 30% and potentially lead shared vehicles to 10% market penetration by 2030 and 33% by 2050.[44] Lyft founder John Zimmer recently said that car ownership will "all but end" by 2025.[45] Several automotive OEMs have moved toward ride-sharing applications, strongly indicating that the market is indeed shifting. Table 6 broadly summarizes these investments, acquisitions, and partnerships. Germany's *Manager Magazin* reported that BMW and Daimler are considering merging their two ride-sharing services to increase competition with Uber and Lyft.[46]

Table 6: Automotive vehicle and technology developer involvement in ride-sharing services

OEM	***Ride-Share Service Partner***	***Type***
Audi	Audi at Home	Internal
BMW	ReachNow (powered by RideCell)	Internal
Daimler	Car2Go	Internal
	Croove	Internal
	Uber	Partnership
Ford	Ford Credit Link	Internal
GM	Lyft	Investment
	Maven	Internal
Toyota	Uber	Memorandum of Understanding/Investment
VW	Gett	Investment
Volvo	Uber	Partnership
	Sunfleet	Internal

41 Spieser et al., "Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems A Case Study in Singapore," Road Vehicle Automation, Springer Lecture Notes in Mobility series (April 2014).

42 Fagnant, Daniel, and Kara Kockelman, "The Travel and Environmental Implications of Shared Autonomous Vehicles, Using Agent-Based Model Scenarios," *Transportation Research Part C: Emerging Technologies* 40 (March 2014), pp. 1–13.

43 Barcham, Raphael, "Climate and Energy Impacts of Automated Vehicles," California Air Resources Board, June 2014.

44 McKinsey, and Stanford University, "Automotive Revolution – Perspective Towards 2030," Stanford University, PEEC Sustainable Transportation Seminar, (January 1, 2016), p. 1–20.

45 Carson, Biz, "Lyft President: Car Ownership Will 'All-But End' in Cities by 2025," *Business Insider*, September 18, 2016.

46 Etherington, Darrell, "BMW and Daimler Could Bring Their Car-Sharing Services Together," *TechCrunch*, December 15, 2016.

Note that this decrease in overall vehicle fleet size does not necessarily imply a massive decrease in annual vehicle sales; with higher utilization rates, fleet turnover will accelerate and offset a portion of the sales lost from reduced personal ownership.

Projected near-term market sales effects from car sharing will be slow. Boston Consulting Group estimates that the trend will reduce overall global vehicle sales by only 0.5% by 2021.[47] However, ride sharing is projected to have major impacts in the near future. Because of ride sharing, shared CAVs are projected to account for 70% of total new car sales in U.S. urban areas by 2040. Personally-owned CAVs, personally-owned conventional cars, and shared conventional vehicles are projected to each account for 10% at this time (see Figure 19).[48]

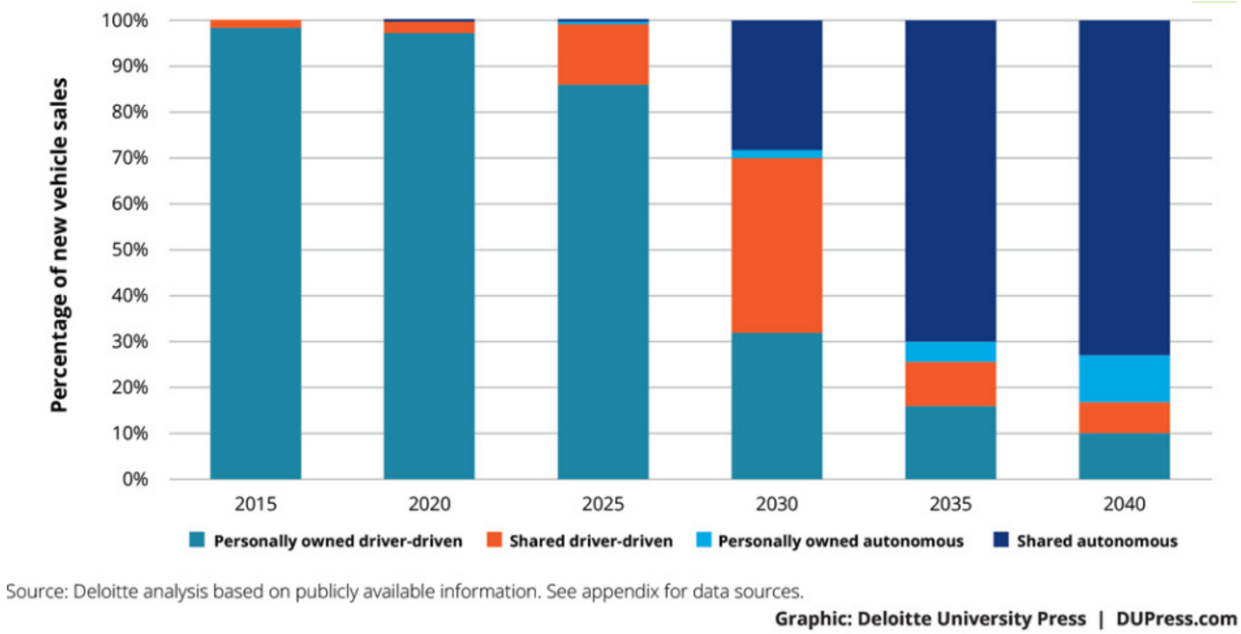

Figure 19: Forecast of new vehicle sales distribution in urban areas in the United States[49]

Other trends such as reduced interest in vehicle ownership, whether by avoiding or delaying purchasing, and driver's licenses in younger demographics, could affect the shared transportation model's market penetration.[50,51]

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[47] Bert, Julien, Brian Collie, Marco Gerrits, and Gang Xu, "What's Ahead for Car Sharing?," Boston Consulting Group, February 2016.

[48] Corwin, Scott, Nick Jameson, Derek M. Pankratz, and Philipp Willigmann, "The Future of Mobility: What's Next?," Deloittee University Press, September 14, 2016.

[49] Ibid.

[50] Kurz, Christopher, Geng Li, and Daniel Vine, "The Young and Carless? The Demographics of New Vehicle Purchases," United States Federal Reserve System, June 24, 2016.

[51] Sivak, Michael, and Brandon Schoettle, *Recent Decreases in the Proportion of Persons with a Driver's License across All Age Groups* UMTRI-2016-4, University of Michigan, Transportation Research Institute, (Ann Arbor, Michigan, January 2016).

8.1.2.9 Vehicle right-sizing

Ride sharing could enable vehicle right-sizing. This could provide benefits similar to vehicle lightweighting. Highly-automated vehicle fleets could send the most efficient vehicle to meet consumer demands. One possibility is that individual travelers could be picked up by single-rider cars, and multiple-rider-cars would only be used for groups or ride-sharing to ensure maximum capacity as often as possible. It has been estimated that a 21% reduction in fuel consumption is possible using currently-available vehicle technology, redistributing groups of 1-2 travelers into compact cars, 3-4 travelers into midsize cars, and 5-7 travelers into minivans.[52] Use of more weight- and size-optimized single-occupancy vehicles has been projected to decrease the per-vehicle fuel consumption by 45% compared to the compact cars they replace.[53] This is the upper bound for minimizing fuel consumption via vehicle right-sizing, since highly-optimized passenger movement is not the primary goal travelers consider when choosing vehicle size. Other considerations include: towing capacity, exterior equipment racks, cargo capacity, and child car seats.

8.1.2.10 Increased Highway Speeds

As driving decisions become less dependent on human reaction times and attention span, the legal roadway speeds could be increased. The potential congestion reduction and increased consumer trust in automated vehicle technology could accelerate this change. Increased highway travel speeds leads to higher aerodynamic losses and increased energy use per VMT. Researchers quantified this effect by estimating how much faster vehicles could travel, assuming that travelers would understand the trade-off between increased fuel cost and decreased travel time. They found that average LDV speeds could increase from 65-70 mph up to 79 mph, and assuming highway travel is 33% to 55% of all miles traveled (based on Federal Highway Administration data), this would yield 7%–22% higher energy use in the LDV sector.[54]

8.1.3 Cumulative energy impacts

The combined effects of each of these metrics and features exhibit wide variability in VMT, congestion, and fuel consumption. This variability is based on potential changes in transportation affordability, convenience, accessibility, efficiency, and performance. Lawrence Berkeley National Laboratory studied the interdependence of the previously discussed potential energy impact factors and classified them based on complexity, uncertainty, and influence. Its proposed list (Figure 20) shows that consumer choice factors are the primary source of uncertainty when analyzing future energy impacts of CAV technology, specifically because those factors are the most influential for actual usage and adoption of automated vehicle technology.[55]

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[52] Wadud, Zia, Don MacKenzie, and Paul Leiby, "Help or Hindrance? The Travel, Energy and Carbon Impact of Highly Automated Vehicles," *Transportation Research Part A*, 86 (2016), pp. 1–18.

[53] Ibid.

[54] Ibid.

[55] Morrow et al., "Key Factors Influencing Autonomous Vehicles' Energy and Environmental Outcome," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 127–135.

Category	Key factors	
Vehicles characteristics	Weight	
	Performance[a]	
	Right-sizing[b]	*Increasing*
Transportation network	Communication[c]	*Complexity,*
	Roadways	*Uncertainty*
Consumer choice	Services (passengers and freight)	*& Influence*
	Vehicle miles traveled	
	Communities (the build environment)	

Figure 20: Key factors influencing the energy outcomes of widespread CAV adoption

On a vehicle efficiency basis, the National Research Council speculated that lightweight, low-speed (100 kilometer-per-hour top speed), 1-2 passenger networked autonomous vehicles have the potential to achieve fuel economies an order of magnitude higher than current cars. Additional research suggests fuel economies of over 500 mpg could be possible if the transportation system exclusively used purpose-built single-passenger pods with vehicle automation technologies to maximize energy efficiency and safety.[56] These vehicles would be for city commuting only, and would require drastic changes in both safety standards and consumer performance and comfort expectations. This does not necessarily indicate a system-wide fuel consumption decrease; rather it identifies the technology potential for one car without considering an increase in vehicle population or VMT. RAND Corporation compiled the research from these studies into Figure 21.[57]

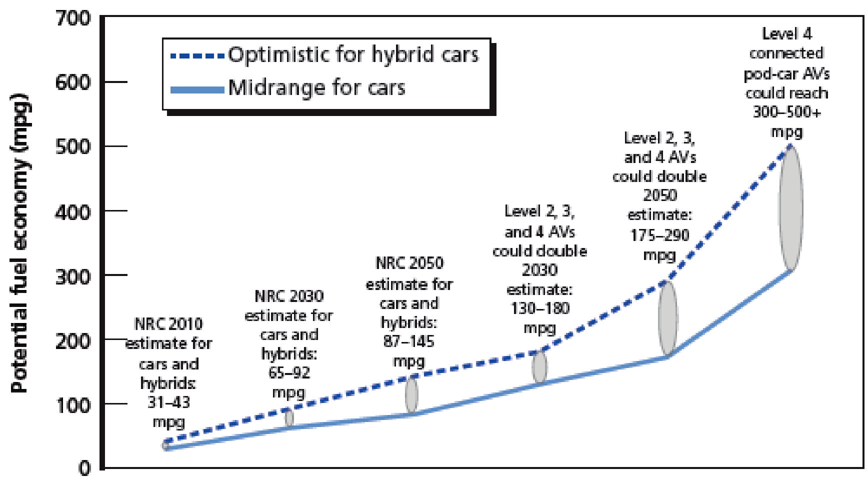

Figure 21: Potential increases in vehicle fuel economy over time by introducing autonomous vehicles into the market[58]

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[56] Folsom, Tyler C., "Energy and Autonomous Urban Land Vehicles," *Technology and Society Magazine*, 31 no. 2 (2012), pp. 28–38.

[57] Anderson et al., *Autonomous Vehicle Technology: A Guide for Policymakers*, RAND Corporation (Santa Monica, California, 2016).

[58] Ibid., "Figure 2.6."

This analysis does not adequately address the *system level* impacts of autonomous vehicles. Evaluating system level impacts must account for the various VMT effects of lowered cost (e.g., faster travel, easier access, and financial savings). Existing research indicates that system energy impacts, accounting for all of the potential changes discussed in this section, are highly uncertain. A 2014 NREL study estimates that the total energy consumption impacts can range from a 90% decrease to a 200% increase in fuel consumption using 2050 baseline energy.[59] Figure 22 and Figure 23 demonstrate the effect widespread use of autonomous vehicles could have on vehicle level fuel consumption in the U.S.[60,61] Lawrence Berkeley National Laboratory reached a similar conclusion, citing a range of an 80% decrease up to a 100% increase in fuel consumption.[62]

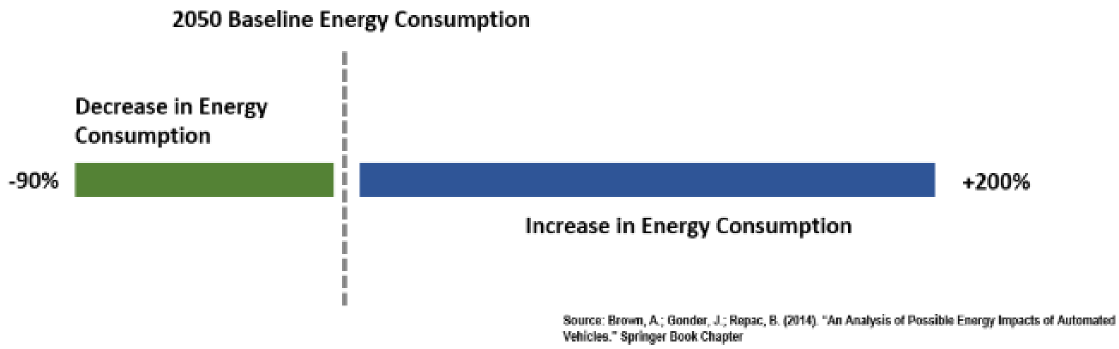

Figure 22: 2050 baseline energy consumption forecasts for autonomous vehicles

[59] Brown, Austin, Jeffrey Gonder, and Brittany Repac, "An Analysis of Possible Energy Impacts of Automated Vehicle," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 137–153.

[60] Wadud, Zia, Don MacKenzie, and Paul Leiby, "Help or Hindrance? The Travel, Energy and Carbon Impact of Highly Automated Vehicles," *Transportation Research Part A*, 86 (2016), pp. 1–18.

[61] Brown, Austin, Jeffrey Gonder, and Brittany Repac, "An Analysis of Possible Energy Impacts of Automated Vehicle," *Road Vehicle Automation*, Springer International Publishing (2014), pp. 137–153.

[62] Morrow et al., "Key Factors Influencing Autonomous Vehicles' Energy and Environmental Outcome*," Road Vehicle Automation*, (2014), pp. 127–135.

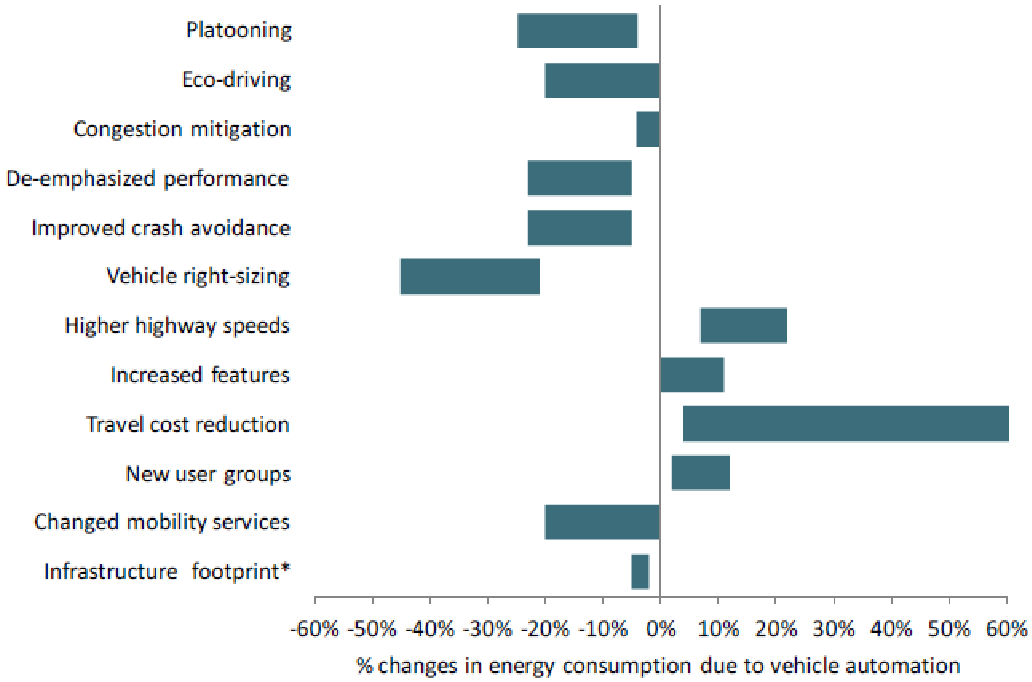

Figure 23: Automated vehicle factors and their respective impacts on fuel consumption

The most recent research on overall system VMT and fuel consumption effects due to vehicle automation is from a multi-laboratory collaboration between Argonne National Laboratory, NREL, Oak Ridge National Laboratory, and U.S. Department of Energy.[63] Researchers forecasted the potential effects of vehicle autonomy on national LDV VMT (see Figure 24) and vehicle efficiency (see Figure 25). The study looks at four scenarios: conventional vehicles (no autonomy), partial autonomy, full autonomy with ridesharing, and full autonomy without ridesharing, and associates upper and lower bounds (UB and LB) with the latter two. There is large variation in the results; VMT estimates range from a decrease of half a trillion miles up to an increase of 6 trillion miles, and average vehicle fuel consumption per 100 miles ranges from a 60% decrease up to a 200% increase.

[63] Stephens et al., *Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles* NREL/TP-5400-67216, National Renewable Energy Laboratory (Golden, Colorado, November 2016).

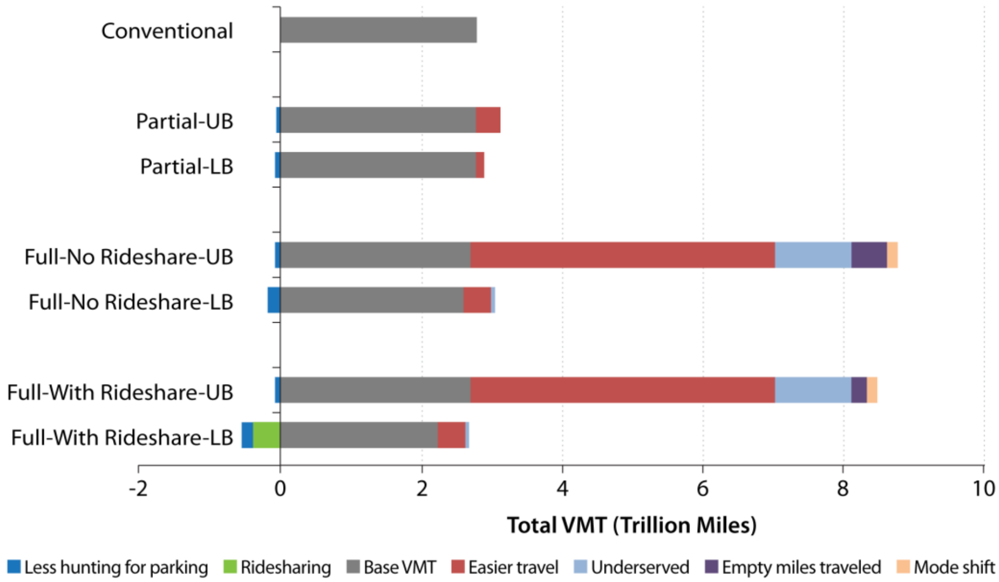

Figure 24: Bounds for potential nation light-duty vehicle VMT, comparing conventional and CAV scenarios[64]

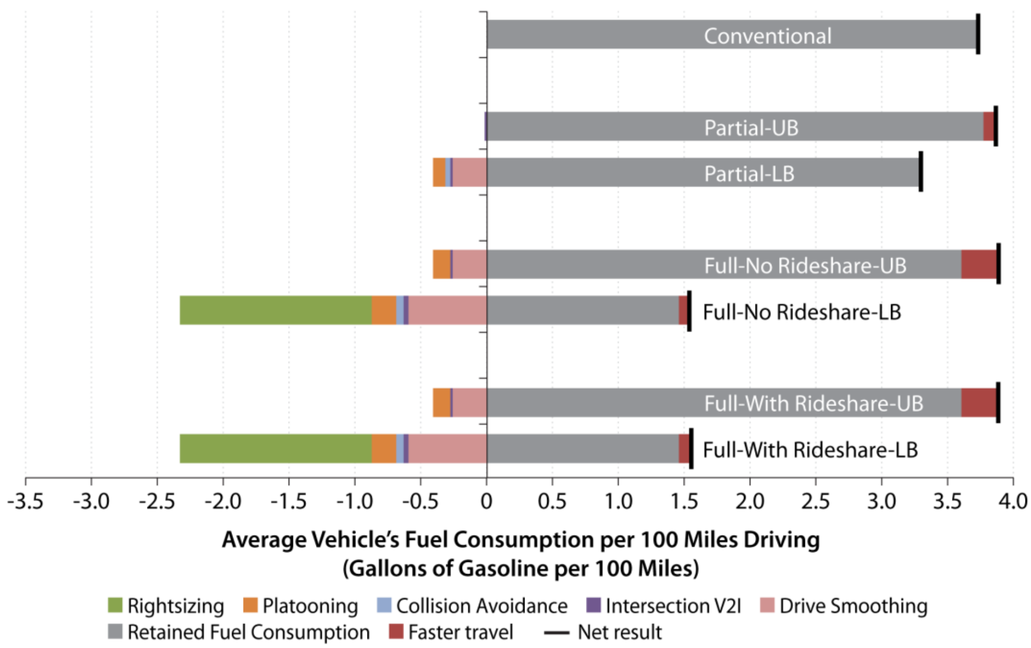

Figure 25: Bounds for potential light-duty vehicle fuel consumption rate, comparing conventional and CAV scenarios[65]

The study used VMT and fuel consumption analyses to predict how CAV technology could affect consumer travel cost, looking at vehicle purchase price, maintenance and repair cost, connectivity service

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[64] Stephens et al., *Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles* NREL/TP-5400-67216, National Renewable Energy Laboratory (Golden, Colorado, November 2016).

[65] Ibid.

fees, insurance adjustments, fuel cost, and travel time cost (see Figure 26). The researchers found that the largest cost decreases came from heavily reduced cost of travel time in the fully autonomous scenarios (both with and without rideshare); up to 60% reductions are estimated in the full-with rideshare scenario. Partial autonomy nets the only increase in consumer travel cost, around 3%–4%, primarily because of increased vehicle purchase cost from new CAV technologies that do not greatly influence vehicle efficiency.

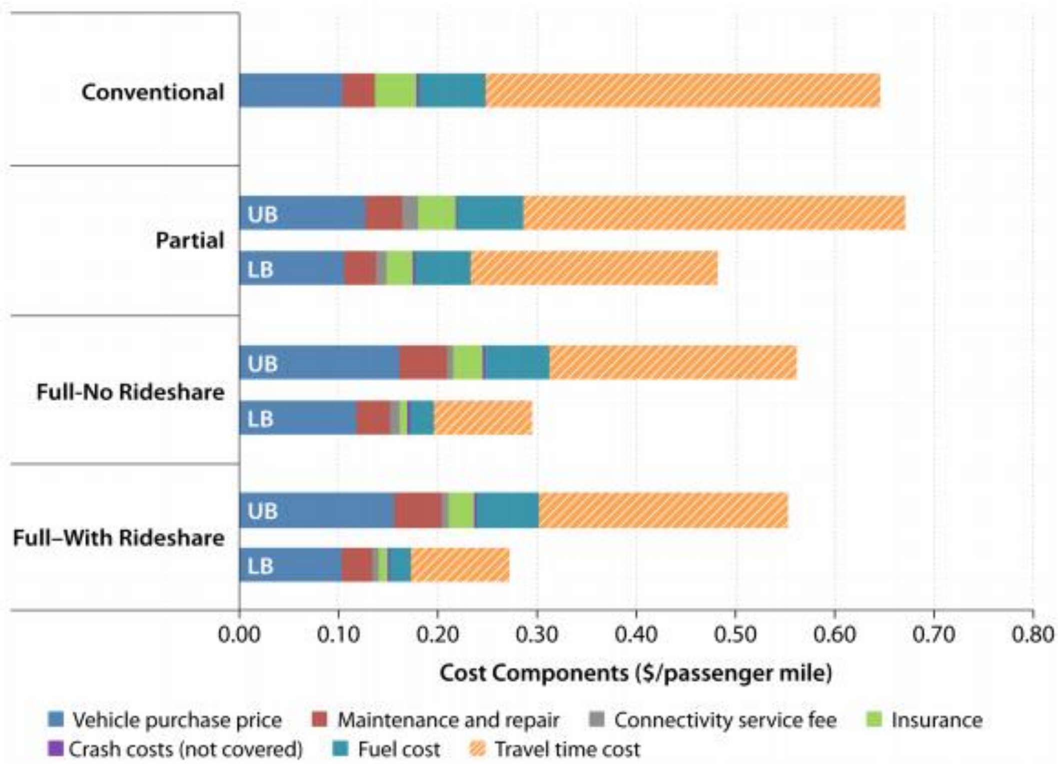

Figure 26: Bounds on potential consumer cost effects under the conventional and CAV scenarios[66]

One of the more important conclusions from this data is the interaction between VMT, fuel consumption, and consumer cost. The lowest cost per passenger mile use cases (full with and without rideshare) are very likely to be associated with the highest VMT; the two trends mutually reinforce each other. As the cost of travel decreases, more consumers will travel. Industry, government, and other stakeholders do not fully understand the extent of this mutual reinforcement. As discussed earlier in this section and shown by the cumulative analysis above, there is additional uncertainty regarding CAV technology effects on vehicle efficiency. The prioritization of eco-driving practices, influence on traffic and congestion, implementation of vehicle right-sizing, and enabling of alternative fuel powertrains are all unknowns. As a result, the full energy impacts of LDV autonomy remain highly uncertain.

8.2 Medium- and heavy-duty automated vehicle impacts

MD and HD truck automated vehicle technologies have the potential to improve fuel efficiency, safety, total operating costs, and roadway throughput. These technologies could help address many of the issues

[66] Stephens et al., *Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles* NREL/TP-5400-67216, National Renewable Energy Laboratory (Golden, Colorado, November 2016).

facing the long-haul trucking, delivery, and transit industry. MD and HD truck automated vehicle technologies come in many forms with various levels of automation, ranging from adaptive cruise control to the potential for driverless trucks in the future. Benefits of this technology vary depending on application and the specific technology employed.

8.2.1 Safety impacts

Safety is one of the largest benefits to automating truck control, because of the risks associated with large vehicle incidents. The primary purpose of lower-level automated vehicle technology is for driver assistance to decrease the likelihood that driver inattentiveness or error will result in an accident. Higher-level technologies build on the driver assistance factors by adding V2V/V2I communication abilities and taking over tasks partially or totally from the driver, thereby eliminating the human error factor in controlling the vehicle.

Since 2000, there has been an average of 222 trucks involved in crashes per 100 million vehicle miles. Human error has been found to cause over 90% of truck-involved accidents.[67] Automated trucks could eliminate many of these accidents. Researchers have projected that automated driving technology could decrease the accident rate to approximately eight crashes per 100 million miles by 2040.[68]

Vehicles that operate primarily in urban settings, such as local delivery and transit vehicles, will also potentially see increased safety levels. While operator injury from accidents is limited because of low operational speeds, accidents involving pedestrians often result in injuries. Automated vehicle technologies in these vehicles can react quicker and provide higher levels of pedestrian monitoring than human drivers are able to provide.[69] Safety benefits for automated low-speed vehicles are not well understood due to limited testing and comparable operations.

8.2.2 Energy savings

Automated vehicle technology on its own has somewhat limited potential to reduce the energy requirements of conventional MDVs and HDVs when they are operated using conventional methods. However, the technology does have the potential to enable operational configurations and methods that could reduce energy use. The energy saving methods, technologies, and techniques vary throughout the MDV/HDV market and long-haul, local delivery, and transit applications require different approaches to minimize energy use and optimize operations.

Fuel efficiency benefits for long-haul automated driving technologies typically focus on platooning applications. While optimized driving dynamics provide some benefit, the reduced aerodynamic drag during platooning provides the most savings. The benefits of platooning are well documented but are subject to a number of influences, including vehicle specifics, ambient conditions, roadway geography, and cargo types. A number of studies estimated the potential savings of platooning technology (results shown for two-truck platoons in Figure 27[70]) with slight variation because of ambient conditions, truck

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[67] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.

[68] Ibid.

[69] National Center for Transit Research, *Evaluation of Automated Vehicle Technology for Transit*, Center for Urban Transportation Research (Tampa, Florida, April 2016).

[70] North American Council for Freight Efficiency and Carbon War Room, *Confidence Report: Two-Truck Platooning*, September 28, 2016.

types, etc. Automated vehicle technology could lead to an estimated 3% fuel savings in single trucks because of efficient driving profiles and up to 10% fuel savings from utilizing automated vehicle technology for long-haul platooning purposes.[71]

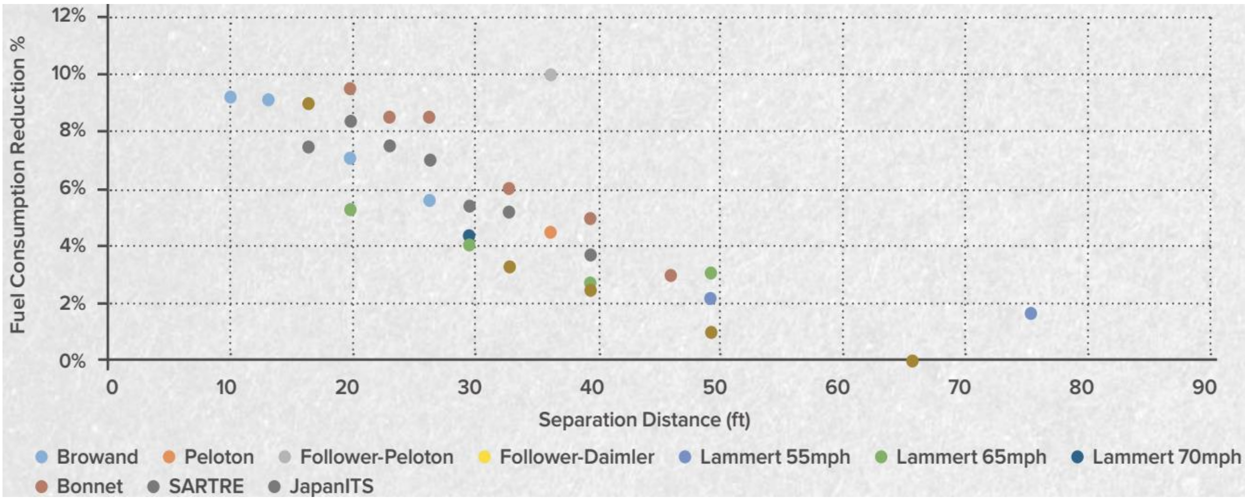

Figure 27: Potential platooning fuel savings[72]

Local-delivery fuel saving benefits from the use of automated vehicle technology are less defined and not as quantifiable as for long-haul transport. Because delivery vehicles operate in the urban environment, high-level automated delivery trucks have not been tested or demonstrated extensively. Fuel savings for conventional vehicles (gasoline and diesel powered trucks) with even high-level automation could have relatively limited fuel savings potential because of similar travel requirements and scheduling. However, automation technology may enable alternative delivery concepts such as completely driverless vehicles (such as Google's concept), small autonomous vehicle pods that transport individual deliveries, or even autonomous drones (such as Amazon's concept). These delivery strategies are still in conceptual stages, and quantifiable energy saving data, compared to conventional practices, are not readily available or established. Overall, there are no published data on the potential energy benefits of using automated vehicle technology for local delivery operations, because the technology is extremely new and untested.

Automated transit vehicle fuel savings are also difficult to quantify as the technology acts as an enabler for alternative vehicle types and concepts to provide personal mobility in and around urban environments. When applied to current transit vehicle types and practices, automated vehicle technology provides minimal savings because of similar duty profiles. There has also been limited in-use testing of high-level automated vehicle technology because these vehicles operate in heavily populated areas. Low-level, driver-assist technologies have been deployed to some extent, but such efforts focus on improved safety and have negligible direct impact on fuel efficiency.

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[71] Frost & Sullivan, "Strategic Outlook for Autonomous Heavy-Duty Trucks," presentation, accessed December 6, 2016.

[72] North American Council for Freight Efficiency and Carbon War Room, *Confidence Report: Two-Truck Platooning*, September 28, 2016.

8.2.3 Roadway throughput impacts

Automated vehicle technologies enable efficient utilization of roadways, particularly for large, heavy vehicles. Potential benefits are optimized driving patterns, decreased distances between vehicles, and decreased human error incidents, which lead to 25% of congestion enable efficient utilization.[73] Roadway throughput benefits will likely be initially realized on limited-access highways where lower-level automated vehicle technologies can be beneficial. Heavy traffic areas within urban centers require more advanced automated vehicle solutions to create an integrated solution with infrastructure, other traffic, and pedestrians. The market penetration of these technologies will be a factor where these vehicles will be required to work together to realize the full potential of the technology.

Long-haul, on-highway benefits for HD trucks are typically realized by safely decreasing the distance between vehicles through the use of adaptive cruise control and V2V communication. Linking vehicles in this platooning configuration also has the benefit of reducing the "accordion" effect of traffic and helps maintain a constant velocity. A typical highway lane, utilized by all-human driven vehicles sees a maximum throughput of about 2,200 vehicles per hour without major issues, resulting in a 5% utilization rate (amount of roadway occupied by vehicles). At low market penetration rates for automated trucks, minimal impacts are realized. However, as penetration rates increase beyond 10%, it is predicted that traffic patterns will smooth out, increasing throughput rates and increasing efficiency.[74] Additionally, the connected vehicle technologies associated with automated vehicles could allow optimized routing and the ability to search for additional cargo along the outline route in real time. This ability could increase trucking revenue, reduce vehicle miles driven, and reduce the number of trucks required while increasing the cargo density of the trucks on the road.[75] Throughput impacts of on-highway vehicles directly correlate with the overall market share of automated vehicles as estimated in Figure 28.

[73] Federal Highway Administration, "Traffic Congestion and Reliability: Linking Solutions to Problems," October 20, 2015.

[74] Pinjari, Abdul Rawoof, Bertho Augustin, and Nikhil Menon, *Highway Capacity Impacts of Autonomous Vehicles: An Assessment*, Tampa Hillsborough Expressway Authority (Tampa, Florida, November 2013).

[75] Frost & Sullivan, "Strategic Outlook for Autonomous Heavy-Duty Trucks," presentation, accessed December 6, 2016.

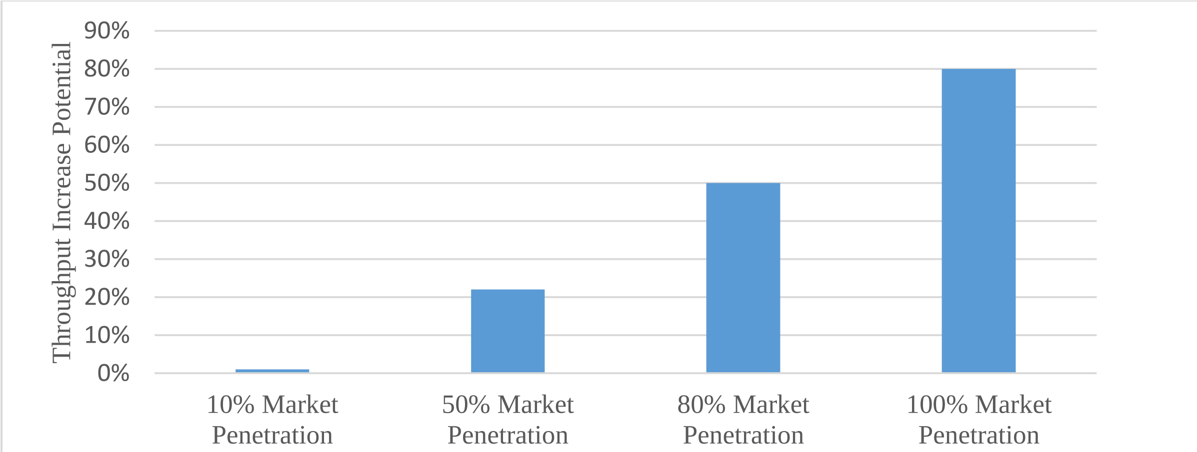

Figure 28: Throughput increase potential based on automated vehicle market share[76]

Automated vehicle technology could improve the throughput of heavily traveled corridors in urban centers. However, how this could be integrated is not yet completely understood. The technology could provide the ability to use smaller, more responsive transportation techniques such as downsized autonomous buses and shared mobility on a much wider scale to reduce travel delays and improve travel time compared to using personal vehicles and conventional buses. An additional benefit for automated transit and delivery vehicles is route optimization and signal priority where the vehicle operations and traffic control infrastructure could work together to smooth traffic flow and increase throughput where needed. For transit applications, automated 20-passenger buses are predicted to reduce travel delays by 46%.[77] Throughput figures for automated delivery vehicles are not well quantified but could be comparable to automated buses because of similar operating parameters (no quantifiable sources currently available).

8.2.4 Operating cost impacts

Unless future legislation requires some level of automation, cost savings will motivate technology adoption by fleets and operators. There are a number of sources of cost savings due to automated vehicles for the long-haul, delivery, and transit marketplaces. Incremental costs for MDV and HDV systems are shown in Figure 29.

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[76] Pinjari, Abdul Rawoof, Bertho Augustin, and Nikhil Menon, *Highway Capacity Impacts of Autonomous Vehicles: An Assessment*, Tampa Hillsborough Expressway Authority (Tampa, Florida, November 2013).

[77] Calthorpe Analytics, "Autonomous Rapid Transit Performance Evaluation," September 27, 2015.

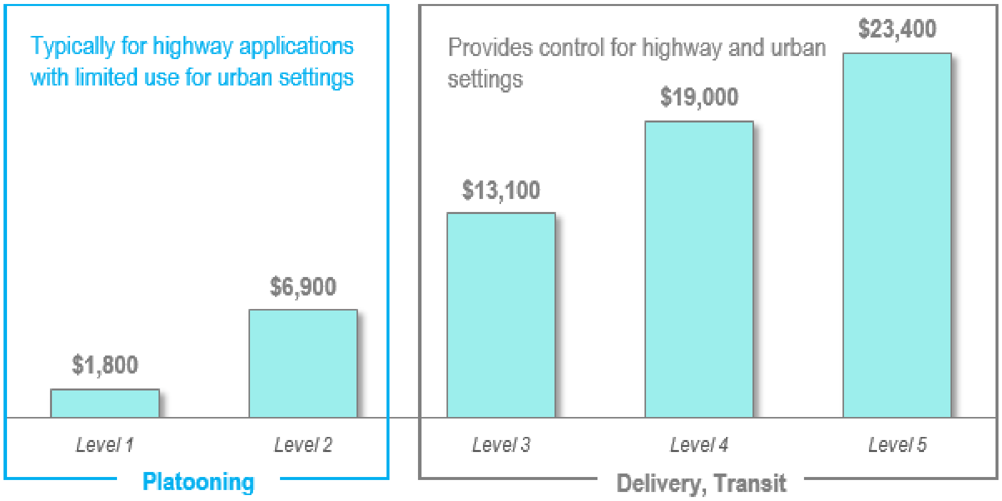

Figure 29: Incremental costs for automated medium- and heavy-duty vehicles[78]

Operational cost savings for long-haul trucking applications of automated vehicle technology are largest when the vehicles are platooned together to reduce aerodynamic drag and reduce fuel consumption. Platooning can be accomplished with Level 1 or Level 2 technology, which further increases the business case with an estimated return on investment within 3.5 years for long-haul trucks.[79] Higher-level automated driving technologies have the potential to create additional sources for operational savings, particularly pertaining to driver costs. With higher-level automation systems, drivers could potentially rest during highway transport. This could result in changes to hours of service regulations to extend the allowable driving time for each driver. While the technology may someday be able to replace human drivers completely, near-term efforts focus on optimizing the tasks required by the driver and assisting where possible. Because of the potential for increased safety levels and decreased accidents, lost and damaged equipment costs and insurance premiums could decrease as well. The overall breakdown of the potential cost savings per mile traveled for a typical long-haul truck is shown in Figure 30.[80]

[78] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.

[79] Frost & Sullivan, "Strategic Outlook for Autonomous Heavy-Duty Trucks," presentation, accessed December 6, 2016.

[80] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.

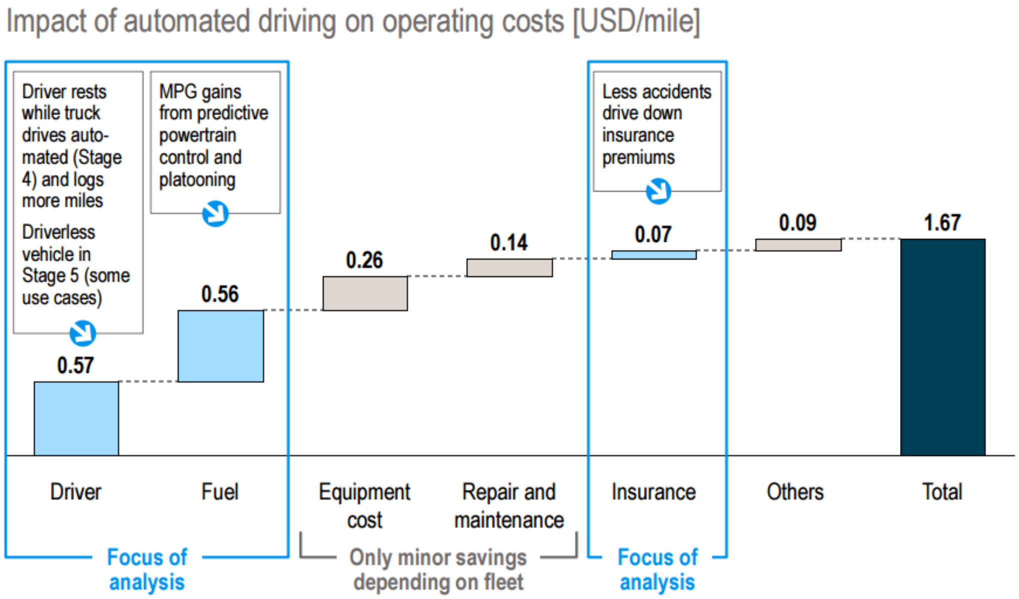

Figure 30: Automated long-haul truck potential cost savings per mile

Costs savings associated with automated delivery trucks are not as high because of limited fuel savings from optimized driving. Most operational savings were predicted to come from reduced driver cost and insurance premiums. No quantifiable savings were estimated for Levels 1-3 because these vehicles would operate in the low speed, urban environment. Higher-level (Levels 4-5) automated trucks could potentially operate for longer durations (without drivers), which could reduce the required fleet size, saving upfront costs but potentially shortening the life of each vehicle. The potential cost savings are shown for Level 4 and Level 5 technology in Figure 31.[81]

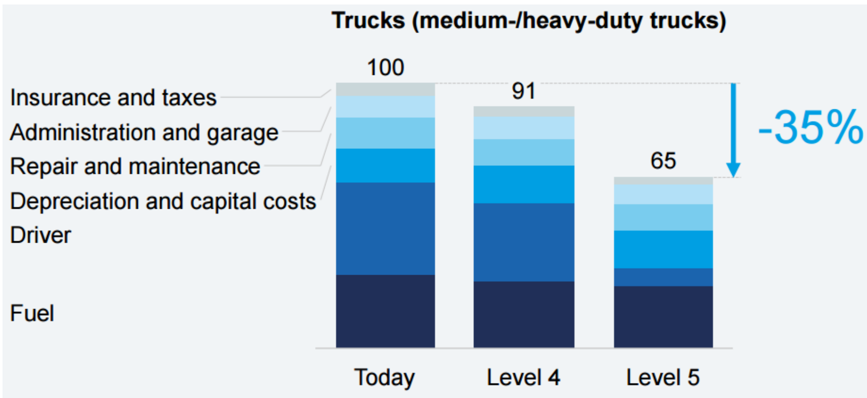

Figure 31: Automated delivery vehicle potential cost savings

Automated vehicle technology used for transit applications typically focuses on removing large diesel buses from operation and replacing them with a greater number of smaller vehicles. The adoption of automated vehicle technology also opens up the possibility of replacing all traffic in urban settings, including buses, cars, taxies, and shuttles, with smaller automated vehicles. The potential cost savings are difficult to quantify because no direct comparison is possible. Some estimates predict a 50% reduction in transit energy requirements for city centers that enact shared mobility concepts. These evaluations

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[81] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.

estimated that only 3% of the existing fleet would be required to meet the transportation needs, and total miles driven could be reduced by 37%. These figures are currently estimates, and the potential of these concepts relies on a number of factors, including a ridesharing system and transit services, working together.[82]

[82] Roberts, David, "Shared Vehicles Could Make Our Cities Dramatically More Livable," *Vox*, July 28, 2016.

9. Fuel Impact Projections Model: Overview, Methodology, and Discussion

9.1 Fuel impact projections model overview

The project developed scenario-based estimates of partial and full-automated vehicle technology deployment and the associated fuel consumption impacts. These projections use the data in "Table 36, Transportation Sector Energy Use by Mode and Type," of the 2017 EIA *Annual Energy Outlook* as inputs to provide the Reference case (both with, and without, the Clean Power Plan) energy consumption estimates.[1] The model was developed to follow the available estimates for vehicle types in accordance with EIA categories — LDVs, commercial light trucks, buses, and freight trucks — from 2014 to 2050.[2] The relevant subsets of these vehicle categories are shown in Table 7.

Table 7. Vehicle types considered in fuel impact projections

Light-Duty Vehicles	Commercial Light Trucks[a]	Buses[a]	Freight Trucks
• Automobiles • Light Trucks	• Commercial Light Trucks	• Transit • Intercity[b] • School	• Medium (10,001-26,000 lbs) • Large (>26,000 lbs)

[a] Commercial light trucks, transit buses, and school buses are assumed to follow the same fuel impact and technology deployment assumptions due to similar driving patterns and technology applications.

[b] Intercity busses are assumed to follow heavy duty fuel impact and technology deployment assumptions due to similar driving patterns and technology applications (a bus designed for high-speed, long-distance travel).

The potential energy impact and market adoption (introduction and ongoing adoption) determined by the project's research were used as model inputs. These data are reported in the preceding sections and included in the accompanying data spreadsheets. For each vehicle type and energy-consumption reference case, multiple fuel impact scenarios are projected as illustrated in Table 8.

Table 8. Scenarios considered in fuel impact projections

Starting Energy Baseline	CAV Technology Impact on Fuel Consumption	Automation Level[a]	CAV Impact on Vehicle Miles Traveled[b]
Annual Energy Outlook 2017 Reference ❯	1. Lower Bound 2. Upper Bound ❯	1. Partial Automation (1-3) 2. Full Automation (4-5) ❯	1. No effect 2. Low VMT Increase 3. High VMT Increase
The combination of these scenarios results in: 12 light-duty scenarios; 4 commercial light truck scenarios; 6 bus scenarios; and 4 freight truck scenarios, that are applied to the Annual Energy Outlook 2017 Reference case and Reference case without the Clean Power Plan			

[a] Automation levels were grouped to levels 1-3 and 4-5 respectively as a simplifying assumption based on available data sources.

[b] Impacts on Vehicle Miles Traveled are only considered for automobiles and transit buses.

The model measures each of the above as individual scenarios, exploring the impacts of deploying partial or fully automated vehicles. Limited data is available and uncertainty remains due to the early stage of CAV technologies and deployment. As such, the purpose of these estimates is to establish a range of fuel consumption outcomes, influenced by multiple factors, caused by the adoption of CAV technology. The projections do not account for an additive relationship between the partial and fully automated vehicles,

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[1] U.S. Energy Information Administration, "Transportation Sector Energy Use by Mode and Type," *Annual Energy Outlook 2017*, accessed January 23, 2017.

[2] 2014 values are from the 2016 Annual Energy Outlook

but they contribute to the range of outcomes due to each suite of technologies and their potential effects on fuel consumption and VMT.

9.2 Fuel impact and vehicle miles traveled assumptions and methodology

The primary reference for fuel impact and VMT assumptions is a recently released literature review and analysis published by NREL, with contributions from Argonne National Laboratory, Oak Ridge National Laboratory, and the DOE.[3] The NREL report pulls data from multiple studies to quantify lower and upper bounds for LD CAV fuel consumption impacts for city and highway driving due to the following factors: drive profile and traffic flow smoothing, faster travel, intersection V2I communication, collision avoidance, platooning, and vehicle/powertrain resizing.[4] The literature search verified that the CAV fuel impact assumptions were consistent with other published estimates.

The NREL report also provides estimates on VMT impacts to automobiles due to the introduction of CAV technologies. The impacts include less hunting for parking, more travel due to ease of travel, more travel by underserved populations, mode shift to vehicles, increase in ridesharing, and increased passenger-less miles traveled by CAVs. In the fuel-impact projection model, the VMT effects are applied to automobiles (all effects) and transit vehicles (mode shift only). As a simplifying assumption, VMT percent increases were considered to be an equivalent percentage increase in fuel consumption (e.g., if VMT doubles in a scenario, so does fuel consumption in that scenario).

Fuel impacts for commercial light trucks and transit/school buses correspond to the NREL city-driving impact scenario and do not consider influences from vehicle/powertrain resizing. Only transit buses are assumed to have VMT impacts due to a mode shift from buses to automobiles. Fuel impacts for intercity buses and freight trucks correspond to the NREL highway-driving impact scenario and do not consider influences from faster travel, intersection V2I/I2V communication, and vehicle/powertrain resizing. Multiple sources were used to calculate the platooning impacts for freight trucks and intercity buses (e.g., HDV that travel long-distances).[5,6,7] A set of companion documents to this report compiles the relevant numerical data and references collected by the project.

It is important to note that CAV technologies will likely have both holistic impacts on all vehicle types on a given roadway, and individual impacts that will depend on the vehicle type and use application. Additionally, there may be an aggregate effect of having a plurality, or majority, of fully autonomous vehicles on the road. For example, CAVs may be able to communicate with each other more effectively and amplify impacts such as drive profile and traffic flow smoothing when there are fewer manually operated vehicles on the road. This and other instances represent a tipping point where CAV impacts may

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[3] Stephens et al., *Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles* NREL/TP-5400-67216, National Renewable Energy Laboratory (Golden, Colorado, November 2016).

[4] The NREL analysis focuses on CAV technology impacts in conventional internal combustion engine powertrain vehicles and does not consider the combined influences of electrification, alternative fuels, and CAV technologies on vehicle petroleum consumption. Additionally, vehicle/powertrain resizing offers large but highly uncertain potential reductions.

[5] Roland Berger, "Automated Trucks: The Next Big Disruptor in the Automotive Industry?," presentation, Chicago/Munich, April 2016.

[6] Frost & Sullivan, "Strategic Outlook for Autonomous Heavy-duty Trucks," presentation, accessed December 6, 2016.

[7] Mohr et al., "Automotive Revolution – Perspective Towards 2030: How the Convergence of Disruptive Technology-Driven Trends Could Transform the Auto Industry," McKinsey & Company, Advanced Industries, January 2016.

jump from lower bound to upper bound projections, however data is insufficient to estimate where such tipping points might be.

9.3 Technology deployment assumptions and methodology

Statistics from the IIHS, Highway Loss Data Institute (HLDI), were used to develop technology deployment and adoption curves for CAVs. HLDI provides publicly available data sets that have tracked and projected the deployment and adoption of autonomy-related technologies over time.[8] These curves represent the percentage of registered vehicles with an available technology. Deployment curves for comparable technologies (electronic stability control and front-crash prevention) were selected as a proxy for the partial automation (Levels 1–3) and full automation (Levels 4–5) deployment cases. These curves were normalized by the starting year of deployment, which is estimated based on a literature review and conversations with industry stakeholders as summarized below.

Table 9: Predicted technology introduction timing

	Year Technology Will be Introduced	
Vehicle Type	Level 1–3	Level 4–5
Light-Duty Vehicles	2014	2018
Commercial Light Trucks/Transit	2016	2018
Heavy-Duty/ Freight Long-Haul	2016	2025

The fleet penetration of new technologies is traditionally slow. According to Matt Moore, HLDI vice president, "Even if the U.S. government were to require all new vehicles sold to be autonomous tomorrow, it would take at least 25 years until nearly 95% of the vehicles on the road would have the capability."[9] Electric Stability Control (ESC), introduced in 1995, became required on all new LDVs beginning in 2011 (16 years after introduction). It is predicted that ESC will not be equipped on 95% of registered vehicles until 2032, which is 37 years from its introduction and 21 years after it became a required feature.[10]

However, commercial interests may influence the rate of adoption of technology. As such, the model allows the technology deployment curves to be adjusted up or down in the case that a reasonable impact factor is determined. For example, the deployment curves are based on the addition of CAV technologies through new vehicles only. It may prove economically beneficial to retrofit existing HDVs to accommodate platooning. This would accelerate platooning technology adoption. However, no reliable quantification of such a factor has been identified, so these impacts are not yet considered.

9.4 Summary of projections

The estimates primarily showed a potential for energy reductions due to the deployment of automated vehicles across all vehicle types. In LDV projections, scenarios with a large VMT increase resulted in the potential for increased fuel consumption. Some of the fuel consumption increase could be counteracted by technologies that increase vehicle efficiency such as hybrid- or full-electric powertrains. Multiple

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[8] Highway Loss Data Institute, "Predicted Availability of Safety Features on Registered Vehicles – A 2015 Update," *HLDI Bulletin*, 32 no. 16 (September 2015).

[9] Insurance Institute for Highway Safety, Highway Loss Data Institute, "Robot Cars Won't Retire Crash- Test Dummies Anytime Soon," *Status Report*, 51 no. 8 (November 10, 2016), Special Issue: Autonomous Vehicles.

[10] Highway Loss Data Institute, "Predicted Availability of Safety Features on Registered Vehicles – A 2015 Update." *HLDI Bulletin*, 32 no. 16 (September 2015).

scenarios were used to demonstrate how low- and high-technology impacts interact with low and high VMT impacts. Fuel impacts due to CAVs naturally become more pronounced with increased deployment. While the effects of fuel consumption, compared to the EIA Reference Case, due to CAV deployment in LDVs only range from a -2% to 2% in 2030, by 2040 this range increased to -16.6% to 16.1% and then from -44.4% to 42.0% in 2050. As shown in Figure 32, there is still considerable uncertainty surrounding the fuel consumption impacts and VMT impacts of LD CAVs, and this is particularly pronounced for Level 4-5 fully autonomous vehicles. The largest influencer in potential fuel reduction due to Level 4-5 CAVs stems from vehicle and powertrain resizing. Alternatively, as mentioned earlier, fully autonomous vehicles could drastically increase VMT due to the ease of travel and more travel by underserved populations (such as the elderly and disabled).

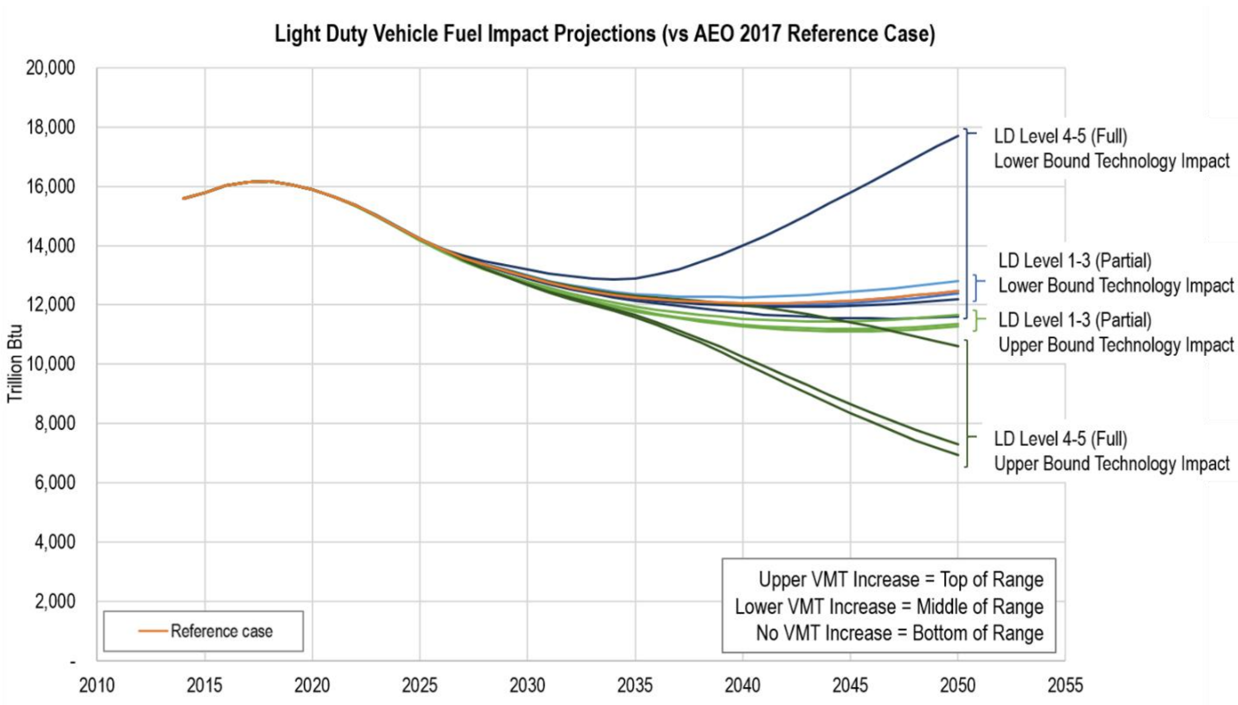

Figure 32. Light-duty vehicle fuel impact projections versus the EIA Annual Energy Outlook 2017 Reference Case

The other vehicle categories (commercial light trucks, buses, and freight trucks) only resulted in a potential for reduced fuel consumption compared to the reference case. By 2050, compared to the EIA reference case fuel consumption could be reduced from 1.7-18.2% for commercial light trucks, 2.3-17.8% for buses, and 6.7-18.6% for freight trucks. Current research indicates that most automated truck manufacturers expect to initially limit the top speed of freight trucks below conventional vehicles. This will be done to maximize safety. The energy use model does not incorporate the potential fuel consumption impact from increased highway speeds. For commercial light trucks and buses, the maximum savings are estimated to stem from drive profile and traffic flow smoothing along with the deployment of Level 4-5 fully autonomous vehicles. Alternatively, freight trucks stand to benefit from partial automation in a more near-term time frame. As of 2016, assisted-platooning technology has already started introduction and could result in fuel savings for the industry. Compared to the EIA Reference case fuel consumption could be reduced by 4.5% as early as 2030, increased to 13.9% in 2040, and 18.6% in 2050 for the freight trucking industry due to Level 1-3 technology alone.

As CAV deployment increases, real-world data may provide guidance as to which technology and mobility scenarios and impacts are most accurate. This model may serve as a useful tool that can be updated to account for a changing transportation landscape.

10. Opportunities and Challenges

10.1 Opportunities

There are myriad opportunities for future work in automated vehicles. With increased investment in CAV technologies, funding for academic and industrial R&D should become more available. Future investment in automated vehicles has the potential to advance important aspects of CAV technologies, such as technology road mapping, modeling, data collection, and analysis.[11] Technology road mapping will help determine subsequent energy impacts from automated vehicles.[12] Modeling and data analysis will then progress the technology road maps by developing tools to comprehend and interpret these energy impacts and the roles CAVs play in these scenarios.[13] These research needs enable outreach to institutes such as Transportation Research Board and the PATH program to determine energy impacts.[14]

10.2 Challenges

The transitional period between the current all-conventional vehicle population and the upper bound for autonomous vehicles is challenging to project due to the factors previously mentioned in this report. Two main overarching questions affect automated vehicle deployment and subsequent market growth:

- How will the transition period be handled and how long it will last?
- Will there be a time when all cars will be CAVs?

Depending on the penetration projected in literature sources, first generation CAVs are projected to arrive in 2020, while mainstream acceptance and availability are expected to reach a tipping point by 2050.[15] As presented in this report, higher CAV market penetration faces a range of challenges:

- **Technology**. Automated vehicles have demonstrated promising capabilities in a variety of situations, but cost and performance remain barriers to full deployment. Continued R&D is needed to achieve high reliability, operability, and affordability. Additionally, researchers and software designers must consider the effects of CAV technology on cybersecurity.
- **Consumer opinion/adoption**. Consumer trust remains a key barrier to major market gains of highly automated driving. Most consumers are actually afraid to ride in self-driving vehicles; this fear is strongly proportional to the level of experience consumers have with ADAS technologies. Vehicle original equipment manufacturers, suppliers, and transportation network companies need to approach this challenge by giving potential customers some level of introductory experience to the idea of automated driving. Approaching the market through ride-sharing applications, as most of these companies plan to do, could meet the experience threshold consumers need to increase interest.
- **Uncertain energy and economic impacts**. There is a growing realization of the breadth of interdependent energy and economic impact factors that are not yet fully understood. A summary

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[11] U.S. Department of Energy, "Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies: Connected and Autonomous Vehicles," *Quadrennial Technology Review 2015* (Washington, DC, September 2015).

[12] Ibid.

[13] Ibid.

[14] Shladover, Steven E., and Douglas Gettman, *Connected/Automated Vehicle Research Roadmap for American Association of State Highway and Transportation Officials*, National Cooperative Highway Research Program, accessed January 13, 2017.

[15] Rousseau, John, and Brad Crane, "The Human Transition to Autonomous Vehicles," Artefact, accessed December 13, 2016.

of the potential energy impacts was provided in Section 8: Energy and Safety Impacts, but the full energy and economic factor implications from CAV deployment need more extensive research. Effects on travel demand, vehicle efficiency and redesign, as well as consumer response are all highly uncertain.

- **Policy and regulation**. In the industry, many have stated that federal and state policy development must address the common ground between encouraging innovation and ensuring traveler safety. NHTSA's recent proposal to mandate Vehicle-to-Vehicle communication indicates that policymakers are working toward this end. Usage data is not available to inform policymakers, because automated vehicle technology is not yet widely commercially available. Researchers need to find accurate technology analogs, or new measurement methods, to determine how consumers might react and how policy can play a role in propagating the technology.
- **Insurance and liability**. U.S. drivers are currently required to personally insure their vehicles against liability, but this model will need to adapt to new shared-ownership or MaaS transportation systems.

An Institute of Electrical and Electronics Engineers survey of 200 researchers, practitioners, university students, society members, and government agencies in the field of automated vehicles found that legal liability, policy, and consumer acceptance are the biggest obstacles; cost, infrastructure, and technology factors are the "smaller speed bumps."[16]

The report's purpose was to identify and discuss the key factors associated with CAV technology and its usage that could affect U.S. transportation energy consumption through 2050. The results will inform the EIA and other stakeholders about the state of on-road LDV, MDV, and HDV automated vehicle technology. Vehicle manufacturers have commercialization plans for automated vehicles with initial introductions in the next five years. However, widespread vehicle availability, consumer adoption hurdles, mobility option shifts, and the many years until these vehicles represent a large portion of the vehicle population result in any potential fuel consumption impacts occurring in 2035 and later. A lot of work remains before government, industry, and academia fully understand how CAV technology will affect the transportation sector's structure and energy consumption. The conclusions highlight the uncertainty that underlines the potential impact of CAVs on U.S. transportation energy consumption.

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[16] Institute of Electrical and Electronics Engineers, "IEEE Survey Reveals Mass-Produced Cars Will Not Have Steering Wheels, Gas/Brake Pedals, Horns, or Rearview Mirrors by 2035," July 14, 2014.

Appendix A: Automated Off-Road Vehicles and Technologies

A-1. Introduction

A brief study of automated off-road/non-road technologies and manufacturers was conducted to determine the technologies, manufacturers, and deployment timelines. The investigation was not intended to produce a comprehensive state of the automated driving off-road/non-road vehicle industry. Rather, the primary purpose was to determine whether this development could be used to complement and accelerate automated on-road medium- and heavy-duty vehicle deployment.

Vehicle guidance systems are now broadly used in the agricultural industry and for certain applications in construction and mining. Off-road vehicles were among the first automated vehicles developed, dating back to the first automatic tractor steering mechanism, patented in 1924.[1] Technology progressed to the first “driverless tractor” prototype using a leader cable-guidance system in 1958 and developed to use radio beacons and GPS in the 1990s.[2,3,4] In 1997, more than 70 years after the initial patent, John Deere demonstrated how a tractor could automatically steer on a straight line entered by an operator via its AutoTrac™ system. John Deere commercialized the technology in 2002[5] According to the U.S. Department of Agriculture’s Agricultural Resource Management Survey, in 2010 guidance or auto-steer systems were used on about one-third of all corn and soybean farms and more than 80% of all large corn farms over 2,900 acres.[6]

Advancements in off-road CAV technologies have accelerated over the last decade, and offerings now range from guided steering and positioning to full automation in agriculture, construction, and mining. An important difference between off-road and on-road vehicles is the different driver responsibilities that need to be automated. The primary function for most of these systems is to reduce driver fatigue, so the drivers can do the rest of their jobs more efficiently. In agriculture, the driver is not only responsible for keeping the tractor on course but also for managing the implement connected to it. Mowing and tillage in agriculture and haulage in mining present near-term opportunities for automation.

Off-road automated vehicles are designed in a controlled system with programmed operating parameters and are monitored remotely to ensure proper functioning. Another important difference from on-road vehicles is that humans can more easily be completely removed from CAVs in off-road applications. This is because these applications typically operate in locations that are not heavily populated (e.g., a field or mine). The equipment will continue to run without a driver input or any outside human interference, such as other vehicles. Errors will more commonly result in property damage as opposed to injury or loss of human life. This arrangement makes machine error in an off-road environment more tolerable and potentially less expensive than in an on-road environment. Economic drivers such as energy savings,

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[1] Willrodt, Fred L., “U.S. Patent 1506706: Steering Attachment for Tractors,” July 17, 1924.

[2] Morgan, K. E., “A Step towards an Automatic Tractor.” *Farm Mech*, 10 no. 13 (1958), pp. 440–441.

[3] Erbach, D. C., C. H. Choi, and K. Noh, “Automated Guidance for Agricultural Tractors,” Automated Agriculture for the 21st Century, ASAE, 1991.

[4] Nebot, E., S. Sukkarieh, and H. Durrant-Whyte, “Inertial Navigation Aided with GPS Information,” *Mechatronics and Machine Vision in Practice*, proceedings at the Fourth Annual Conference (1997), pp. 169–174.

[5] Picket, T., “How John Deere Hands-Free Guidance Was Developed,” *The John Deere Journal*, March 29, 2016.

[6] Schimmelpfennig, David, *Farm Profits and Adoption of Precision Agriculture*, Economic Research Report Number 217, U.S. Department of Agriculture Economic Research Service, October 2016.

productivity, liability costs, and equipment costs will influence the investment, adoption, and success or failure of off-road automated vehicle technologies.

A-2. Vehicle technology

A-2.1 Off-road vehicle technology

Off-road vehicles operate in a very different environment than on-road vehicles. Their systems lack the visual cues found in roadways such as lane lines, signage, and other vehicles. However, every element of an off-road environment—including other vehicles, routes and schedules, and infrastructure and obstacles—could be accounted for, and programmed into, a controlled operating system. Current off-road systems are heavily reliant on GPS or the use of radio beacons to provide absolute positioning for CAVs. These systems offer varying levels of precision depending on the application. Mousazedeh (2013) and Li (2009) provide thorough reviews on the history and development of navigation systems, technologies, and sensors for agricultural automated off-road vehicles.[7,8]

In addition to navigating a very different environment than on-road vehicles, automated off-road vehicles must account for and automate a different slate of activities to be useful. In agriculture, the driver is responsible for keeping the tractor on course as well as managing the implement connected to it. Autosteering systems have gained popularity and widespread adoption in agriculture because they reduce driver fatigue and enable farmers to focus on their many responsibilities other than keeping a tractor moving straight. Other applications, such as haulage in Western Australian mines, are more straightforward. In 2015, the mining company Rio Tinto began running two iron mines in Western Australia exclusively on 69 driverless trucks that can maintain continuous operations 24 hours a day, 365 days a year without a driver in need of breaks or at risk of injury due to fatigue.[9] Additional system cost decreases and technology improvements will allow for more reliable applications beyond the remote mines of Western Australia. The following sections describe some of the companies and their technologies that have made it to commercial, or near-commercial, deployment.

A.2.1.1 Agricultural technologies

The leading technology developers in the automated agricultural vehicle space include John Deere, CNH Industrial (partnered with Autonomous Solutions Incorporated), Kubota, Autonomous Tractor Corporation (ATC), AGCO/Fendt, and Kinze (partnered with Jaybridge Robotics). These OEMs use similar GPS-based systems for their commercially available guidance and autosteering technology. For example, the John Deere AutoTrac guidance system can rely exclusively on GPS (accurate within a few feet) or can be coupled with a field transmitter, such as the Real Time Kinematic system, to calculate corrected positioning and achieve ±2 centimeter of accuracy.[10] The John Deere iTEC Pro Guidance system, launched in 2008, uses satellite-linked dome antennas to guide tractors and combines on

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[7] Mousazadeh, Hossein, "A Technical Review on Navigation Systems of Agricultural Autonomous Off-Road Vehicles," *Journal of Terramechanics*, 50.3 (2013), pp. 211–232.

[8] Li et al., "Review of Research on Agricultural Vehicle Autonomous Guidance," *International Journal of Agricultural and Biological Engineering*, 2.3 (2009), pp. 1–16.

[9] Diss. Kathryn, "Driverless Trucks Move All Iron Ore at Rio Tinto's Pilbara Mines, in World First," *ABC*, October 18, 2015.

[10] Deere & Company, "John Deere Guidance Systems Brochure: Guidance You Can Grow With," accessed November 15, 2016.

programmed tracks while giving operators the capability of taking control of the vehicle.[11] No manufacturers have announced production plans for fully autonomous agricultural vehicle.

Emerging agricultural CAV technologies are expanding beyond GPS with possible products that include vehicle platooning and full autonomy. Fendt won a gold medal at Agritechnica 2011 for its Guide Connect technology, which connects two tractors via global navigation satellite systems signal and radio (the unmanned fully autonomous tractor follows an operator-driven tractor leads).[12] Although Fendt Guide Connect does not appear to be commercially available, Fendt Variotronic offers V2V integration and data sharing; Real Time Kinematic vehicle guidance systems are accurate to 2 centimeter and some implement automated activities. Kinze was the first major equipment manufacturer to publicly state its pursuit of autonomous vehicle technology. Kinze announced its Autonomy Project in 2011 and released a concept self-driving tractor and autonomous grain cart.[13] Despite adding new functionality to its autonomous harvesting solution in 2014, Kinze stopped its fully autonomous vehicle development. The entire staff of its technology partner, Jaybridge Robotics, was hired by the Toyota Research Institute in March 2016.[14]

CNH Industrial, Kubota, and ATC have each unveiled fully autonomous concept vehicles. The Kubota prototype can be used for tilling and applying fertilizers and pesticides, and it is anticipated to come to market as early as 2018.[15] CNH Industrial released two fully autonomous concept vehicles through its Case IH and New Holland brands, offering cab-less and cabbed versions respectively.[16, 17] Through the use of radar, LiDAR, and onboard video cameras, the vehicle can sense stationary or moving obstacles in its path and will stop until the operator assigns a new path. The vehicle will also stop immediately if the GPS signal or position data is lost, or if the manual stop button is pushed. Machine tasks can also be modified in real time with remote interface or automatic weather warnings. CNH Industrial has not indicated when these concept vehicles may become commercially available. Lastly, ATC released a fully autonomous prototype tractor in 2012. The company decided that GPS was not satisfactory for an autonomous tractor, and instead the navigation system uses two lasers mounted on the tractor that bounce signals from three or four mobile transponders placed around the field. The lasers are supplemented with 150-megahertz radios to overcome the line-of-sight issues that laser systems encounter.[18]

A.2.1.2 Mining and construction technologies

Mining and construction companies such as Caterpillar and Komatsu offer fully autonomous systems. These systems are used primarily in remote, high-value mines such as those in Western Australia. The

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[11] Simpson, Burney, "Farmers Ponder Driverless Tech for Precision Farming, Labor Needs," *DriverlessTransportation*, August 31, 2015.

[12] Fendt, "Fendt Variotronic: Operating Concept, Guide Connect," accessed November 15, 2016.

[13] Kinze Manufacturing, Inc., "Kinze Manufacturing Unveils First Autonomous Row Crop Technology," July 29, 2011.

[14] Brown, Jeremy (President and Chief Executive Officer, Jaybridge Robotics and program manager, Toyota Research Institute), personal interview, November 8, 2016.

[15] Nikkei Asian Review, "Drones, Self-Driving Tractors May Make Life Easier on the Farm," January 23, 2016.

[16] Case IH, "Case IH Reveals New Tagline, New Focus and a New Autonomous Concept Vehicle," August 30, 2016.

[17] New Holland Agriculture, "The New Holland NHDrive Concept Autonomous Tractor Shows a Vision into the Future of Agriculture," August 30, 2016.

[18] Farm Industry News, "Spirit Autonomous Tractor Eliminates Need for Driver," November 9, 2012.

Caterpillar CAT® Minestar™ command system offers fully autonomous hauling and operator assistance, remote control, or semi-autonomy for other applications, including dozing, underground loading, longwall, and drilling.[19] The Komatsu Autonomous Haulage System is a comprehensive fleet management system for mines. The dump trucks, which are equipped with vehicle controllers, a high-precision GPS, an obstacle-detection system, and a wireless network system jointly developed by Komatsu Ltd., Komatsu America Corporation, and Modular Mining Systems, Inc., are operated and controlled via a supervisory computer, enabling them to be unmanned.[20] Both Caterpillar and Komatsu promote operator safety as the primary driver of automated equipment; however, they also advertise productivity increases of up to 25% and more work up time because of remote operator control.

A.2.1.3 Retrofits, original equipment, and off-road automated vehicle technology platforms

Off-road vehicles are high-cost investments for the agricultural, mining, and construction industries. A new tractor can cost $300,000 along with a guidance system that can range from $1,500 for an entry-level system to $25,000 for an advanced system that includes implement guidance.[21] A new mining dump truck without automated functionality can cost as much as $1 million.[14] The existing off-road vehicle fleet in both agriculture and mining consists of multiple brands, sizes, models, ages, and other features that make customization and aftermarket autonomy upgrades challenging. They are also built off mechanical engines and gearboxes or hydraulic systems that can become extraordinarily complex and expensive to integrate with automated systems.

Jeremy Brown, president and Chief Executive Officer of Jaybridge Robotics, was interviewed about his experience developing automated systems for off-road vehicles.[22] He described how Jaybridge partnered with Kinze in the agricultural space to develop its automated systems as a built-in fully autonomous product. Since the launch of the autonomy project in 2011, Kinze has received positive feedback on the technology from farmers. However, corn prices fell from a high of over $330 per metric ton in July 2012 to less than $150 per metric ton in November 2016.[23] According to Mr. Brown, the collapse of agricultural commodity prices has resulted in farmers avoiding investments in new equipment; Kinze has laid off nearly half its workforce in recent years.

Jaybridge Robotics was also active in the mining and construction space in which it took an aftermarket approach to retrofit trucks used for haulage. These retrofits require adding switch boxes, hydraulics systems, valves, and control equipment to enable autonomous operation. The retrofits cost between a 20% and 25% markup on a base truck price ($200,000–$250,000 per retrofit) followed with approximately $40,000 in service and operational charges. Mr. Brown described these systems as a “no-brainer in a healthy market” and received significant interest from mine operators. Mining commodities, however, faced a similar collapse as in the agricultural space, with iron ore declining from a high of over $150 per metric ton in February 2013 to less than $60 per metric ton in 2016.[24] Jaybridge Robotics has not been able to overcome current market conditions to offer an economically viable approach to autonomy using

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[19] Caterpillar, “CAT Minestar Command: Take Command,” accessed November 16, 2016.

[20] Komatsu, “Autonomous Haulage System,” accessed November 16, 2016.

[21] Zemlicka, Jack (technology editor, FarmEquipment.com), personal interview, November 7, 2016.

[22] Brown, Jeremy (President and Chief Executive Officer, Jaybridge Robotics and program manager, Toyota Research Institute), personal interview, November 8, 2016.

[23] IndexMundi, “Maize (corn) Monthly Price – U.S. Dollars per Metric Ton,” accessed November 16, 2016.

[24] IndexMundi, “Iron Ore Monthly Price – U.S. Dollars per Dry Metric Ton,” accessed November 16, 2016.

either original equipment (agriculture) or retrofit (mining) technology. In March 2016, Toyota Motor Corporation hired the entire Jaybridge Robotics staff to join the Toyota Research Institute to help develop, test, and support its automated vehicle products.[25]

Kraig Schulz, President and Chief Executive Officer of ATC, presented a different perspective on technology platforms for automated vehicles.[26] Despite having developed the SPIRIT—a fully autonomous tractor prototype—in 2012, Mr. Schulz feels that the current market and available technologies are insufficient for fully autonomous agricultural operations.[27]He believes that although the technology to automate a tractor has been around for decades, farmers will be reluctant to relinquish responsibility fully to a system that goes beyond simple, low-precision applications such as tillage, mowing, and bailing. Based on his experience, he is doubtful that farmers will invest in expensive, highly complex systems with limited applications. Kraig has also noted that compared to electric drivetrains, the mechanical and hydraulic systems found on off-road vehicles are less efficient and more expensive, require more frequent maintenance, and do not lend themselves to control equipment, data collection, and automation.

Electrical equipment offers an integrated technology platform that provides the feedback and observational data that is difficult to acquire from a mechanical system. As such, ATC is focusing on replacing inefficient hydraulic drivetrains with its electrical eDrive drivetrain for tractors and implements (such as sprayers and combines) that offers an immediate cost and performance value proposition and lend itself to automation in the long term. The eDrive system, expected to be commercially available in 2017, does not rely on batteries and derives its power from an electrical generator that can be integrated with any existing tractor engine and fuel design. This approach may also be suitable to today's low prices for agricultural commodities. Although farmers are less willing to invest in new equipment, they still must undergo repair cycles for their existing equipment and may find savings by transitioning their equipment to electric drivetrains. ATC hopes to succeed where others have failed by focusing first on deploying an underlying platform that is more amenable to automation.

A-2-2. Off-road regulation

In 2015, Western Australia launched the world's first code of practice for safe fully autonomous mining.[28] The code of practice comes after a 2014 collision event at the BHP Billiton Jimblebar iron ore mine in Pilbara, Australia, between an autonomous haul truck and a manned water cart.[29] The United States does not have similar regulation or codes of practice for autonomous off-road vehicles, which are typically operated on private land. Automated mining and construction equipment remain capable of human operations in case they need to be operated on public roads.[14] Conversely, the ATC SPIRIT and Case IH Magnum autonomous concept tractors do not have operator cabs that would allow for manual control and at this stage it is unclear how and whether they would be exposed to public vehicles. In the near term, it is

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[25] Ramsey, Mike, "Toyota Hires Entire Staff of Autonomous-Vehicle Firm," *The Wall Street Journal*, March 9, 2016.

[26] Schulz, Kraig (President and Chief Executive Officer, Autonomous Tractor Corporation), personal interview, November 7, 2016.

[27] Ibid.

[28] Department of Mines and Petroleum, *Safe Mobile Autonomous Mining in Western Australia – Code of Practice: Resources Safety, Department of Mines and Petroleum, Western Australia*, 2015.

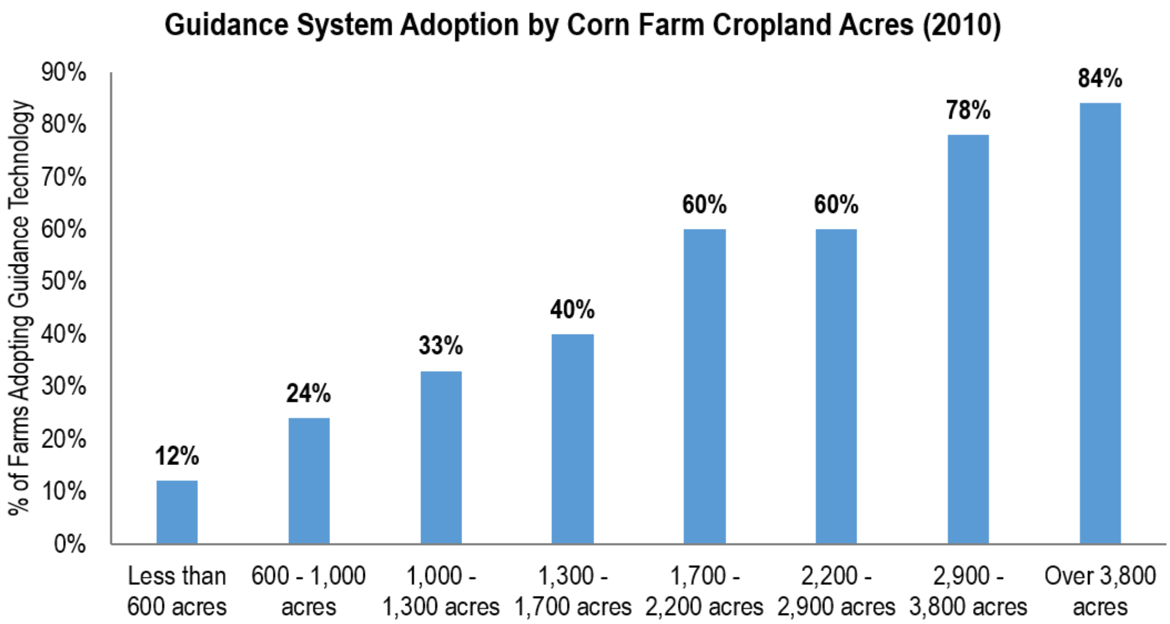
[29] Latimer, Cole, "Mining Automation: The Be All and End All?," *Australian Mining*, September 8, 2015.

most likely that off-road autonomous vehicles will remain on private property and be insulated from any on-road regulations.

A-3. Timeframes for adoption

A-3.1 Adoption of off-road guidance and autonomous systems

Autosteering and guidance systems were introduced to the agricultural industry in the early 2000s and have steadily increased their adoption since then. A 2016 U.S. Department of Agriculture Economic Research Service report presenting findings from the U.S. Department of Agriculture Agricultural Resource Management Survey found that in 2010, guidance or auto-steer systems were applied to a larger percentage of corn acres (54%) than corn farms (29%), implying that larger farms are more likely to adopt these technologies. [30] Findings from the Agricultural Resource Management Survey, shown in Figure A-1, reveal that nearly 80% of farms with over 2,900 acres use guidance systems compared to less than 24% of



those with less than 1,000 acres.

Figure A-1: Guidance system adoption by corn farm cropland acres (2010) Note: Cropland acres are all farm acres planted to any crop, whether owned or rented.[31]

Guidance systems have also increased in adoption since their release in the early 2000s. Figure A-2 shows similar adoption rates between 2001 and 2013 for guidance systems across all surveyed crops in the Agricultural Resource Management Survey. By 2013, guidance systems were used on 45%–50% of all crops except cotton (which may show a jump in adoption when cotton survey results for 2015 become available).

[30] Schimmelpfennig, David, *Farm Profits and Adoption of Precision Agriculture*, Economic Research Report Number 217, U.S. Department of Agriculture Economic Research Service, October 2016.

[31] Ibid.

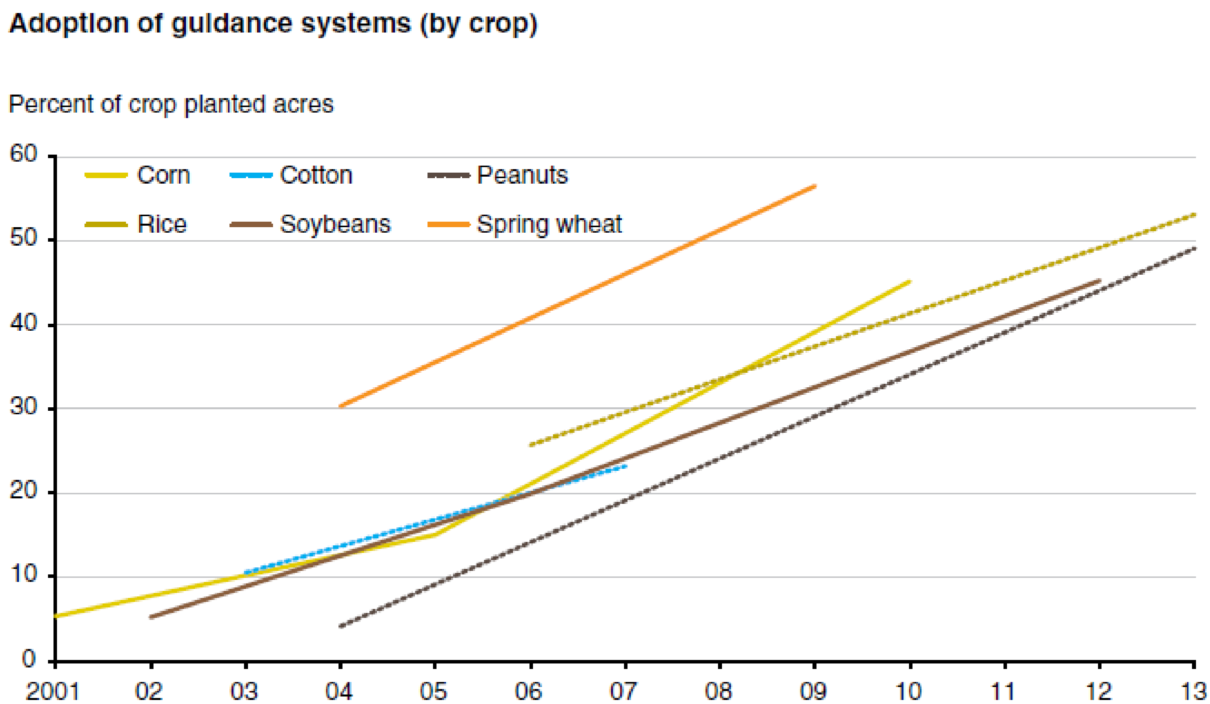


Figure A-2: Adoption of guidance systems (by crop)[32]

Although guidance systems are not standard equipment on new tractors, most tractors are guidance systems-ready, although they require the additional investment in a GPS receiver with the level of spatial resolution desired. Continued deployment of guidance systems in agriculture is expected, particularly as combine harvesters and other implements start to become fitted with guidance systems to help keep equipment precisely on corn and soybean rows.[33]

In an interview with Jack Zemlicka, technical editor for industry publication Farm-Equipment.com, he predicted a three-year minimum before fully autonomous agriculture vehicles become commercially available.[34] Market research from Tractica also sees automated tractor sales growth beginning in the 2018–2019 timeframe and projects that global revenues for the driverless tractor market will reach $30.7 billion by 2024.[35] For these projections to be realized, improvements are likely needed to effectively automate or remotely operate the non-trivial, non-driving agricultural activities. Otherwise, it may be difficult for farm operators to justify investments that fully remove them and their staff from the tractor, particularly in times of low agricultural commodity prices. Time will tell whether the fully autonomous concept vehicle from CHN Industrial, the eDrive retrofit technology platform from ATC, or another approach to agricultural vehicle automation will be successful at penetrating agricultural markets.

Similar deployment data and market projections are not readily available for the mining and construction industries. However, we could expect a slower deployment curve outside of high-value remote mining

[32] Schimmelpfennig, David, *Farm Profits and Adoption of Precision Agriculture*, Economic Research Report Number 217, U.S. Department of Agriculture Economic Research Service, October 2016.
[33] Erickson, Bruce, and David A. Widmar, "Precision Agricultural Services Dealership Survey Results," CropLife Magazine, and The Center for Food and Agricultural Business, August 2015.
[34] Zemlicka, Jack (technology editor, FarmEquipment.com), personal interview, November 7, 2016.
[35] Tractica, "Driverless Tractors and Drones to be among the Key Applications for Agricultural Robots," January 20, 2016.

operations because of higher costs and unfavorable market conditions, and because existing equipment is not guidance-systems ready. Technology improvements and cost reductions stemming from expanded use in Western Australian mines may enable new applications and broader deployment of automated mining vehicles elsewhere.

A-4. Off-road benefits

A-4.1 Safety and liability benefits

Autonomy for off-road vehicles offers safety, liability, productivity, and energy benefits. Both Caterpillar and Komatsu promote safety as the primary value proposition for their automated mining equipment.[36,37] These systems are used in remote mines in Western Australia. Fleet control and obstacle detection systems are designed to prevent collisions with other trucks, equipment, and people. The automated equipment has been shown to eliminate driver fatigue and mitigates other risks caused by human error.

In an article describing Rio Tinto's autonomous mining operations in Western Australia, Yandicoogina mine manager Josh Bennett states, "We have taken away a very high-risk role, where employees are exposed to fatigue." Tim Bay, who was in charge of deploying BHP Billiton's automation program at the Jimblebar mine, said that of the several decision drivers for the automation program, "the single biggest reason is safety."[38]

In conversation, agricultural stakeholders did not indicate increased safety as a primary motivator for adopting autonomous technology, but they did acknowledge the importance of systems being able to sense and avoid obstacles, other vehicles, and people. For both mining and agricultural applications, stakeholders indicated that they expected a shared liability for autonomous off-road vehicles that will be evaluated on a case-by-case basis. Mr. Schulz of ATC, noted that the insurers and equipment owners he has interacted with were excited by the liability prospect for autonomous vehicles, because the cost of damaged property is less than for human injuries or fatalities.[39]

A-4.2 Productivity benefits

After safety benefits, increased productivity is the largest driver for autonomous off-road technologies. The 2010 U.S. Department of Agriculture Agricultural Resource Management Survey estimated that guidance systems raise operating profit on corn farms by an estimated 2.5% and net returns by 1.5%. Caterpillar notes that some of its customers have witnessed speed and efficiency increases that shorten cycle times and increase production by up to 25%.[40] These systems are also particularly useful in underground mining operations that would otherwise be interrupted by shift changes, operator breaks, and the need to evacuate areas for ventilation after blasting. Automated off-road vehicles allow for operations in areas where it is hard to find sufficient manpower, and autonomy enables mining trucks to follow a complex plan with greater reliability and continuity than would be possible with human operators.

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[36] Caterpillar, "CAT Minestar Command: Take Command," accessed November 16, 2016.

[37] Komatsu, "Autonomous Haulage System," accessed November 16, 2016.

[38] Diss, Kathryn, "Robotic Trucks Taking Over Pilbara Mining Operations in Shift to Automation," *ABC*, April 25, 2015.

[39] Schulz, Kraig (President and Chief Executive Officer, Autonomous Tractor Corporation), personal interview, November 7, 2016.

[40] Caterpillar, "Autonomous Mining: Improving Safety and Increasing Productivity," 2016.

A-4.3 Fuel savings and energy benefits

Fuel savings and energy efficiency are not broadly publicized as part of the value proposition for automated off-road vehicles, but they represent substantial benefits that can be realized from smoother operations and technology choices. Jeremy Brown, president and Chief Executive Officer of Jaybridge Robotics, estimates that improvements in mining operations from automation could produce a 10% fuels savings by eliminating vehicle idling, reducing vehicle stops and starts, and ensuring consistent vehicle speeds.[14] A 2013 report found that automated haul trucks have about 5%–7% better fuel consumption than manually driven haul trucks and that these vehicles drive more consistently with less or no side-to-side swaying, accelerate and brake more efficiently, and do not waste fuel driving to break or shift change areas.[41]

Fuel savings and equipment efficiency can also be realized by the choice of technology platform for the automated system. ATC is focusing its business on replacing hydraulic and mechanical systems to use its eDrive electric drivetrain. Mr. Schulz boasts an 8% increase in efficiency over mechanical transmissions and a 13% benefit over hydraulic systems. Mr. Schulz also claims that the eDrive will cost $105,000 compared to $120,000 and $110,000 for mechanical and hydraulic systems. Lastly, Mr. Schulz claims that the 25,000-hour eDrive repair cycle vastly surpasses the 10,000-hour and 3,000-hour repair cycles of typical mechanical and hydraulic systems.[42] Although real-world operational data is not well documented in publicly available literature, independent research and statements from equipment manufactures indicate that the operational and technology efficiencies stemming from automated off-road vehicles are likely to achieve fuel savings compared to human-operated equipment.

A-5. Off-road challenges and opportunities

Off-road industries pioneered CAV technology and will continue to expand as costs decrease and technology improvements allow for more reliable applications. The largest challenge facing CAVs in the agricultural industry is configuration, meaning that the tractor is not the only piece of equipment that needs to be automated. The farmer is still needed in the tractor to handle the most important non-driving tasks such as planting, spraying, and operating a combine. Additionally, farming implements often rely on inefficient hydraulic and mechanical systems that require frequent maintenance and are not easily integrated with control equipment, data collection, and automation. New or retrofitted agricultural equipment with electrical drivetrains may help to enable greater control and automation; however, this approach appears to be the exception rather than the norm for the industry. Until these issues are addressed, it may difficult for farm operators to justify investments that fully remove them and their staff from the tractor, particularly in times of low agricultural commodity prices.

The biggest challenge facing CAV deployment in the mining and construction sectors is cost. Mining and construction have several driving-only applications that are ripe for automation but currently are only economically feasible in high-value operations. For instance, autonomous haul trucks are now commonplace in the remote, hostile mines of Western Australia that must overcome labor shortages. These early adopters will help identify and improve inadequacies in both mechanical efficiency and software efficacy. Cost reductions and technology improvements over time will help mining CAVs broaden their deployment.

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[41] Brundrett, Scott, "Industry Analysis of Autonomous Mine Haul Truck Commercialization," Simon Fraser University, 2014.

[42] Schulz, Kraig (President and Chief Executive Officer, Autonomous Tractor Corporation), personal interview, November 7, 2016.

Off-road CAVs offer greater safety, reduced liability, enhanced productivity, and increased fuel savings to the industries that adopt them, all of which benefit their economic bottom line. Interviews conducted during the course of this research indicate that farm managers and mine operators are pragmatic. Stakeholders in these industries will want to see the technology work firsthand and may require a test run in their field or mine, but they will get on-board quickly once shown that the technology is cost effective and reliable.