Quadrennial Technology Review 2015

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies

Technology Assessments

Connected and Automated Vehicles

Fuel Cell Electric Vehicles

Internal Combustion Engines

Lightweight Automotive Materials

Plug-in Electric Vehicles

U.S. DEPARTMENT OF ENERGY

Connected and Automated Vehicles

Chapter 8: Technology Assessments

Introduction to Connected and Automated Vehicles

Summary

Connected vehicles are able to communicate with other vehicles and infrastructure automatically to improve transportation system function. Vehicle automation refers to the ability of a vehicle to operate with reduced or without direct human operation. Using a combination of advanced sensors and controls, sophisticated learning algorithms, and GPS and mapping technologies, demonstration vehicles have been able to operate in a wide variety of operating circumstances and over long distances with a human driver present but not operating the vehicle. This new technology has led to speculation that automation could enable dramatic changes to the transportation system, with a focus on improved safety, reduced congestion, and novel services and business models. However, automation, especially at high levels, may also have dramatic effects on transportation energy use. While the final effects will depend on an enormous variety of behavioral factors, system effects, and policies, early estimates point to the potential for a dramatic improvement in vehicle petroleum use and greenhouse gas emissions if only benefits manifest, or a significant increase in petroleum use and emissions in the event of unintended consequences.

Terminology

The Department of Transportation defines automated vehicles as "those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) occur without direct driver input." Autonomous vehicles are the subset of automated vehicles where self-driving operation is possible, often intended to mean with limited or no connection to nearby vehicles or infrastructure. The transportation research community has moved towards the term "Connected and Automated Vehicles" (CAVs) to represent a broad category of vehicles with advanced information technology functionality. Connected refers to the ability of vehicles to communicate with each other ("vehicle-to-vehicle", or V2V), and/or with the physical infrastructure, ("vehicle-to-infrastructure", or V2I). Connectivity can allow advanced transportation systems benefits on its own and also may support key automation technologies.

Automated Vehicle (AV) Functionality Levels

NHTSA (2013) has defined five levels of AV functionality, ranging from no AV features (Level 0) to full automation without the need for a human driver (Level 4).[1] Levels 1 and 2 are defined as more limited AV capability, including lane assist, adaptive cruise control, and collision avoidance technology, either operating independently (Level 1) or in unison (Level 2). Level 3 refers to limited automation, defined as enabling "the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions," but expecting the driver "to be available for occasional control" with adequate warning. The Society for Automotive Engineering (SAE) has expanded these definitions to include Level 5 (full automation without driver controls), as summarized in IHS (2014).[2] Relative to the definitions above, Levels 1-5 can all be considered at least partially automated, while only levels 3 and above allow some operation of the vehicle without human intervention.

Technology Requirements

CAVs require a confluence of sensors, automotive technologies (such as drive-by-wire), communications technologies, and advanced information technology (such as machine learning). Although work on automation has been conducted in academic labs since at least the 1980s, the modern fully automated vehicle has its roots in a series of Defense Advanced Research Projects Agency (DARPA) "grand challenges" beginning in 2004 that required teams to build vehicles that could navigate a desert or urban course with no human intervention. These vehicles used advanced sensors and sophisticated decision-making software to navigate complex environments, but the technology was pre-commercial. Researchers and private companies have continued advancing and commercializing supporting components, such as these sensor technologies:

- **Cameras**: mounted on various locations to monitor traffic signals and road markings. Video feeds can be used with computer vision to identify pedestrians, cyclists, other vehicles, and inanimate obstacles.
- **Radar**: often mounted on the front and rear bumpers for detection and range finding of faraway objects.
- **LIDAR**: (a portmanteau of light and radar), uses spinning lasers in a radar-like application. It may be mounted on the roof of the car and scans a wide radius to measure the distance to nearby objects and map physical terrain.
- **Sonar**: an acronym for sound navigation and radar, uses ultrasound to sense nearby objects such as for backup warning or parking assist systems.
- **Global Positioning System (GPS) unit**: uses data from satellites to determine vehicle location. Data is mapped to detailed maps of physical features, known hazards, and lane and traffic structures.
- **Inertial Navigation Systems**: use accelerometers and gyroscopes to continuously calculate acceleration, rotation, speed, and position.

For connected functions, wireless communication technology is necessary, ideally subject to interoperability standards, for the communication to and from the vehicle (telematics). Significant current focus is on the use of Dedicated Short Range Communications (DSRC), which uses a reserved band of spectrum for high-speed vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) transportation communications. High-bandwidth cloud connectivity (such as through commercial wireless networks) may also be a valuable technology, as it allows updates of data to be provided to the vehicle in real time, indirect communication between more distant vehicles, and continual updates of externally-stored maps (including traffic, road work, conditions, and other information).

Beyond sensor and communication technologies, extensive R&D is involved in the automation process. For CAVs to be successful on a broad scale, they will need to operate at extremely low failure rates and under a wide variety of situations and stimuli. Given the system complexity and high reliability requirements, CAVs likely represent one of the most challenging computational problems ever addressed.

Technology Assessment and Potential

Potential Energy Impacts

The most commonly cited potential benefits of CAVs are improved safety, reduced or more manageable traffic congestion, increased road capacity, higher service quality, and availability of affordable transportation to those who are currently underserved. But there is a growing awareness that automation is a key factor for the future of transportation energy as well. Researchers have noted that there are a wide variety of possible effects of a highly automated transportation system, some of which are likely to be beneficial for energy, while others could increase energy demand.[3] For example, Anderson 2014 found that level 4 connected and automated pod cars could reach 300-500 MPG or more, but that VMT was likely to increase in many scenarios.

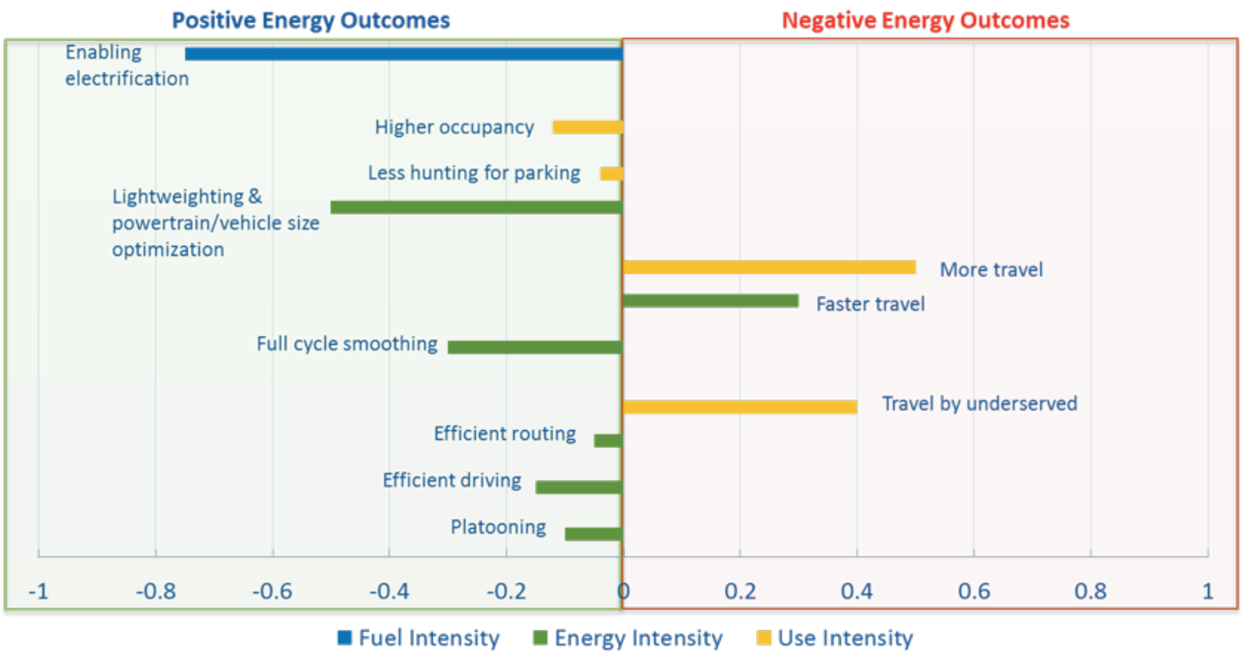
Estimates of these effects and their possible interactions vary widely. The summary below is from Brown, and is illustrative.[4] The purpose is to make an initial assessment of the possible benefits or risks of advanced CAVs from an energy perspective. Many of these effects would only manifest at high levels of automation or in a system where most vehicles are shared use, and so are decades away from manifesting, but will be steered directly by investments made now. Possible energy impacts of automation include:

- **Platooning**: multiple CAVs could safely follow in a group for fast travel, significantly improving aerodynamic performance at highway speeds. Likely to decrease fuel use and emissions.
- **Efficient Driving**: smooth starts and stops can improve fuel economy, and CAVs are able to provide efficient acceleration and deceleration. Likely to decrease fuel use and emissions.
- **Efficiency Routing**: combined with maps that are aware of terrain and traffic, CAVs could select the most fuel efficient route to a destination. Likely to decrease fuel use and emissions.
- **Travel by Underserved**: the young, elderly, and disabled travel less than others, at least in part due to the unavailability of transportation services. CAVs could provide a large social benefit, but increased travel may be a side effect. Likely to increase fuel use and emissions.
- **Full Cycle Smoothing:** A system containing mostly CAVs could have much smoother drive cycles and very few starts and stops. Likely to decrease fuel use and emissions.
- **Faster Travel:** Speed limits are currently determined by safety considerations. With CAVs, safe faster operation may be possible. Likely to increase fuel use from higher aerodynamic drag.
- **More Travel:** CAVs may significantly reduce the marginal cost of travel by allowing productive use of time in the vehicle. Likely to increase fuel use and emissions.
- **Lightweighting and Rightsizing:** In a shared use model, a vehicle can be chosen that matches the characteristics of the trip need (for example, a small vehicle to go to the grocery store but a larger vehicle for recreational trips.) This can allow small, efficient vehicles to serve most trips. Likely to decrease fuel use and emissions.
- **Less Hunting for Parking:** Could decrease fuel use and emissions, unless vehicles autonomously travel far to park.
- **Higher Occupancy:** CAV technologies may facilitate ridesharing (while avoiding the typically much longer journey times associated with mass transit). Likely to decrease fuel use and emissions.
- **Enabling Electrification:** CAVs can overcome several of the current barriers to electric vehicles. Shared use business models distribute capital costs among many users, and allow a vehicle of the appropriate range to be summoned depending on the trip. CAVs would also be able to find a charging station and charge autonomously, removing the customer burden of long fueling times. Likely to decrease fuel use and emissions through increased electrified vehicle penetration.

Freight technology can also be improved with automation. Platooning has been demonstrated to improve fuel economy 5-10% in test hauls (Lammert et al 2014), and routing and logistics can potentially be improved. However, automation could enable rapid at-home delivery 24 hours a day, potentially increasing overall goods movement.

Overall, early analyses have indicated that the energy implications of CAVs may be large, with cases from the illustrative example described here ranging from more than a 90% savings in petroleum use and emissions if only benefits occur, to between a two- and three-fold increase if only the fuel-increasing effects manifest.

Figure 8.A.1 Possible impacts of positive and negative energy outcomes on petroleum use. Positive outcomes are shown as a fractional reduction in petroleum demand (i.e. -0.2 is a 20% reduction) and negative outcomes as an increase in petroleum demand. Fuel, Energy, and Use Intensity refer respectively to the relative levels of vehicle petroleum reliance, operating efficiency, and driving distances. Adapted from Brown, Gonder, and Repac (2014).[5]



Projections

Most major manufacturers have announced plans for some level of CAVs and are actively researching systems. All manufacturers that have announced plans for CAVs already offer or plan to release vehicles with some automated features by 2017, and Level 3 systems are expected by 2017-2020. Google has announced plans to release a Level 4 (full AV) system by 2017,[6] and Tesla has announced its intention by 2020[7] and begun roll-out of some automation in its vehicles by software update.[8] Researchers disagree on when AVs will become generally available, however, and how widespread they will become. IHS (2014) projects Level 3 functionality by 2020, Level 4 by 2025 and Level 5 by 2030, with AVs reaching 9% of sales in 2035 and 90% of the vehicle fleet by 2055.[9] Navigant (2013) was much more bullish, expecting 75% of light-duty vehicle sales to be automated by 2035,[10] and III (Insurance Information Institute) (2013) claims that all cars may be automated by 2030.[11] Others are more cautious; Gomes (2014) reported that among 500 experts attending a recent AV conference, half did not expect to see Level 4 AVs until 2030, with 20% putting the date at 2040, and 10% "never" expecting them.[12] Troppe (2014) believes that AVs will be "inevitable within the 21st century."[13]

Impact Potential Summary

The combination of uncertain deployment projections and uncertain impacts of the technology if deployed makes projections of potential energy and climate impacts premature at this stage. Significant research (see below) will be necessary to model and understand the potential for energy benefits or risks, as well as the mechanisms to increase the benefits. However, because of the large individual possible impacts identified, the potential for energy benefits should not be ignored, nor treated as inevitable.

Program Considerations to Support R&D

Because CAVs are under active development by industry, and many transportation-focused organizations are involved, a key question for the QTR is what public research investments are needed—leveraging private investments—to provide public benefits that will not likely be adequately addressed solely by private activities. Even given the identified energy benefits, it is unclear what role would steer CAVs specifically on a pathway to increase energy benefits and facilitate the technology in general. This section presents a brief current policy landscape and several R&D opportunities.

Landscape

Challenges

There is extensive ongoing analysis of the barriers to widespread CAV use and how to address them. This assessment only summarizes a few major categories as context. Challenges include:

- **Technology:** Although vehicles have been demonstrated in many situations, technology cost and performance are still barriers to future deployment. For example, cameras and computer vision may need to be improved for use in all applications, and both LIDAR and radar face challenges detecting certain classes of objects. Ensuring overall system robustness, interoperability and backward compatibility will also be critical.
- **Public opinion and acceptance:** CAVs are a highly novel technology, and will face a high bar for many in the public to accept them. Even if CAVs are able to be statistically much safer than human drivers, people often react more strongly to failure in a system where they lack individual control. For example, commercial airlines are dramatically safer than personal vehicles, but fear of flying is common and any mishaps are widely reported.
- **Insurance and liability:** In the US, drivers are required to be insured against liability. This model will need to be adapted to work for automation under personal ownership, shared ownership, or business-owned models. If accident rates and corresponding costs decline significantly, this could be a major opportunity to reduce insurance costs, but business models and policies will need to be adapted.
- **Legal:** States need to develop licensing rules and address other legal issues such as rules for attentiveness and driver availability.
- **Understanding transition scenarios and effect interactions:** Further research will need to address the analysis challenges presented by technology transitions (e.g., how realized value and individual behavior might change across different technology penetration rates) and interactions between potential CAV impacts (e.g., relative benefits of electrified vehicles will be lower if vehicles overall encounter less stop-and-go driving). Other example questions include: Could individual vehicle eco-driving actually be harmful to overall traffic flow in some scenarios? How might price elasticities interact with technology- and behavior-induced changes to fuel demand? And how might CAV-enabled mobility changes lead to changes in urban form that would in turn incur energy consequences?
- **Other impacts and unintended consequences:** Even with successful deployment, technology changes at the scale that may be caused by CAVs tend to have significant side effects within the sector and beyond. For example, widespread automated taxis would result in fewer available jobs operating vehicles while demanding new job skillsets in system and data management, security and reliability. In addition to the potential travel increases discussed earlier, uncertain impacts on fuel use will translate to uncertain infrastructure funding from fuel taxes and a potential need for different funding models to support CAV-optimized infrastructure investments.

While many of these challenges will be addressed by the private sector, some may benefit from targeted technology investment or other engagement.

Policy Developments

Uncertainty is widespread as to how CAVs will interact with current and future policies. It is not totally clear if and where autonomous operation might be legal today.

The U.S. Department of Transportation has released an initial policy statement on CAVs, defining the levels of automation, stating long-term interest, defining a research plan, and making recommendations for state policies.[14] The guidance also discouraged states from making operation in automated modes legal at this stage. There has also been significant activity at the state level to try to define the governing policies for automated vehicles. Several states, including California, Nevada, Florida, and Michigan, have moved to allow testing by automakers on public roads. Nevada was first to act, and offered a pathway to sell and license automated vehicles based on certified testers, while also requiring extensive data collection. In other states automated operation may be explicitly prohibited, or in the absence of explicit regulations one way or the other, may be implicitly permitted already.[15]

The future policy landscape for CAVs is highly uncertain at the federal and state level. Legal allowance of automated function, licensing for vehicles, fault/liability and insurance issues will all need to be worked out over time for long-term policy success. Technology will be a key part of these discussions, as the performance of the vehicles and their rate of safe operation is at the heart of each of these policy issues.

The energy implications of CAVs may also be shaped by current and future policies. Current fuel economy standards do not take the in-use operation of the vehicle into account, so the rating of a vehicle would not be affected by either an efficient or inefficient driving algorithm. There is the potential for “off cycle” credits to allow automakers to receive fuel economy credits for efficient CAVs, which will require extensive testing, validation, and monitoring.

Ongoing Programs

Most federal investment in CAVs is through the Department of Transportation’s Intelligent Transportation Systems (ITS) Joint Program Office (JPO).[16] This program cuts across DOT’s modes, and includes investment in a variety of transportation technology. Recent activities include the Connected Vehicle Safety Pilot in Ann Arbor, MI, which concluded in 2014. This focused on V2V and V2I, but has implications for automation. The Applications for the Environment: Real-Time Information Synthesis (AERIS) subprogram has been the portion of the ITS JPO program specifically examining technologies to reduce emissions and environmental impact. It includes policy considerations, educational tools, and performance measures for five operational scenarios, “Eco-Signal Operations, Eco-Lanes, Low Emissions Zones, Eco-Traveler Information, and Eco-Integrated Corridor Management,” each of which is directly relevant for CAVs. Major on-going projects still under development with ITS JPO support include the Connected Vehicles Pilot Deployment Program, which in September 2015 announced up to $42 million to support pilots in New York City, Tampa, FL and rural Wyoming.[17]

The Advanced Research Programs Agency – Energy (ARPA-E) recently issued a funding opportunity for “Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET),” which will address some system and communication activities with relevance for vehicle (and specifically traveler) connectivity.

The Transportation Research Board (TRB) of the National Academies is increasingly involved in CAVs and energy use. The 2015 TRB had 31 sessions related to CAVs across numerous subcommittees and topical foci. Since 2012, TRB has also held a symposium on automation,[19] and energy impacts have been a breakout or subtopic at all of them.

Demonstrations

There is significant technology demonstration activity in progress. These examples are non-exhaustive, and the space is rapidly evolving. Most existing private and public efforts to demonstrate CAV technology focus on technology viability, safety, and systems behavior; relatively few address the energy impacts. Several demonstrations that may allow testing of energy impacts are in the planning phase.

The Defense Advanced Research Projects Agency (DARPA) was an early and influential actor in showing the viability of automated vehicles. In a series of grand challenges culminating with the 2007 Urban Challenge, they brought together research teams from universities to showcase vehicles operating fully autonomously while navigating challenging environments.

The U.S. DOT has invested heavily in connected vehicle technologies (particularly based around DSRC) and conducted its large Connected Vehicle Safety Pilot field evaluation in Ann Arbor, Michigan.[20] This project instrumented approximately 3,000 vehicles with communications technology that could improve safety by relaying position and speed information 10 times per second as part of a basic safety message. Various options are being considered for expanding this project in the future, with energy application testing as a possibility. Other states, such as Florida, have also started promoting automated vehicle pilot projects.[21]

On the international stage, Japan's significant investment in truck automation included the Energy ITS project, which was funded by a pair of government ministries at roughly $12 million per year for five years beginning in 2008. The project succeeded in demonstrating three-truck automated platoons driven at 80 km/hr with 10 m gaps. Additional simulations of platooned trucks together with surrounding traffic flow estimated that overall fuel savings on a typical expressway could be between 2%-5% through a combination of reduced aerodynamic drag and improved road capacity.[22]

In Europe, the Safe Road Trains for the Environment (SARTRE) project[23] ran from 2011 to 2012 and specifically evaluated the energy savings from platooning based on sensors and wireless communication. It identified highway savings of 8% for the lead vehicle and 16% for following vehicles, with a strong dependence on following distance. The project also tested safety and performance under various scenarios. Additional European projects such as CHAUFFEUR, KONVOI and City Mobil have been documented in a review of international activity conducted by the University of California Partners for Advanced Transportation Technology (PATH) Program, which is itself active in the CAV space.[24]

Other active CAV-related university programs include those at Stanford,[25] UC Riverside,[26] the University of Texas,[27] Virginia Tech,[28] Carnegie Mellon[29] and the University of Michigan[30] to name just a few. Noteworthy activities include recent opening of Mcity at the University of Michigan's Mobility Transformation Center, which is a 32 acre test facility with simulated urban and highway areas designed for CAV testing. It contains "approximately five lane-miles of roads with intersections, traffic signs and signals, sidewalks, benches, simulated buildings, street lights, and obstacles such as construction barriers."

One demonstration and evaluation project that has been supported at a DOE lab was the National Renewable Energy Laboratory's recent fuel consumption testing of two typical U.S.-style Class 8 tractor-trailer combinations platooned together at different vehicle loadings, speeds and following distances as compared to their standalone fuel consumption. The results showed team fuel savings on the order of 6% for the two trucks together.[31]

Demonstration facilities and projects will be a key component of efforts to estimate the energy benefits and impacts of CAVs and will be able to improve modeling by validating or challenging analysis results.

Research Needs and Opportunities

Connected and automated vehicles have not previously been a significant DOE investment, though as the scope of possible energy impacts becomes clear, DOE may consider a larger role. However, there are key questions as to how DOE investment can make an incremental difference in either the success of the technology, the effect of the technology on energy use, or both. There is already extensive private investment in CAV technology, so careful partnering with industry, with DOT and other stakeholders will be essential to avoid duplicative or inconsequential research. In general, investment in CAVs could take any combination of several forms, including technology road-mapping and investment, modeling, data collection and analysis.

Technology road-mapping research can elucidate the combinations of technologies that will enable CAVs, and to help identify both barriers and enablers to beneficial outcomes for energy and climate change mitigation. Technology investment could include research support for technologies that are needed for current and future CAV technology but are either underdeveloped or high cost. Early demonstration models with high levels of automation contain tens of thousands of dollars' worth of sensors, cameras, controls, and computers and would, if produced en masse today, likely be prohibitively expensive for the average consumer.

Modeling and analysis investment could include development of new tools to better assess and understand the possible role of CAVs and the resulting energy impacts as they integrate into future transportation systems. To aid and instill confidence in the modeling, it will also be important to support testing and data collection on various CAV implementations as well as on near-term approximations (e.g., from new mobility concepts offered by various app developers and companies such as Uber and Lyft) in order to better anticipate changes to travel demand that the technology may induce. Because the deployment, use, and impact of CAVs will depend on a variety of technology, built environment, human behavior, and system interaction factors, any analysis approach will require modeling of a wide variety of systems and scales. Data and testing at different scales will also be important to inform system modeling, such as from demonstrations, test facilities, or industry partnerships. These analyses could help identify technology development needs as well as future policy to encourage energy-beneficial outcomes.

To help guide research into better understanding factors affecting the future of CAVs, the National Cooperative Highway Research Program commissioned development of a research roadmap for the American Association of State Highway and Transportation Officials (AASHTO), which focuses on transportation institution concerns in areas such as infrastructure design, operations and planning implications.[32] Additional research needs published by the Transportation Research Board of the National Academies focused on four classes of impact particularly relevant for energy efficiency: Vehicle Design, Vehicle Operation, Travel Demand, and System Effects.[33]

- **Vehicle Design:** To assess how CAV technologies may affect possible vehicle design, and the resulting energy implications. Includes possible lightweighting from reduced crash risk, potential for less emphasis on vehicle acceleration, and mobility-on-demand vehicles.
- **Vehicle Operation:** To assess how CAVs may change vehicle operating conditions and the resulting effects on energy, including smoother traffic flow, automated eco-driving and platooning.
- **Travel Demand:** To assess how various levels and types of automation could affect demand for transportation, including impacts of reduced cost of driving, changes in the nature of car ownership, and increased travel access.
- **System Effects:** To assess how the various effects may interact with each other and with other sectors.

The diversity of these research needs reflects the early state of understating of the interactions with CAVs and the energy system. R&D can increase the viability of CAVs as well as allow development to improve their potential energy and climate change mitigation benefits (while minimizing adverse impacts from potential increases in travel and energy demand).

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Acronyms/Glossary

AASHTO	American Association of State Highway and Transportation Officials
AERIS	Applications for the Environment: Real-Time Information Synthesis (within Department of Transportation's Intelligent Transportation Systems Joint Program Office).
ARPA-E	Advanced Research Programs Agency – Energy
AV	Automated Vehicle
CAV	Connected and Automated Vehicle
DARPA	Defense Advanced Research Projects Agency
DOT	Department of Transportation
DMLS	Direct metal laser sintering
DSRC	Dedicated Short Range Communications
III	Insurance Information Institute
ITS	Intelligent Transportation Systems (Department of Transportation)
JPO	Joint Program Office
NHTSA	National Highway Traffic Safety Administration
PATH	Partners for Advanced Transportation Technology
SARTRE	Safe Road Trains for the Environment (European Union)
TRANSNET	Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation
TRB	Transportation Research Board (of the National Academies)
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle