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# *INTERIM MEMORANDUM- DRAFT*

## Air Quality Issues Related to Alternative Modes and Fuels - Emissions and Air Quality Impacts of Connected and Automated Vehicle Technology

Prepared by the Texas A&M Transportation Institute
Prepared for the Texas Department of Transportation
August 2015

***DRAFT FOR REVIEW***

# Air Quality Issues Related to Alternative Modes and Fuels - Emissions and Air Quality Impacts of Connected and Automated Vehicle Technology

## Air Quality and Conformity Inter-Agency Contract

## Subtask 2.2 – FY 2015

***Prepared for***

***Texas Department of Transportation***

***By***

***Texas A&M Transportation Institute***

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**Texas A&M Transportation Institute**

# TECHNICAL MEMORANDUM – DRAFT FOR REVIEW

## Inter-Agency Contract (Contract No: 50-4XXIA032)

## Sub-Task 2.2 Air Quality Issues Related to Alternative Modes and Fuels - Emissions and Air Quality Impacts of Connected and Automated Vehicle Technology

**DATE:** August 9, 2016

**TO:** William Knowles, P.E.
Texas Department of Transportation (TxDOT)

**COPY TO:** Janie Temple, TxDOT
Laura Norton, TxDOT
Justin Malnar, Research Development Office, TTI

**FROM:** Reza Farzaneh, Ph.D., P.E.
Suriya Vallamsundar, Ph.D.
Tara Ramani, P.E.
Joe Zietsman, Ph.D., P.E.
Environment and Air Quality Division,
Texas A&M Transportation Institute

**FOR MORE INFORMATION:**

Reza Farzaneh
(512) 407-1118
Reza.Farzaneh@tti.tamu.edu

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# EMISSIONS AND AIR QUALITY IMPACTS OF CONNECTED AND AUTOMATED VEHICLE TECHNOLOGY

## 1. INTRODUCTION

Advances in connected vehicle (CV) and automated vehicle (AV) technologies have the potential to change the way we travel through the creation of a safe, interdependent network that enables vehicles to interact with each other and with the roadway infrastructure. According to U.S. Department of Transportation (U.S. DOT), connected and automated vehicle (CAV) technology is collectively expected to revolutionize transportation connectivity, in a manner analogous to the internet that revolutionized information technology advancements (*1*).

This report synthesizes current knowledge on CAVs, with a focus on the potential emissions and air quality impacts of these vehicles, especially with their potential future wide-scale deployment. For this purpose, an extensive literature review of studies completed to-date quantifying potential environmental impacts of CAV technology was performed. Factors favorable and unfavorable to achieve air quality benefits are discussed followed by an overview of ongoing pilot research programs.

The report is organized as follows: Section 1.1 provides a brief discussion on an overall framework for understanding the emissions and air quality impacts of CAVs. Section 1.2 discusses the background and relationship between CAV technologies. A more detailed discussion about factors favorable and unfavorable to achieve air quality benefits through CAV technology is provided in Section 2. An overview of ongoing pilot programs developed for analyzing the capabilities of CAV technologies is provided in Section 3. Lastly, conclusions are drawn in Section 4.

Although CAVs are different systems, many of the technologies overlap between the two and they are often collectively discussed under the CAV umbrella. Vehicle connectivity refers to the ability for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, and CV technology is an important input to realizing the full potential benefits and broad-scale implementation of the highest level of automation (*2*). Figure 1 graphically represents the evolution of CVs to AVs. These two technologies may converge or diverge from each other based largely on developments in the private sectors (e.g., vehicle manufacturers, third-party vendors). While some sectors envision a completely AV that does not require communication with other entities, others see synergies between the two technologies (*3*).

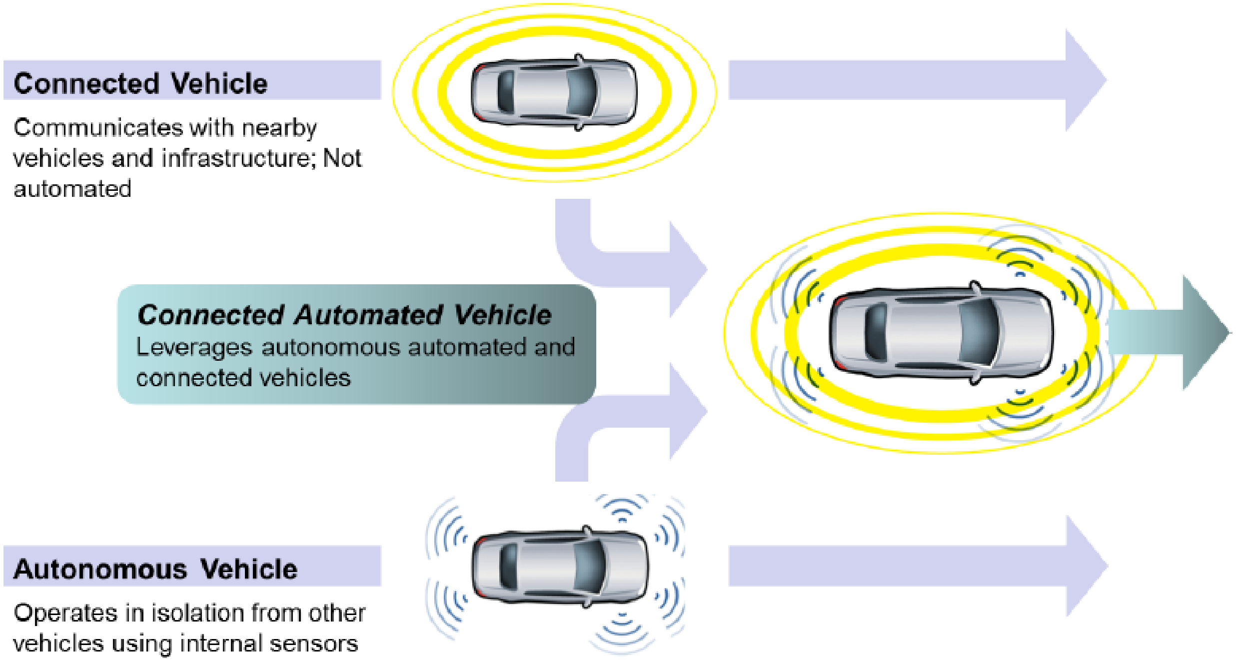


**Figure 1. Evolution of Connected to Automated Vehicles (*2*).**

## 1.1 Framework for Emissions and Air Quality Impacts of CAV

There have been a number of studies that have identified the ways CAV technology would influence the current transportation system in terms of vehicle operations, vehicle design, traffic flow, travel access, vehicle ownership, and land use patterns (*3*). These studies have noted substantial air quality benefits through more efficient traffic flows, vehicle platooning, light weight design, optimizing routing, and shared ridership schemes. However, studies have also pointed out possibilities of rebound effects in terms of driving larger distances due to productive use of in-vehicle time, increased speed, reduced driver burden, and travel access for the disabled, young, and old people. These rebound effects could have a negative impact on the air quality benefits received through energy consumption. One way to balance the rebound effects is to integrate CAV technology with alternative vehicle technology (*4*).The overall air quality impacts of CAV technology depends on the interaction between the following categories:

- Fuel economy.
- Synergies with alternative vehicle technology.
- Rebound effects on travel demand.

The overall impact depends upon to what extent the potential effects of the above categories are realized, interaction between different effects and impact of policy measures to balance the benefits with travel demand rebounds (Figure 2).

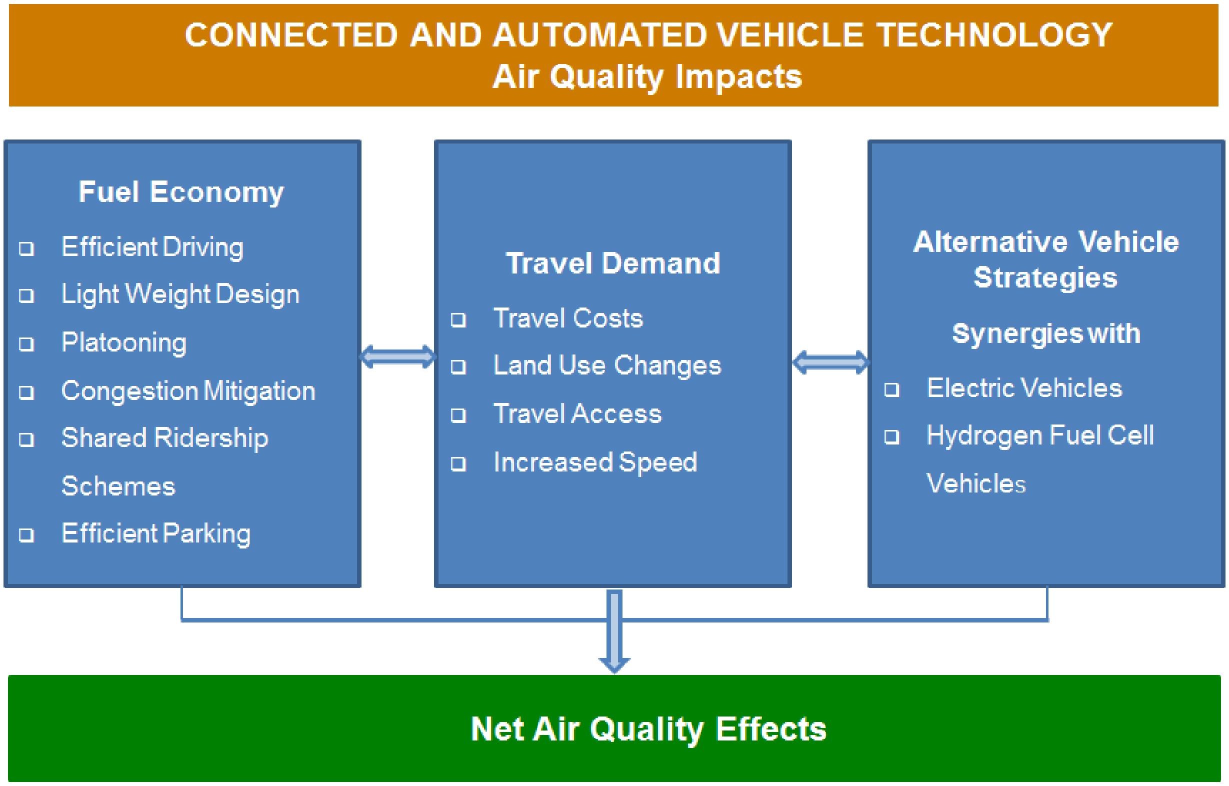


**Figure 2. Air Quality Impacts of CAV Vehicles.**

Studies have quantified the emissions and air quality impacts mostly in terms of fuel savings and energy consumption. Other indicators that studies have used include travel demand, travel time, and total emissions (mostly related to carbon dioxide [$CO_2$] emissions). The studies have taken different approaches to quantify air quality impacts. While some studies have simulated a network of CAV vehicles, few studies have performed real-world testing and few others have relied on assumptions or estimates from other automobile and travel studies in identifying a range of outcomes. Section 2 discusses these in further detail.

## 1.2 Overview of CV and AV Technology

The CV technology enables vehicles to communicate wirelessly with other vehicles (V2V), roadway infrastructure (V2I), vehicle-to-grid (V2G), and to other modes such as pedestrians, bicyclists, and internet clouds. CVs, which have been widely approved by the U.S. DOT, use technologies based on dedicated short-range communications (DSRC) and wireless communication through cellular networks for information exchange. For V2I interaction, information about vehicle location (e.g., latitude, longitude, brake status, length, width) are communicated with cell towers or DSRC roadside units, information about traffic, signal phase, timing; speed limit and parking information are communicated from traffic management centers to roadside units and the onboard units inside the vehicles. Some examples of CV are the

General Motor's OnStar, Ford's Sync, and Chrysler's Uconnect. The U.S. DOT's National Highway Traffic Safety Administration (NHTSA) announced a decision to move forward with incorporation of required V2V technologies on light duty vehicles primarily to help with collision prevention between vehicles and roadway infrastructure (*5*). The most advanced demonstration of CV systems is the U.S. DOT Safety Pilot in the Mcity test facility in Ann Arbor, Michigan, where 3000 vehicles were outfitted with DSRC to demonstrate safety applications including warnings of potential collisions.

AVs are defined by NHTSA as "those in which operation of the vehicle occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode." As AVs do not necessarily need to communicate with other vehicles or infrastructure, technologies such as DSRC or cellular technology are not required. AVs are typically equipped with standalone technologies based on LIDAR, video cameras, and on-board sensors for information exchange without direct driver input or interference. NHTSA defines five levels of increasing vehicle automation described as follows (*6*):

- Level 0: No Automation assumes the driver completely controls the vehicle at all times. Only warning systems such as those for speed limits and blind spots are included. Most CV safety applications fall under this category.
- Level 1: Function Specific Automation automates individual vehicle controls such as electronic stability control, automatic braking, or adaptive cruise control (ACC). The control functions operate independently from one another. Driver is responsible for safe operation of the vehicle and may choose to cede limited authority over specific functions as in case of ACC.
- Level 2: Combined Function Automation automates at least two controls in unison, such as ACC in combination with lane keeping. As in case of level 1, the driver is still responsible for safe operation of the vehicle and may choose to cede limited authority over combined functions.
- Level 3: Limited Self-Driving Automation allows the driver to fully cede control of all safety-critical functions in certain conditions. The car senses when conditions require the driver to retake control and provides a "sufficiently comfortable transition time" for the driver to do so. The second-generation Google car is an example of limited self-driving automation.
- Level 4: Full Self-Driving Automation allows the vehicle to perform all safety-critical functions for the entire trip, with the driver not expected to control the vehicle at any time. As this vehicle would control all functions from start to stop, including all parking functions, it could include unoccupied cars. The third-generation Google car is an example of full self-driving automation.

Of these five levels, only up to level 2 (e.g., ACC, blind spot warning) is currently available to the public. Vehicles with automation levels above 3 must also incorporate CV technologies. Under the broad category of AVs is a subset called autonomous vehicles based on the level of automation. The above levels defined by NHTSA correspond to different levels of automation, in which some functions are automatically controlled and some require driver intervention. Fully AVs or driverless vehicles refer to AVs where the driver is not expected to control the vehicle sometimes or all the times (levels 3 and 4).

There has been a growing interest in vehicle automation in recent years, with a number of scientists and automobile manufacturers working to incorporate autonomous technology into vehicles. Fully autonomous vehicles are still in the research and developmental phase. Current known prototypes are the Google driverless car, General Motors EN-V, CityCar, and MIT Car. Level 1 and 2 automation features are becoming more common in new vehicles, with a number of auto manufacturers offering partial automation features such as anti-locking braking systems, electronic skid protection, ACC, lane keeping assistance, etc. According to a recent report published by J.D. Power in 2014 titled U.S. Automotive Emerging Technologies Study (*7*), purchasers of new vehicles are willing to pay for improved connectivity and increased automation in their vehicle. The study measured vehicle owner interest and purchase intent regarding 61 emerging automotive technologies. The study found an increase in respondent interest to 24 percent in 2014 from 21 percent in 2013 and 20 percent in 2012, with wireless connectivity systems and autonomous driving mode quoted as the most preferred automotive technologies. Further, the report found continued exposure and experience with semi-autonomous features would gradually increase consumer awareness and trust in autonomous driving and help in transitioning to fully autonomous vehicles in future (*7*).

# 2. EMISSIONS AND AIR QUALITY IMPACTS

This section discusses the air quality impacts of CAV technology realized through fuel economy gains (and allied reduction in emissions), increase in travel demand, and synergies with alternative vehicle technology. Several studies have indicated that these impacts could result in a major transformation of the transportation system. The studies cited in this report have taken different approaches to quantify air quality impacts, including simulations and real-world testing. The following sections present a synthesis of air quality impacts from these studies in order to give a sense of the directionality and possible magnitude of impacts.

## 2.1 Fuel Economy

As noted by a number of studies, CAV technology has great potential in improving fuel economy, resulting in emission reduction and energy consumption. The key factors leading to an increase in fuel economy include efficient driving, lighter weight vehicle design, platooning, efficient route selection, congestion mitigation, shared ridership schemes, and efficient parking. These factors are discussed in detail in the following sub-sections. Studies have quantified air quality impacts in terms of fuel economy that is correlated to greenhouse gas (GHG) emissions and energy consumption. However, existing literature is limited in terms of quantification of other pollutant emissions.

### *2.1.1 Efficient Driving*

Features that help in modifying driver behavior can be an effective way to reduce fuel use and emissions. Examples of these features include eco-driving information and assistance, ACC, and eco-routing navigation systems. Eco-driving refers to a set of practices that tend to decrease in-use fuel consumption without changing vehicle design. If a vehicle receives automated speed recommendations as it travels down a road, it can avoid stop-and-go driving patterns that produce more emissions. When the various features are combined, eco-driving applications can result in a 20 percent reduction in fuel consumption and 20 percent reduction in GHG emissions (*8*). A real-world experiment was conducted by the University of California at Riverside to compare the total emissions between a vehicle that gets speed advice based on forward-looking local traffic conditions and another vehicle that does not get this information. They found both vehicles to arrive at the destination approximately at the same time; however the vehicle that got speed advice was found to produce lower emissions and consume less energy primarily by not having to make sharp accelerations and decelerations whenever there was queueing of vehicles upstream. They estimated the emission reduction effects between eco-driving and non-eco-driving to be in the range of 12 to 48 percent for different pollutants (*9*).

Another application of eco-driving is eco-routing enabled by CAV technology that helps in guiding drivers to use more fuel-efficient routes. Eco-routing tools ranges from an indicator that highlights optimal fuel efficiency, to sophisticated eco-routing functions that employ real-time traffic data or roadway data to suggest the most efficient path to a destination based on current driving conditions (*10*). However, there is a need to address several barriers related to availability of traffic data, parking data, environmental data, and alternative modes to implement eco-driving applications (*10*). Eco-routing could help vehicles to select the most efficient route in terms of energy savings and operation. This could be due to avoidance of traffic, use of a shorter but modestly slower route, or selection of a route with fewer emissions. A study in Buffalo, New York (*11*), estimates a 13 percent reduction in emissions, and a corresponding 8 percent increase in travel time due to green route selection.

### *2.1.2 Light Weight Design*

Studies estimate that CAVs would overcome many of the obstacles faced by people in complex environments by reducing the number of accidents caused by human error (90 percent of roadway accidents are caused by human error) (*12, 13*). By reducing the probability of accidents, CAV technology could enable a shift from heavy vehicle chassis and shells designed for passenger protection to autonomous controls. This could enable CAVs to be designed with lighter and more aerodynamic vehicle designs. The weight of vehicles directly affects the amount of power, which has a direct impact on fuel consumption. A reduction in vehicle weight is expected with the progression of automation levels from levels 0 through 4 (*14*). A yardstick for the relationship between vehicle weight and fuel consumption is that a 10 percent reduction in weight results in a 6 to 7 percent reduction in fuel consumption (*15*). A recent study estimated a 50 percent savings in energy intensity as a result of light weight design (*16*).

### *2.1.3 Platooning*

Platooning refers to a system of running vehicles together for a closer headway that reduces the air drag resistance. The reduction in air resistance leads to a reduction in fuel consumption. The air quality benefits received through platooning depends on the vehicle shape, number of vehicles, fraction of time spent platooning, and following distance between vehicles (*16*). The Partial Automation for Truck Platooning (*17*) project tested automated truck platoons on a closed track in 2003 and found significant fuel savings ranging between 12–18 percent. Further, real-world testing by PATH in Nevada in 2009 confirmed the fuel savings benefits. A 10 percent reduction in energy consumption for a 3-truck platoon at 80 km/h, with a 20 m gap between trucks (15 percent reduction at 5 m gap) was estimated in an automated truck platooning study (*18*). Fuel consumption savings of 4 percent, 10 percent, and 14 percent for first, second, and third trucks, respectively, in a 3-truck platoon with 6 m spacing was reported in a truck platooning field study (*19*). Combining the estimates (*18, 19*) with the Federal Highway Administration (FHWA) travel statistics (*20, 21*), estimated energy savings range between 10 to 25 percent for heavy trucks for the entire country. Fagnant and Kockelman (*12*) point out the need for new or modified infrastructure with dedicated platoon lanes to alleviate potential problems faced by other vehicles trying to exit or enter the highway due to tight vehicle spacing. The Applications for the Environment and Real-Time Information Synthesis (AERIS) research project funded by the U.S. DOT on examining how CAV technology can be used to support green transportation choices based on field testing found platooning freight vehicles have the potential to reduce fuel consumption by 10 to 20 percent (*22*).

### *2.1.4 Congestion Mitigation*

Congestion mitigation encompasses the benefits achieved through traffic smoothing and platooning. Platooning of CAVs leads to a greater utilization of lane capacity, which leads to congestion mitigation and reduces the need for infrastructure expansion. Smoother braking and fine speed adjustments through V2V communication helps reduce the amount of stop-and-go traffic and selection of more efficient route choices. Multiple studies have investigated the potential for CAVs to reduce congestion under differing scenarios. Adoption of different levels of automation could result in increasing the congested traffic speeds by 8 to 13 percent and fuel economy by 23 to 39 percent, depending on the level of V2V communication and extent of traffic smoothing algorithms implementation (*23*). Complete elimination of congestion by CAV was estimated to result in a reduction of 2 percent today and 4 percent in 2050 in energy intensity or fuel consumption in vehicle travel (light-duty and heavy-duty) (*21*). The authors developed their estimates by combining estimates on annual volume of fuel wasted due to congestion (*24*) and total gasoline and diesel consumption (*25*).

### *2.1.5 Shared Ridership Schemes*

CAV technology could enable new forms of shared ridership and ownership schemes. The level 4 automation could enable car-sharing and driverless taxis that could automatically pick up a number of people. This could lead to a reduction in vehicle ownership. Fagnant and Kockelman (*26*) estimated that a single shared CAV could replace 9 to 13 vehicles in an urban scenario. Reduction in vehicle ownership could lead to a reduction in vehicle miles traveled (VMT). A reduction of 12 percent in VMT was estimated as a result of dynamic ridesharing to match riders in real time (*16*). A 20 percent reduction in GHG emissions and energy use as a result of car sharing schemes was estimated (*21*). However, studies argue that a growth in shared ridership schemes could impact public transit as more people shift to car-sharing or driverless taxis compared to transit, which would increase overall VMT (*12*).

### *2.1.6 Efficient Parking*

CAVs can assist with smart parking decisions such as locating a parking spot directly without cruising and idling while searching for a spot, which helps in reducing traffic and idling emissions. According to the Texas A&M Transportation Institute's *Urban Mobility Report* (*24*), about 19 gallons of fuel per person per year is wasted in looking for parking. A 4 percent reduction in VMT is estimated due to using CAVs smart parking features (*16*).

## 2.2. Rebound Effects on Travel Demand

The same factors that led to an increase in fuel economy as discussed in Section 2.2 could result in an increase in travel demand causing a rebound effect, offsetting the initial savings achieved through technical efficiency. Adoption of CAV technology leads to an increase in travel demand through the following factors.

### *2.2.1 Reduction in Travel Costs*

Adoption of CAVs could lead to a reduction in travel costs due to a number of factors. First, congestion reduction due to traffic smoothing, platooning, and efficient driving could lead to a reduction in travel time and cost. Second, the automation made possible by CAV technology could enable the driver to use the time to focus on other tasks that are more productive, rather than being at the wheel. Third, the safety gains due to more efficient vehicle design and V2I communication, fuel economy gains could lead to a reduction in insurance premiums, reducing the travel costs. The adoption of CAVs would have a similar effect of reducing travel costs for heavy duty vehicles as a result of efficient driving, effective usage of travel time and insurance costs (*21*). The authors performed a detailed analysis to quantify the impact of automation on travel cost that results in an increase in travel demand. They combined published vehicle travel elasticity estimates, and present day vehicle running and fixed costs with estimates on reduction in travel costs from switching to CAV (*21*). The reduction in travel costs consisted of two components, 1) an estimate of 60–80 percent reduction in insurance costs resulting from around 90 percent reduction in accidents (*27*) and 2) reduction in cost of travel time assumed to range between 5 percent (for Level 2) and up to 50–80 percent (for levels 3 and 4). They estimated a travel demand increase ranging from 4 percent for low level automation to as high as 156 percent for level 4 automation for light duty travel.

### *2.2.2 Land Use Change*

Changes in travel demand are expected to have a secondary effect on land use change. Decrease in travel costs due to efficient driving and congestion reduction, and opportunity to productively use in-vehicle travel time for other purposes may result in behavioral and land use changes (*28*). This could result in people staying farther away from the urban core and using the longer commute productively, leading to greater urban sprawl. Efficient parking enabled by CAV requires a smaller parking space as the vehicle can locate an available parking space and position itself closer to another vehicle more efficiently than humans. This would reduce the need for car parking, which is highly valued within the city limits (*14*). However, a large penetration rate of CAV with a higher level of automation is needed for these vast infrastructure changes to be beneficial (*4*).

### 2.2.3 Travel Access

CAVs provide travel access to groups that are currently unable to drive such as older adults, disabled and children, people without a driver's license, etc. The provision of travel access to these groups could result in an increase in the overall VMT. There are not many studies looking at the increase in travel demand for such underserved population with the provision of travel access. An approximate increase of 40 percent in travel demand as a result of travel access is reported in a study by Brown et al. (*28*). The authors (*28*) examined data from the 2009 National Highway Transportation Survey (*29*) and the 2003 Freedom to Travel study (*30*) and estimated additional VMT to increase by 40 percent if all people over the age of 16 had travel access.

### 2.2.4 Increased Speed

Efficient driving, platooning and reduced vehicle weight could result in increasing the average highway speeds. Faster travel is found to increase air resistance energy loss. Because of this, drag losses could become very significant at high speeds. A study (*28*) extrapolated energy savings from observations on the German Autobahn (which does not have speed limits) (*31*), and the effects of 100 mph travel on highways becoming legal in the United States based on a study for fueleconomy.gov (*32*) that reported a 10 mph increase in speed to result in a 13.9 percent increase in energy use. Based on these studies, they reported an aggregate energy savings of 30 percent due to possibility of faster travel by CAV.

Anderson et al. (*14*) summarized various factors that produce a rebound effect on travel demand along with their relevant levels of automation (Table 1). On balance, VMT seem likely to increase in the near term following introduction of CAVs, but the exact effect will depend on the relevant magnitude of the different influencing factors. The report notes that "Even increases in total VMT can have neutral effects on energy and environmental impacts as long as vehicle efficiencies and/or GHG intensities of fuels are reduced. In addition, development of CAV carsharing would counteract the VMT increase, although is only likely to materialize at a later date."

**Table 1. Potential Positive and Negative Effects on Total VMT (*14*).**

| Influencing Factor | Increases VMT | Decreases VMT | Likely Automation Level |
|---|---|---|---|
| Car-sharing and reduced vehicle ownership | | X | 2, 3, 4 |
| Driverless Taxis | X | | 4 |
| Greater Sprawl | X | | 2, 3, 4 |
| Substitute for intracity or intercity public transportation | X | | 4 |
| Rebound Effect | X | | 2, 3, 4 |

## 2.3. Synergies with Alternative Vehicle Technologies

Studies point out a way to balance the rebound effect between increase in fuel economy and travel demand is to integrate CAVs with alternative fuel technology. CAVs and alternative fuel technology vehicles complement each other as they are both well suited for the same types of trips, such as regular commutes in urban agglomerations that are short trips focused on mobility rather than recreational driving (*4*). While a number of studies have pointed out the ways CAVs when coupled with alternative vehicle technology could improve the environment, none of the studies have estimated the extent of energy savings or emission reduction.

### *2.3.1 Electric Vehicles*

With different levels of vehicle automation expected to decrease the vehicle weight, integrating CAVs partially or fully with electricity would enable it to travel the same range using batteries that are smaller and cheaper. Smaller batteries would also reduce the overall life-cycle environmental impacts that occur both during producing batteries and recycling toward the end of their useful life (*33*,*34*). Other benefits of integrating CAVs with alternative fuel technology is the ease of refueling as the driverless vehicle can search and refuel or recharge the battery, making alternative fuel vehicles more convenient to use (*4*). Further, V2I interaction could enable two-way charging between electric CAVs and the electricity grid, through wired or wireless communications (*35*). Studies have pointed out that availability of two-way charging could be a possible source of revenue, enabling energy storage and grid stabilization (*36*,*37*). The ease of recharging and use of smaller batteries that reduce the overall vehicle cost would accelerate the adoption of electric vehicles as a result of coupling with automation (*14*).

### *2.3.2 Hydrogen Fuel Cell Vehicles*

In addition to accelerating growth of electric vehicles equipped with automation, CAVs have the capability of hastening the growth of hydrogen fuel cell vehicles. According to a report (*35*), a greater barrier to the adoption of hydrogen fuel cell vehicles is the cost of producing hydrogen and building the infrastructure for hydrogen refueling. CAVs equipped with level 4 automation have the potential to overcome this barrier by enabling vehicles to drive on their own to refuel, optimizing the refueling schedules and locations (*14*). In addition, the light weight design of CAVs (available with any level of automation) increases the vehicle range, requiring less hydrogen fuel to travel more distance, which in turn reduces the vehicle costs.

In spite of the potential advantages of integrating CAVs with alternative fuel technology, there is an uncertainty in terms of potential and intention of auto manufacturers in combining the two technologies together. Most of the current CAVs tested in the field are conventional vehicles equipped with different levels of automation. Several synergies between CAVs and alternative fuel technology are being explored by auto manufacturers (such as Google car being built on Toyota Prius (Hybrid) and efforts to upgrade the electric Nissan Leaf to an AV) (*4, 38*).

## 2.4 Summary of Findings from Literature

Table 2 provides a summary of findings from the literature. It contains a compilation of findings with regard to the potential magnitude of effects on air quality for different studies (listed by reference number). As noted previously, each of these studies have used different indicators to measure the impact of CAV technology on air quality. These indicators measure the impact of CAV technology on fuel savings, energy consumption, travel demand, travel time, and total emissions. Additional notes are provided in the table as relevant.

A number of research studies have analyzed the net air quality benefits of CAV technology by taking into account all factors of fuel economy, travel demand, and synergy with alternative fuel technology. Wadud et al. (*39*) estimated a range of 20 percent fuel reduction to an increase of fuel consumption by 50 percent. This range corresponds to the lower end of reduction and higher end of consumption. Studies have also expressed the overall energy savings in terms of Kaya Identity, which is a framework to model the multiple combined effects of different factors that determine the level of human impact on climate, in the form of emissions of GHG (*40*). Brown et al. (*28*) used the Kaya Identity to project the effect of different categories (fuel economy, travel demand, synergy with alternative vehicle technology) on emission reduction. Figure 3 shows the effect on emission reduction classified in terms of use intensity, energy intensity, and fuel intensity. Use intensity refers to factors affecting VMT, energy intensity corresponds to factors affecting energy, and factors affecting fuel are referred to as fuel intensity. The figure highlights the potential of CAVs to result in large fuel savings and use intensity depending upon the extent of incorporation and interaction between different factors. Combining all the categories (fuel, use, and energy intensity), this study illustrates that CAV technology would likely result in greater travel demand but travel would be made in a more efficient manner and potentially be coupled with alternative fuel technology.

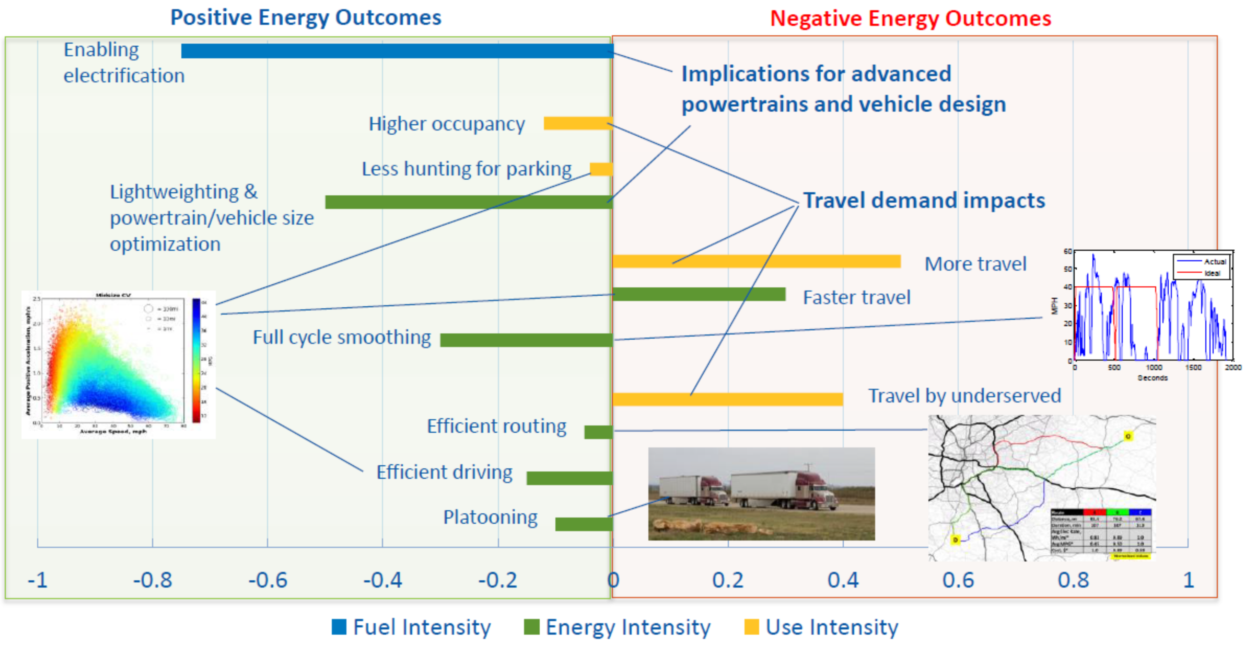


Figure 3. Overall Environmental Impacts (*28*).

Table 2. Summary of CAV Air Quality Effects.

| Effect | References | Potential Effect | Additional Notes |
|---|---|---|---|
| | | **Fuel Economy Effects** | |
| Efficient Driving: eco-driving, smooth start stop, stop elimination | (*9*) | Emission reduction:<br>12% of $CO_2$, 37% of NOx, 41% of HC, 48% of CO<br>Fuel consumption savings of 13%<br>Travel time increase of 6% | Simulation results compared with real-world experiments in Southern California for passenger vehicles |
| | (*8*) | 20% decrease in $CO_2$ emissions<br>20% decrease in fuel consumption | Simulation modeling results from testing the application of intelligent transportation systems (ITS) strategies in Europe |
| | (*11*) | 13% reduction of CO emissions due to eco-routing<br>8% increase in travel time | Integrated TRANSIMS – MOVES framework was used to evaluate real world Greater Buffalo–Niagara Region transportation network considering passenger cars and single-unit short-haul diesel trucks |
| Light Weight Design | (*9*) | 50% reduction of energy consumption | Assuming vehicle weight to be reduced by ~75% and each 10% reduction to be associated with 6–8% energy intensity saving |

| Effect | References | Potential Effect | Additional Notes |
|---|---|---|---|
| **Fuel Economy Effects** | | | |
| Platooning: running vehicles together for a closer headway that reduces the air drag resistance | (*17*) | 12–18% reduction in fuel consumption | Partial Automation for Truck Platooning (*17*) project tested automated truck platoons on a closed track in 2003; real-world testing by (*17*) in Nevada in 2009 confirmed the fuel savings benefits |
| | (*18*) | 10% reduction in energy consumption | 10% reduction in energy consumption was found for a 3-truck platoon at 80 km/h, with a 20 m gap between trucks |
| | (*20*) | 4–14% reduction in fuel consumption | Fuel use savings of 4%, 10%, and 14% was estimated for the first, second, and third trucks, respectively, in a 3-truck platoon with 6 m spacing |
| | (*21*) | 10–25% reduction in energy consumption | Combining the estimates reported by (*18*), (*19*), and (*20*) for heavy trucks for the entire United States |
| | (*22*) | 10–20% reduction in fuel consumption | Field testing of freight trucks by AERIS research project |
| Congestion Mitigation | (*23*) | 8–13% increase in traffic speed<br>23–39% increase in fuel economy | The authors estimate an increase in traffic speed and fuel economy for all vehicles to vary depending upon the level of V2V communication and extent of traffic smoothing algorithms implementation |
| | (*21*) | 2% reduction in fuel consumption today that increases to 4% in 2050 | The authors developed their estimates by combining estimates on annual volume of fuel wasted due to congestion (*24*) and total fuel consumption (*25*) for vehicle travel (light-duty and heavy-duty) |
| Shared Ridership Schemes | (*16*) | 12% reduction in VMT | Assumption based on a study (*22*) that used surveys and focus groups to study the effects of dynamic ridesharing among single occupancy vehicles |
| | (*21*) | 20% reduction of $CO_2$ emissions | Assumption based on a study (*41*) that estimated a reduction of 8.8% GHG emissions through car-sharing in North America based on surveys |
| Efficient Parking | *(16)* | 4% reduction in VMT | Assumption based on an estimate by (*24*) that 19 gallons of fuel per person per year is wasted in looking for parking |

| | | | |
|---|---|---|---|
| | | **Rebound Effects on Travel Demand** | |
| Reduction in Travel Costs | (*21*) | 4–156% increase in travel demand | Combined published vehicle travel elasticity estimates and present day vehicle running and fixed costs with estimates on reduction in travel costs from switching to CAV<br>Travel demand increase ranging from 4% for low level automation to 156% for level 4 automation for light duty vehicles |
| Land Use Changes | (*4*, *14*, *28*) | Decrease in travel cost<br>Increase in urban sprawl<br>Decrease in the need for parking spaces | Qualitative estimates |
| Travel Access for underserved population (youth, disabled, and elderly) | (*28*) | 40% increase in travel demand | Based on data from the 2009 National Highway Transportation Survey (*29*) and the 2003 Freedom to Travel study (*30*) for the entire United States |
| Increase Speed due to efficient driving, platooning, and reduced vehicle weight | (*28*) | 30% reduction in energy consumption | Extrapolated energy savings from observations on the speed limitless German Autobahn (*31*) and energy savings from increase in speed (*32*) |

A study analyzed the net effect of different categories on energy consumption using the Kaya Framework summarized in Figure 4 (*21*). Rather than precisely predicting the impact of automation on energy consumption and travel demand, the authors have developed several scenarios to illustrate how the effect of automation might impact the overall transportation system over time. These scenarios vary in terms of the level of automation, level of incorporation and integration of different categories found to have an impact on environment, cost of travel time, and people's behavioral response. The scenarios as adapted from their paper (*21*) are listed below:

1. "Have our cake and eat it too": The scenario is based on adoption of level 3 automation with eco-driving and platooning widely adopted. The authors estimate the net effect of this optimistic scenario to be a 40 percent reduction in total transportation energy demand as a result of slight increase in travel demand balanced by greater benefits in energy savings (Figure 5a).

2. "Stuck in the middle at Level 2": The scenario is based on adoption of level 2 automation. Benefits are obtained through partial adoption of platooning and eco-driving, travel access to groups currently unable to drive, and lower insurance costs due to decrease in accidents. The energy intensity benefits in this scenario are partially offset by higher travel demand, yielding a 7 percent reduction in total energy (Figure 5b).

3. <u>"Strong responses":</u> The impact of automation on the overall transportation system is greater in scenario 3 compared to scenarios 1 and 2 with major shifts to automated eco-driving, platooning, travel access, and light weight vehicle design balance. All of the envisioned factors balance out the increase in travel demand, resulting in no change in total transportation energy (Figure 5c).

4. "<u>Dystopian nightmare</u>"<u>:</u> The scenario is based on adoption of level 4 automation. Effects of congestion relief, increased speed, travel access, and better usage of travel time results in rebound effects of travel demand increase. Dystopian nightmare is a pessimistic case in which travel time costs reduces; travel demand and speed increases resulting in the doubling of transportation energy demand (Figure 5d).

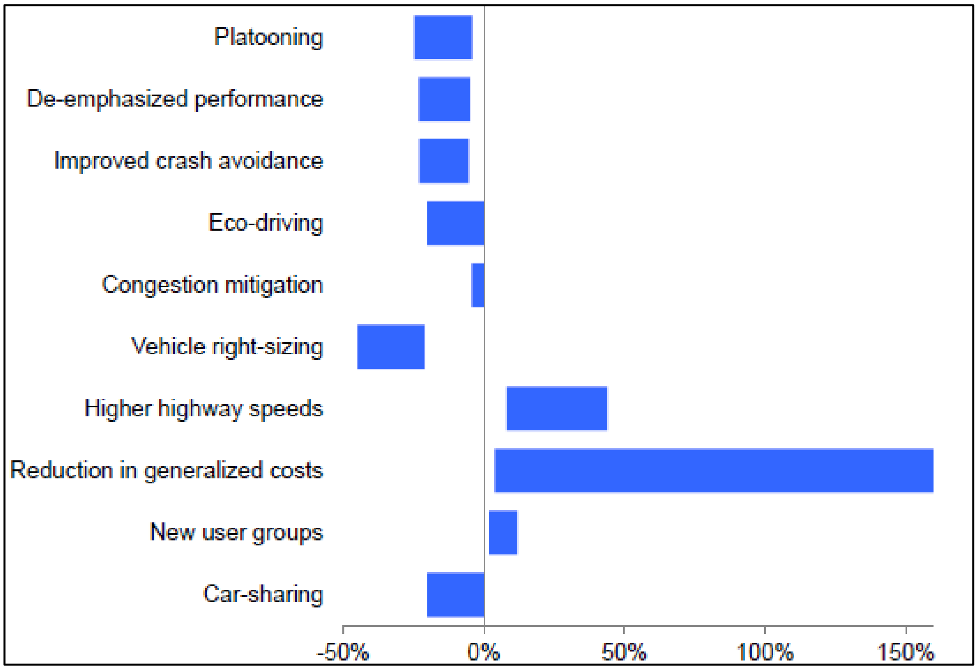
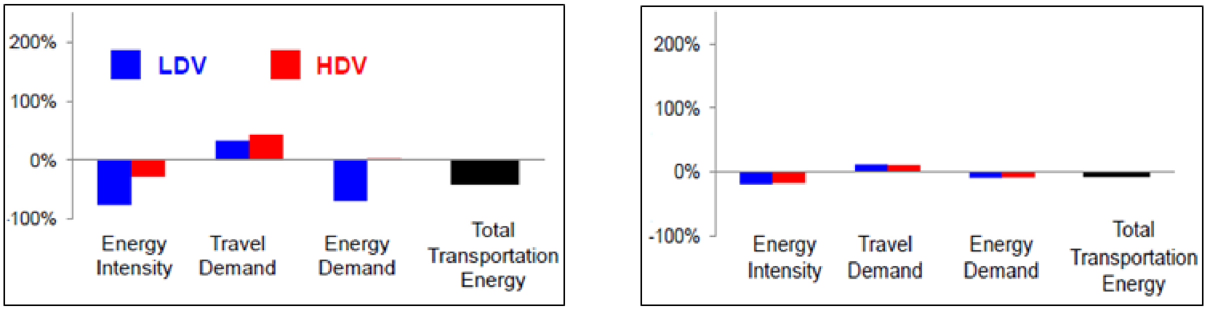
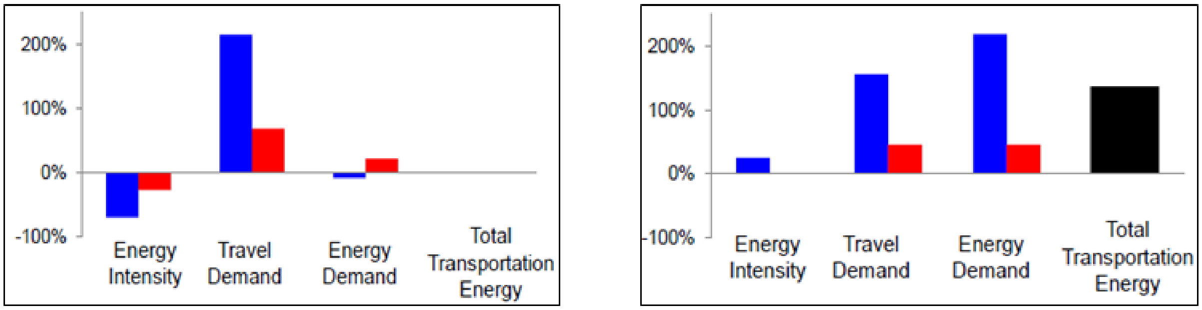


**Figure 4. Net Effects on Energy Consumption due to Vehicle Automation (*21*).**



**(a) "Have our cake and eat it too"**

**(b) Stuck in the middle at Level 2**



**(c) Strong Responses**

**(d) Dystopian Nightmare**

**Figure 5. Changes in Energy Intensity per Kilometer, Travel Demand, and Total Energy Consumption under Varying Automation Scenarios (*21*).**

## 3. CAV ONGOING RESEARCH PROGRAMS

U.S. DOT is undertaking large amounts of research on CAV technology through its ITS research program. The program on CAV technology has been broadly organized into three focus areas. Figure 6 shows the focus areas and their corresponding pilot programs.

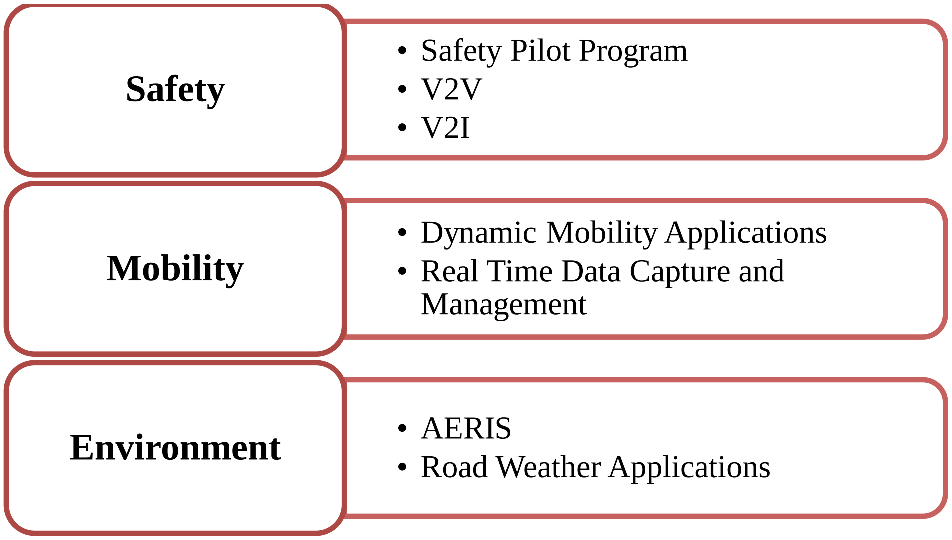


**Figure 6. CAV Focus Areas and Pilot Programs.**

Safety applications are designed to test the applicability of CAV technology in crash prevention through V2V and V2I data transmissions. Mobility applications are designed to capture real time information from equipment located on board vehicles and within the roadway infrastructure to help manage the transportation system for optimum performance. Environmental applications are designed to evaluate the use of relevant real time transportation information through V2V/V2I interactions to support green transportation choices (fuel efficient and eco-friendly routes). As the focus of this report is on air quality effects, details of AERIS programs are discussed in detail in the following subsection. In addition to environmental pilot programs, an overview of test beds that collect air quality data in addition to other information is also provided in this section. Descriptions about other focus areas can be found in reference *42*.

## 3.1 AERIS

The U.S. DOT's ITS Joint Program Office (JPO) sponsored a University of California, Riverside research project called AERIS. The vision for the AERIS program is "Cleaner Air through Smarter Transportation." The program aims to test the capability of different CV applications and analyze the effect of these applications on emissions and fuel consumption. The program (*43*) is investigating whether it is possible and feasible to:

- Identify CV applications that could provide environmental impact reduction benefits via reduced fuel use, improved vehicle efficiency, and reduced emissions.
- Facilitate and incentivize green choices by transportation service consumers (i.e., system users, system operators, policy decision makers).
- Identify V2V, V2I, and V2G data (and other) exchanges via wireless technologies of various types.
- Model and analyze CV applications to estimate the potential environmental impact reduction benefits.
- Develop a prototype for one of the applications to test its efficacy and usefulness.

To answer the above research questions, the program has identified five operational scenarios or bundles of applications to test the capability of CV technology. The scenarios include 1) Eco-Signal Operations, 2) Eco-Lanes, 3) Low Emissions Zones, 4) Eco-Traveler Information, and 5) Eco-Integrated Corridor Management. Each operational scenario consists of a set of applications, regulatory tools, education tools, and performance measures (Figure 7). Applications are technological solutions that consist of software, hardware, and interfaces designed to ingest, process, and disseminate data in order to address a specific strategy (e.g., traffic signal priority). Regulatory/policy tools are authoritative rules that govern transportation, land development, and/or environmental behavior. Educational tools are required to educate the public and transportation agencies on environmental benefits of each scenario. Performance measures include goals and objectives for quantifying the performance of each scenario that relates to reducing emissions, improving traffic flow, etc. More details on all scenarios and their related components can be found in reference *43*.

Among the different operational scenarios, the AERIS Program identified three high priority scenarios that include Eco-Signal Operations, Eco-Lanes, and Low Emissions Zones for detailed modeling and analysis. Analysis includes the integration of traffic simulation models (such as activity based travel demand models, dynamic traffic assignment models) and emissions models (U.S. Environmental Protection Agency's microscopic MOVES emission model) to evaluate the potential fuel use reductions and resulting emissions reductions that can be achieved through CV applications. Modeling of AERIS operational scenarios and applications is currently in progress. While the results are not yet final, preliminary results are listed below (*43*).

### *3.1.1 Low Emissions Zones*

Low Emissions Zones *(44)* are geographically defined areas that seek to improve air quality by encouraging eco-friendly traveler decisions into and within the zone. These areas restrict specific categories of high polluting vehicles; provide incentives for eco-vehicles based on the vehicle's engine emission standards; and support geo-fencing the boundaries of the zone, allowing these areas to be responsive to specific traffic and environmental conditions (e.g., Code Red Air Quality Day, Special Event). The modeling of the AERIS Low Emissions Zones Operational Scenario was undertaken at a regional scale (i.e., for an entire metro area) to capture the possible impact and change in travel patterns resulting from the implementation of a Low Emissions Zone in the urban center. The scenario found an effective low emissions zone to include a combination of incentives to eco-vehicles and enhanced transit services to attract non-eco travelers. The scenario found a 3 percent to 5 percent energy and emissions savings at modest levels of eco-vehicle penetration coupled with enhanced transit services.

### *3.1.2 Eco-Lanes*

**Eco-lanes *(*45*)* correspond to dedicated freeway lanes optimized for the environment that encourage use from vehicles operating in eco-friendly ways (that reduces energy and emissions, reduces unnecessary braking and acceleration, and encourages green behavior). The eco-lane scenario has a number of applications that include Eco-Speed Harmonization, Eco-Cooperative Adaptive Cruise Control (ECACC), Eco-Ramp Metering, Connected Eco-Driving, Wireless Inductive/Resonance Charging, and Eco-Traveler Out of these applications, only eco-speed harmonization and ECACC have currently been modeled. Speed harmonization assists in maintaining traffic flow, reducing unnecessary and starts, and maintaining consistent speeds, reducing fuel consumption, GHG emissions, other emissions on the roadway. ECACC coordinate the maneuvers of neighboring vehicles V2V communication to encourage eco-friendly operation. Expanding on existing ACCs, use radar and LIDAR measurements to identify the location of the preceding vehicle, CV technologies can be used to collect the preceding vehicle's speed, acceleration, and location feed these data into the vehicle's ACC. These data are transmitted from the lead vehicle to following vehicle. Modeling was performed for a generic highway link and a real world corridor in California.**

Table 3 presents the modeling results.

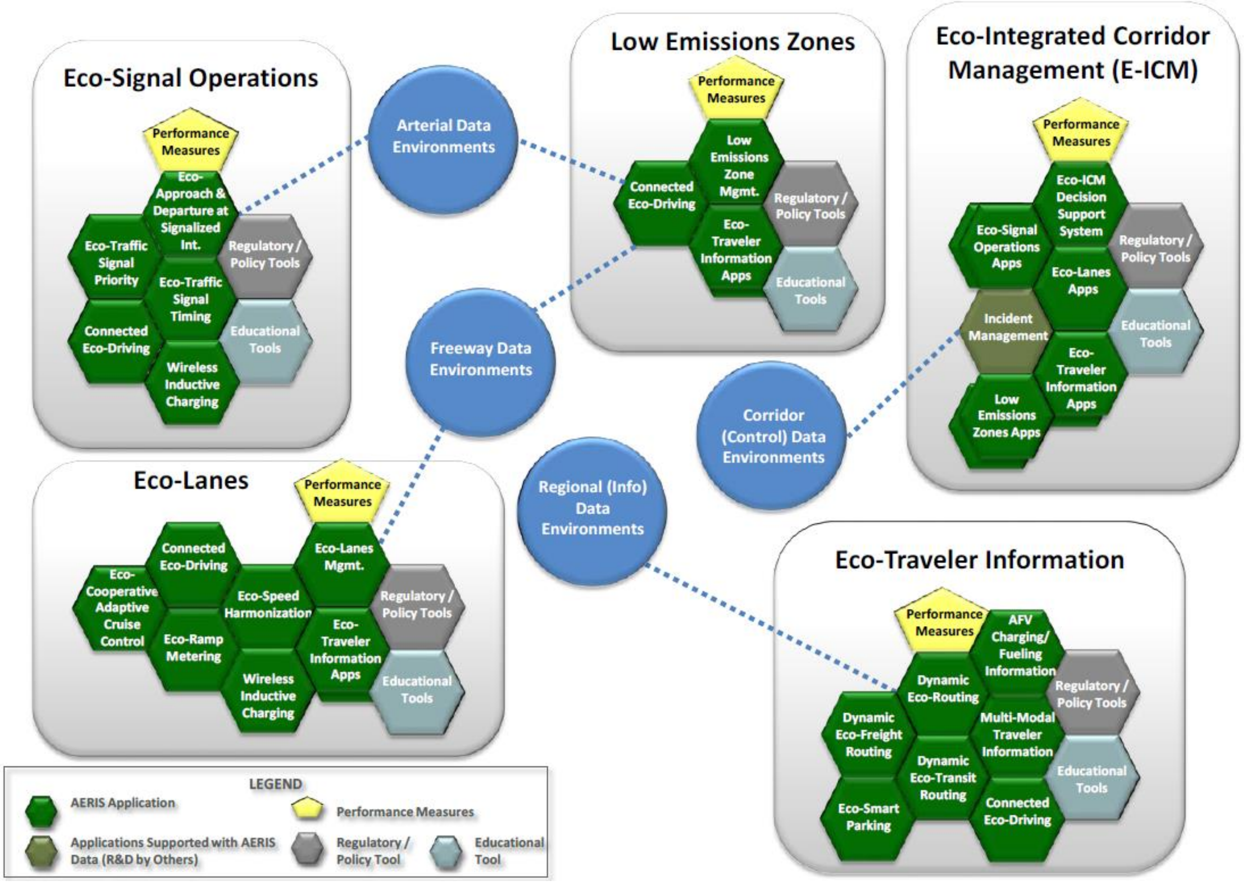


**Figure 7. Overview of AERIS Operational Scenarios (*9*).**

**Table 3. Eco-Lanes Modeling Summary Results.**

| Eco Lanes Modeling | Generic Freeway | Real-world (California) |
|---|---|---|
| Eco-Speed Harmonization | • Up to 12% energy savings with ~8% reduction in mobility<br>• 4% to 8% energy savings with no mobility impact | • Expected 3–10% energy savings |
| ECACC | • Up to 30% energy savings<br>• Increased capacity (2x) | • Expected 10–15% energy savings; improved mobility |
| ECACC + Eco-Speed Harmonization | • Expected 15%+ energy savings | • Expected 10%+ energy savings |

### *3.1.3 Eco-Signal Timing Applications*

Eco-signal timing applications *(46)* seek to optimize traffic signals, with an environmental focus, using data from CV technology to process and record emissions data at signalized intersections, such as fuel consumption and overall emissions along a corridor or for a region. This information is used to create an optimized signal timing plan for minimizing environmental impact and fuel consumption. The performance measure used to optimize signal timing is $CO_2$ vehicle emissions. The signal timing optimization based on emissions is implemented through a Genetic Algorithm methodology. Modeling was performed on a number of highway links in Northern California. Modeling results exhibited a 4 percent to 5 percent improvement in fuel consumption and environmental measures at full CV penetration, while a 1 percent to 4 percent at partial CV penetration. In addition to the environmental savings, a similar improvement in travel time was seen on the corridor with the optimized signal timing plans.

## 3.2 Other CV Programs

### *3.2.1 Road Weather Applications*

The aim of the road weather application program is to collect, forecast, and analyze the impacts of weather on roadway infrastructure and vehicles and to develop strategies or tools that mitigate those impacts. It builds on the previous Clarus Research initiative that developed an integrated surface transportation weather observation data management system to provide anytime, anywhere road weather information to transportation users and operators. The program aims to continue the objectives of Clarus Initiative by further expanding the capabilities of road weather data sources, technologies, traffic management, and decision support tools. The program also aims to coordinate with the other focus areas on dynamic mobility applications, safety (V2V, V2I), and environment (AERIS) to determine how the resulting information from these areas could be used to optimize the existing road weather technologies (*47*).

### *3.2.2 Virginia Department of Transportation*

FHWA partnered with the Virginia Department of Transportation, Virginia Tech, and University of Virginia to launch a research study on CV technology and infrastructure across Virginia (Figure 8). As part of this partnership, test beds were developed to explore the applications of CV technology by analyzing the V2V, V2I, and V2G interactions. The test-bed areas are equipped with wireless infrastructure units and mobile wireless units to collect data related to acceleration, braking, curve handling, and emissions (*48*).

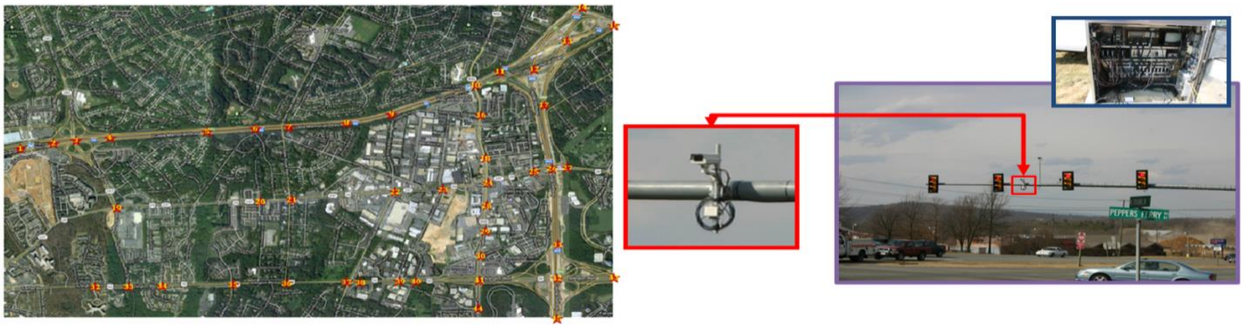


**Figure 8. Connected Vehicle Virginia Test Bed (*48*).**

### *3.2.3 Safety Pilot Study Deployment at Michigan*

FHWA sponsored a real world testing project of CV technology in Ann Arbor, Michigan. The safety pilot study is intended to evaluate the effectiveness of CV technology for crash prevention. The model deployment includes the installation of wireless devices (DSRC) in up to 3,000 vehicles and 29 infrastructure locations along 73 lane-miles of roadway that enables communication with other instrumented vehicles and roadside infrastructure. The simulated town covers a total of 32-acre in northeast Ann Arbor and is referred to as the mini-city or Mcity (Figure 9). Data from the pilot are to be used to evaluate the effectiveness of CV crash prevention technology (*49*).

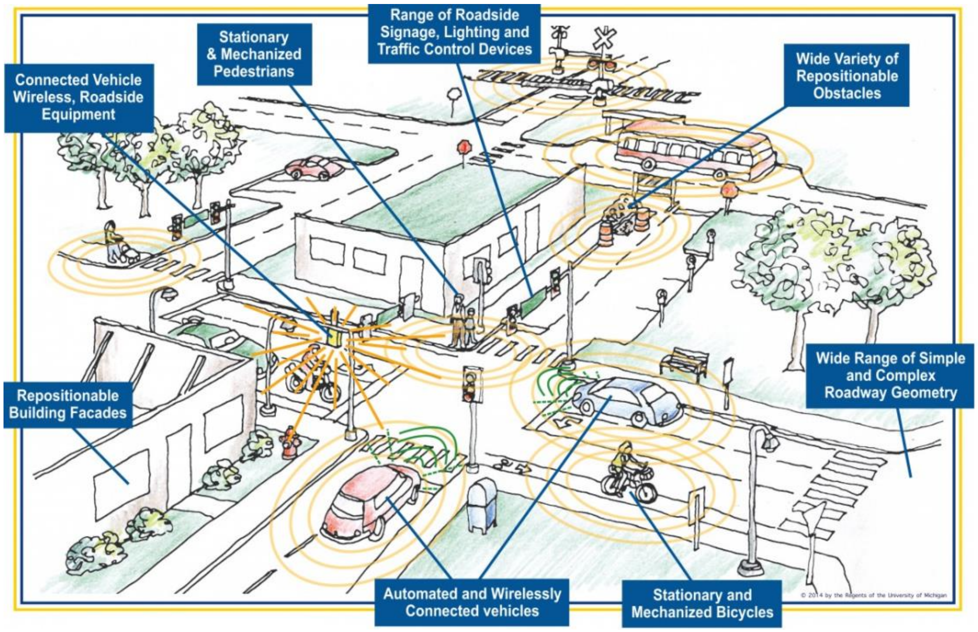


**Figure 9. M-City Test Facility (*49*).**

### *3.2.4 Other CV Test Bed Locations*

U.S. DOT has developed the CV test bed program to provide federally funded resources to developers to establish test beds to examine CV technology under real-world operating conditions (*50*). The mission of the program is to provide a facility where researchers can test new hardware and software for the advancement of CV technology. The facility provides a real world environment where vehicles and infrastructure communicate through wireless technology. The facility provides the capability to test the applicability of CV technology through a variety of tests that includes signal phase and timing communications, security system operations, emission estimation, fuel consumption, crash effectiveness, etc. In addition to test beds located in Michigan and Virginia, test bed capabilities have been established at addition locations in California, Florida, New York, Tennessee, and Arizona (Figure 10). U.S.DOT estimates additional test bed locations to be added in the near future (*50*).

**Figure 10. Upcoming Test Bed Locations (*50*).**

## 3.3 AV Research

AV technology research is still in the preliminary stage compared to the advanced CV pilot programs. The ITS JPO has developed a 2015–2019 multimodal program plan for vehicle automation research at U.S. DOT (*51*). The aim of the program is to foster the development and deployment of AV systems and to identify benefits, dis-benefits, and potential barriers to AV technology. As a first step, a policy study was funded by NHTSA and ITS JPO to study human factors research questions focused on the issue of drivers transitioning into and out of automated driving states enabled by level 2 and level 3 AVs. This project is a joint collaboration between Virginia Tech Transportation Institute, General Motors, Google, Southwest Research Institute, Battelle Memorial Institute, and Bishop Consulting.

## 4. CONCLUSIONS

This exploratory report discussed the potential magnitude and direction of change the CAV technology could have on air quality and emissions. An extensive literature review was performed that discusses the various factors that could affect the emissions and air quality impacts of these vehicles and technologies. Studies point out that CAV technology has the potential to increase fuel economy of vehicles. By providing synergies with alternative fuel technology, they have the capability to reduce the carbon footprint of vehicle travel. However, when CAVs are consolidated into the overall traffic system, the same factors that led to an increase in fuel economy have the possibility of increasing the travel demand through behavioral and land use changes. This leads to a rebound effects where the initial benefits received through an increase in fuel economy is offset by an increase in travel demand. A key question is whether the emission reduction gains through enhanced fuel economy and cleaner fuels outweighs the rebound effect caused by an increase in travel demand. Further, the net effect on air quality depends on the penetration extent of different levels of automation as each level has different factors that are associated with potential favorable and unfavorable air quality impacts. For example, the low levels of automation would have greater energy intensity savings balancing out the modest increase in travel demand; however the higher levels of automation have greater uncertainties as a number of factors come into play and interact with one another (*21*). Hence, it is important to evaluate the impact of each automation level on air quality individually along with its penetration extent compared to analyzing the levels holistically.

Studies also point out that a way to balance out the negative rebound effect is to have policies in place that promote scenarios that mitigate possible travel demand increases and encourage the adoption of CAVs that benefit multiple users through shared ridership programs. Policies should be oriented toward using CAVs to achieve overall travel system optimization such as efficient and integrated corridor management, environmental travel information, etc. (*4*). However, studies have not analyzed the effect of different policies when integrated into the transportation system as a whole. Although CAV technology research has been developing at a faster pace than before, further research is needed especially at the system level in analyzing the net air quality effects of different levels of automation. This is especially true of impacts relating to criteria pollutants and their effects in air quality nonattainment areas, which have not been studied to the extent that energy consumption and fuel economy impacts have.

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