

Chapter

Connected Autonomous Electric Vehicles as Enablers for Low-Carbon Future

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Abstract

Transportation is the main cause of various harmful gases being released into the atmosphere. Due to dependency on fossil fuels, conventional internal-combustion engine vehicles cause major impacts on air pollution and climate change. Achieving greenhouse gas (GHG) reduction targets requires electrification of transportation at the larger scale. Zero-emission vehicles are developing rapidly with consequences for energy use and GHG emissions, and their penetration is rising throughout the world. Such vehicles are widely considered as a promising solution for GHG reduction and a key to low-carbon mobility future. Recent trend in transportation system is a rapid shift toward connected autonomous vehicles. Connected autonomous electric vehicle (CAEV) will play a vital role in emerging revolution in sustainable low-carbon mobility. They can result in major reductions in GHG emissions and be at the forefront of rapid transformation in transportation. CAEVs have great potential to operate with higher vehicle efficiency, if they are charged using renewable energy sources that will significantly reduce emissions and dependency on fossil fuels. This book chapter is intended not only to provide understanding of potential environmental implications of CAEV technologies by reviewing the existing studies and research works but also to discuss environmental impacts including GHG emissions and improvement of vehicle efficiency.

Keywords: connected autonomous electric vehicle, CO₂ emissions, fuel economy, vehicle efficiency, low-carbon mobility

1. Introduction

Transportation is one of the leading causes of various harmful gases being released into the atmosphere. Particularly, due to dependency on fossil fuels, conventional Internal Combustion Engines (ICE) vehicles cause major impacts on air pollution and climate change along with negative impact on the well-beings of the society.

Achieving the global greenhouse gas (GHG) reduction targets requires the electrification of transportation at the larger scale. Zero-emission vehicles (ZEVs) that include hybrid electric vehicle (HEV), plugin hybrid electric vehicle (PHEV) and battery electric vehicles (BEV) are developing rapidly with consequences for energy use and GHG emissions. And the penetration of ZEVs is rising throughout the world. Though no country has yet accomplished a complete transition from

conventional ICEs to ZEVs, some countries such as Norway and Netherlands are leading the way. Electric vehicles (EVs) are widely considered as a promising solution for GHG reduction and key to a low-carbon mobility future. It can be noted that BEV has the lowest amount of CO₂ emissions compared to ICE, HEV, and PHEV.

Recent trend in the transportation system is rapid shift toward autonomous vehicles (AV) [1]. A connected autonomous vehicle (CAV) is an emerging technology that could change the existing transportation system due to advanced communication and sensing capabilities, enhanced travel convenience, and the development of low-carbon mobility business models. Typically, the CAVs are electric, which are more efficient and therefore reduce the carbon emissions.

The connected autonomous electric vehicle (CAEV) will be an important part of the coming revolution in sustainable low-carbon mobility. Four major drivers that include automated driving, electric powertrains, connectivity, and shared mobility can provide compelling transition to a low-carbon future. Thus, they can result in major reductions in GHG emissions from transportation and are at the forefront of this rapid transformation in transportation [2–5]. These technological changes are outstretched and provide several opportunities and challenges.

The CAEVs have the great potential to operate with even higher vehicle efficiency, if they are charged using the electricity generated from renewable energy sources that will significantly reduce emissions as well as dependency on fossil fuels.

This book chapter is intended to provide understanding of the potential environmental implications of CAEV technologies by reviewing the existing studies and research works. We shall analyze environmental impacts including GHG emissions due to the transportation as well as improvement of vehicle efficiency.

2. Connected and autonomous electric vehicles

Connected and Autonomous Electric Vehicles (CAEVs) are complex automotive systems, combining basically connected vehicles (CV), autonomous vehicle (AV) and electric vehicle (EV) [1].

A connected vehicle (CV) is a vehicle with technology that enables it to communicate with nearby vehicles, infrastructure, as well as objects; but may not be automated nor electrically operated.

While, an autonomous vehicle (AV) is a vehicle that is, in the broadest sense, capable of driving itself without human intervention.

And electric vehicle (EV) is a vehicle that powers up and operates with energy stored in the battery.

Typically, CAEV is an electric vehicle that is capable of sensing its environment and navigating with little or no human input. CAEV senses its environment using various sensing devices including Radar, light detection and ranging (LiDAR), image sensors, 3D camera, etc. Basically, CAEV is composed of five major components.

- Perception system which is responsible for sensing the environment to understand its surroundings.
- Localization and mapping system that enables the vehicle to know its current location.
- Driving policy refers to the decision making capability of a CAEV under various situations, such as negotiating at roundabouts, giving way to vehicles and pedestrians, and overtaking vehicles.

- Communication system: as CAVs will be connected to the surrounding environment such as vehicles with vehicle to vehicle connectivity (V2V), to the infrastructure with vehicle to infrastructure (V2I) and to anything else such as the Internet: vehicle to anything (V2X), through wireless communications links.
- Storage battery system: this system includes charger and battery packs in the vehicle. Basically state of charge (SoC) level determines the amount of charge stored in the battery.

CAEVs definitely transform existing mobility paradigm. It can be observed that technological advancements in driving assistants and network connectivity yield further opportunities and services and meet the sustainable development for cleaner, safer, and smarter mobility. **Figure 1** shows CAEV applications and services.

2.1 Advantages of CAEVs

CAEVs offer many potential advantages in terms of sustainable development for environment friendly urban mobility, which are as follows [1].

- Improved safety: may eliminate many of the accidents caused by human error, estimated at about 90% of all accidents.
- Greater mobility: for those who cannot drive, including elderly, disabled, and youth.
- Reduced parking needs: passengers can be dropped off at their destinations without needing a nearby parking space.

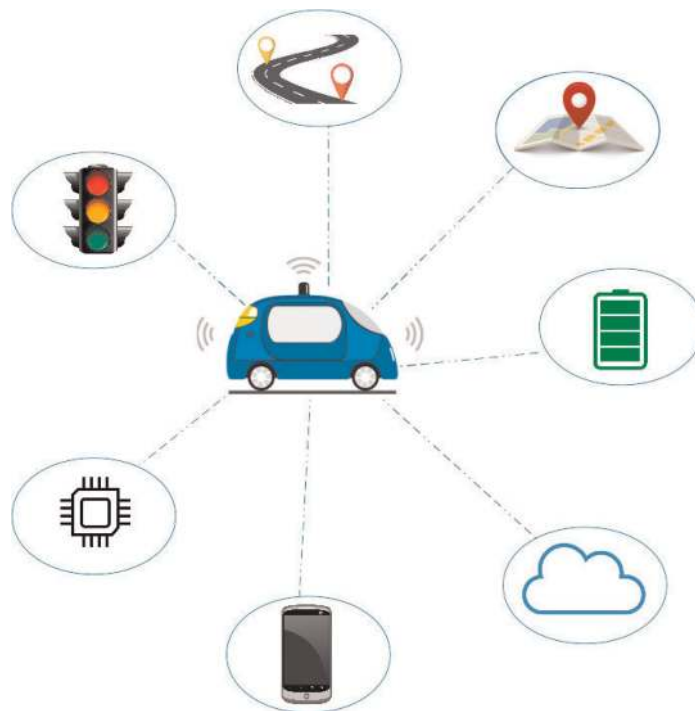


Figure 1.
CAEV applications and services.

- Relaxed drivers: drivers can rest, work, or entertain themselves during a trip.
- Increased car-sharing: reduced need for individually-owned cars.
- Increased road capacity: through fleet platooning, more predictable traffic flow, and reduced congestion.
- Fewer CO₂ emissions and pollutants: using electric power to operate, can reduce GHG emissions as well as air pollution; minimized environmental impact; improve quality of life in urban area.
- Less fuel costs: fossil fuel will not be consumed to run CAEV, so fuel consumption is significant reduced.

With wide adoption of the CAEVs, it is expected to improve road safety, optimize traffic flow, help reduce fuel consumption, and minimize CO₂ emissions in the urban environments.

2.2 Classification of vehicle automation

Society of Automotive Engineers (SAE) released SAE International Standard J3016 that sets out taxonomy and standard to define different levels of autonomy. SAE updated its classification in 2016 as SAE J3016-201609.

Basically, vehicle automation has been categorized into various levels of autonomous vehicle technology ranging from Level 0, corresponding to no automation, to Level 5, corresponding to full automation. For instance, automated driver-assistance systems such as adaptive cruise control correspond to lower automation levels, while fully automated driverless vehicles correspond to higher automation levels.

The SAE defined levels of vehicle automation is depicted as follows:

Level 0—no automation:

In this level, the human driver is responsible for all the driving tasks including control of the car as well as monitoring the road and environment around the car.

Level 1—driver assistance:

In this level, the human driver is assisted with either steering or acceleration/ deceleration by the driver assistance system but not both, for instance, adaptive cruise control.

Level 2—partial automation:

In this level, the driver assistance system take care of both acceleration/ deceleration and steering control of the car, while the human driver monitors the road and environment around the car. It includes more advanced levels of driver assistance and requires continuous supervision of the driver.

Level 3—conditional automation:

In this level, the automated driving system undertakes all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene. Thus it requires partial supervision of the driver.

Level 4—high automation:

In this level, the automated driving system undertakes all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene. This level is basically unsupervised.

Level 5—full automation:

In this level, the automated driving system undertakes all aspects of the dynamic driving tasks in all roadway and environmental conditions. This level does not require driver at all.



















SAE Level	Name	Execution of steering & acceleration/ deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capability (Driving modes)
Human Driver monitors the Driving Environment					
0	No Automation				N/A
1	Driver Assistance				Some Driving Modes
2	Partial Automation				Some Driving Modes
Automated System monitors the Driving Environment					
3	Conditional Automation				Some Driving Modes
4	High Automation				Some Driving Modes
5	Full Automation				All Driving Modes

Figure 2.
 The SAE-defined level of vehicle automation.

Figure 2 shows SAE defined level of vehicle automation.

3. CAEVs for low-carbon mobility

Mainly, due to four revolutions that include vehicular automation, vehicle electrification, vehicular connectivity, and shared mobility, CAEVs can offer great possibilities in expanding mobility and accessibility, and can play a leading role in achieving low-carbon mobility [6, 7].

These major drivers (i.e., automated driving, electric powertrains, connectivity, shared mobility) can provide compelling transition to a low-carbon future. In terms of energy use and carbon emissions, the potential synergies from combining these drivers would be significant.

The studies show that autonomous vehicles with electric powertrains have 40% lower lifetime GHG emissions than ICE-based vehicles. AV technologies along with V2V communications could smooth traffic flows and minimize braking, thus, possibly increasing fuel economy from 23 to 39% [8].

Similarly, the appealing on-demand shared mobility along with vehicular automation may offer the possibilities to expand multi-modal scenario that would reduce car travel by well over half in 2050, thus, would reduce traffic congestion as well as CO₂ emissions in 2050 less than one-third of the conventional vehicles [9].

3.1 Vehicular automation

As Vehicular automation involves the use of AI, and multi-agent system (MAS) to assist the vehicle operation, CAEV can be referred as a smart or intelligent.

Vehicular automation includes automated vehicle dynamics control such as adaptive cruise control (ACC) and automated powertrain operations that can improve vehicle energy efficiency and reduce carbon emissions.

Automated driving would allow to reduce unnecessary accelerations as well as decelerations so that energy efficiency can be improved. Consequently, Vehicular automation may result in optimized efficiency, increased safety, smooth traffic flow, few accidents as well as less pollution due to completely automated fuel control.

3.2 Vehicle electrification

Vehicle electrification, which is referred as zero emission, is one of the appealing ways to reduce transportation related fossil fuel consumption, in turn, minimize carbon emissions and other pollutions.

Due to the vehicle electrification, dependence on fossil fuel oil as well as vulnerability to volatile fuel prices is greatly reduced. Electric vehicles (EV) are significantly energy efficient than conventional ICE vehicles, thus, the formers have drastic reductions in long-term operation costs. Such an efficiency can be improved considerably if productive components (i.e., high-efficient motors, supercapacitors, high-efficient batteries) are utilized, electrical loss is reduced, and overall energy is optimized.

Furthermore, the electricity generation by hydro-power may not be quite clean, so cleaner electricity can be generated by using renewable energy sources such as photovoltaic (PV) solar, wind and other alternative energy sources such as hydrogen-fuel, bio-fuel. Using such technologies, vehicle electrification can provide significant impacts in energy efficiency.

3.3 Vehicular connectivity

Vehicular connectivity accommodates communication systems equipped within the vehicles that allow them to communicate with other vehicles and roadside units (RSU) to provide a wide range of information such as traffic, infotainment.

Motivation for vehicular communication systems is safety and reducing traffic collisions. Advancement of vehicular communication technologies (i.e., V2V, V2I) has not only revolutionized intelligent transportation system (ITS) but also furnishes various promising applications such as collision avoidance, dynamic traffic light.

Efficient use of the vehicular communications shall improve eco-driving (i.e., driving with efficiency maximizing speed, acceleration operating profiles and safety) and encourage more energy efficient driving, such as reducing traffic congestion and unnecessary stop-and-go operations at the intersections as well as shall optimize routing.

The vehicular connectivity can assist in enhancing multimode transportation that shall reduce VMT. The use of eco-driving techniques can improve fuel efficiency, thus in turn, reduce GHG emissions.

3.4 Shared mobility

Shared mobility is referred to Mobility-as-a-Service (MaaS), which can be described as a shift away from personally-owned modes of transportation toward mobility solutions that are consumed as a service. Shared mobility is evolving rapidly and can take several forms including ride-sharing, e-hailing, shared CAVs.

Due to enabling technologies including mobile and wireless, CAV in conjunction with shared mobility have the potential to increase the viability and shared transportation services.

The shared mobility services shall allow to increase roadway capacity by reducing number of vehicles on the road, thus reduce traffic congestion,

and tailpipe emissions as well as reduce vehicle miles traveled (VMT), and vehicle energy consumption.

4. Environmental impacts of CAEVs

Adoption of CAEVs has the possibility to play a key role in addressing environmental impacts due to the existing transportation systems [10–13].

Deployment of CAEVs will yield immense changes in vehicle design, traveler behavior, mobility patterns and even urban planning that will have dramatic environmental impacts [14, 15].

Environmental impacts of CAEVs will depend on several factors. Some of them are listed as follows: effects of the total Vehicle-miles traveled (VMT); adoption of Mobility-as-a-Service (MaaS); Fuel economy; and eco-driving and platooning.

4.1 Vehicle miles traveled

Widespread deployment of CAEVs will lead to a dramatic rise in vehicle miles traveled (VMT) in future. The VMT will be increased mainly due to two factors: vehicles with empty occupancy before pick-up or after drop-off, and increasing demand of ride-hailing or ride-sharing services.

Zero occupancy vehicle travel might contribute significantly to VMT effects of CAEVs. Increase in VMT may lead to the increase in tailpipe emissions.

Adoption of CAEVs will provide independent mobility to non-drivers, including elderly people, people with disabilities, and youths. Since vehicle ownership among these groups will be very low, shared mobility services will be appealing among them. A study estimates an increment of 14% in the overall VMT as a result of wide penetration of CAEVs and mobility services provided to non-driving group.

A study also shows that personally-owned CAEVs are likely to significantly increase the total VMT and carbon emissions, as reduction in parking areas could exacerbate these increases by stimulating more zero occupancy vehicle travels.

4.2 Mobility-as-a-Service

The advancement of CAEV technology and the growth of on-demand shared mobility services may provide essential alternatives to conventional personally-owned vehicles, and have the potential to alter the way in which people move around cities.

Mobility-as-a-Service (MaaS) may be effective means to reduce VMT by combining trips that are temporally and spatially similar, and improve utilization of multi-modal transit providers as more users adopt MaaS as a main source of transit. Thus, MaaS may furnish several benefits including improved energy efficiency, traffic congestion reduction, and carbon emission reductions.

4.3 Fuel economy

Efficient driving generally furnishes increment in fuel economy. And an increase in fuel economy shall provide reduction in energy consumption, tailpipe emissions and air pollution [2].

More efficient driving in CAEVs can be achieved through a variety of mechanisms, including optimal driving cycle, dynamic eco-routing, traffic flow smoothing, and speed harmonization.

A wide-scale deployment of CAEVs could facilitate vehicle platooning that could lead to improved aerodynamics. These advances in CAEVs could lead to considerable improvements in fuel economy.

4.4 Eco-driving and platooning

Eco-driving may include route planning, trajectory optimization, and driving behavior improvement. And it is an effective way to reduce vehicle fuel consumption and achieve significant reduction in carbon emissions.

Platooning is based on Cooperative ACC (CACC) technologies that use V2V communication to enable constant time-gap following and ad hoc joining and leaving the platoon. Platooning dynamically chains CAEVs to maximize fuel efficiency.

Platooning is appealing due to the fact that it provides energy savings from aerodynamic drafting, more stable vehicle following dynamics, reduced traffic flow disturbances as well as potential safety improvements.

5. Discussion

Several research works, studies have been conducted for analyzing the environment impact of CAVs [16–18].

Collaborative research from Argonne National Laboratory, National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory, and U.S. Department of Energy illustrates the overall system VMT and fuel consumption effects due to vehicle automation [16].

In the study [16], the researchers have considered four scenarios: conventional vehicles, partial autonomy, full autonomy with ridesharing, and full autonomy without ridesharing, and associates upper (UB) and lower (LB) bounds with the latter two. **Figure 3** shows the upper bound and lower bound estimates on total U.S. Light-duty vehicle (LDV) fuel consumption for various CAV scenarios compared with the base Conventional scenario.

In **Figure 3**, it can be seen that there is large variation in the results; the total U.S. LDV fuel consumption (billion gallons per year) ranges from approximately 64% decrease in case of full autonomy with ridesharing LB up to approximately 205% increase in case of full autonomy without ridesharing UB.

Viewing the deployment of the CAVs (partial or full autonomy), the effects of travel demand and fuel efficiency were further investigated.

Possible changes in travel demand due to connectivity and increased vehicle automation are uncertain. The potential effects of CAVs on travel demand are classified into the following categories: less hunting for parking; easier travel; increased travel by under-served populations; mode shift from walking, transit and regional air; increase in ridesharing; and Increased empty miles traveled by automated vehicles [16].

Similarly, connectivity and vehicle automation have the potential to impact driving patterns, vehicle design as well as fuel efficiency. However, the impacts are uncertain. The categories of potential energy impact may include: drive profile and traffic flow smoothing; lesser congestion; efficient V2I/I2V communication; collision avoidance; platooning; and vehicle/powertrain resizing [16].

The researchers have elaborated the methodology that accommodates the above-mentioned travel demand and fuel consumption effect assumptions to estimate

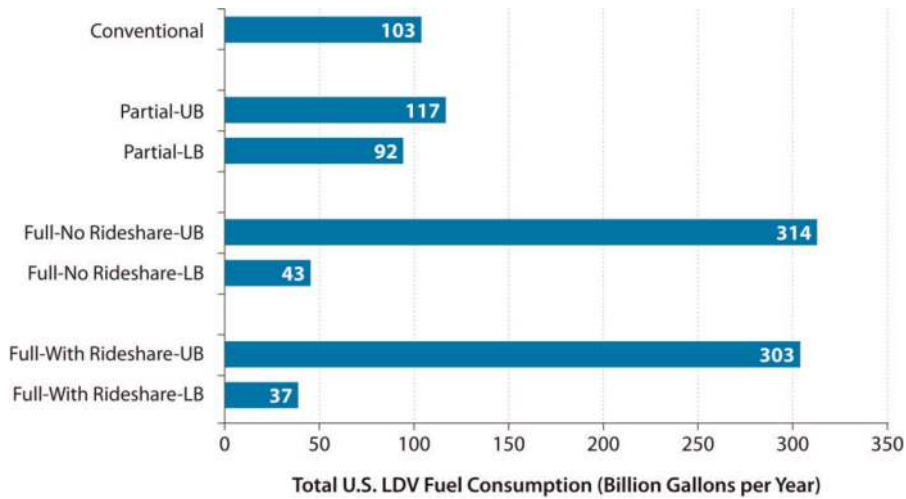


Figure 3. Total U.S. LDV fuel consumption for various CAV scenarios compared with the base conventional scenario [16].

national-level fuel use impacts. **Table 1** shows the notations used in the equations for the computation of national fuel consumption impacts [16].

Referring to **Table 1**, the impacts $r_t^{i,j}$, $q_t^{i,j}$ are the fractional changes in the fuel consumption per mile over and above the fuel consumption per mile including all impacts considered earlier, that is, [16]

$$r_t^{i,j} = \left(\frac{FC_t^{i,j}}{FC_{t-1}^{i,j}} \right) - 1, q_t^{i,j} = \left(\frac{FC_t^{i,j}}{FC_{t-1}^{i,j}} \right) - 1 \quad (1)$$

and analogously for $p_t^{i,j}$, and $s_t^{i,j}$:

$$p_t^{i,j} = \left(\frac{VMT_t^{i,j}}{VMT_{t-1}^{i,j}} \right) - 1, s_t^{i,j} = \left(\frac{VMT_t^{i,j}}{VMT_{t-1}^{i,j}} \right) - 1 \quad (2)$$

Using the notations in **Table 1**, the baseline conventional fuel use in the U.S. (without CAVs) is calculated as: [16]

$$\sum_{i \in I, j \in J} (VMT_0^{i,j} * FC_0^{i,j}) \quad (3)$$

i	Set of road type I, {city, highways}
j	Set of time of day J, {peak hours, non-peak hours}
t	Set of technologies T, {partial automation technology, full automation technology}
$r_t^{i,j}$	Fuel impact estimated by partial automation technology t, on road type i, and time of day j
$q_t^{i,j}$	Fuel impact estimated by full automation technology t, on road type i, and time of day j
$p_t^{i,j}$	VMT impact estimated by partial automation technology t, on road type i, and time of day j
$s_t^{i,j}$	VMT impact estimated by full automation technology t, on road type i, and time of day j
$FC_0^{i,j}$	Original fuel consumption rate (gallon per mile), on road type i, and time of day j
$VMT_0^{i,j}$	Original vehicle miles traveled, on road type i, and time of day j

Table 1. Notations used in equations for the computation of National fuel consumption impacts [16].

Consequently, the total fuel consumptions under partial automation and full automation scenarios can be calculated as follows: [16]

$$\sum_{i \in I, j \in J} \left(\left(VMT_0^{i,j} \prod_{t \in T} (1 + p_t^{i,j}) \right) * \left(FC_0^{i,j} \prod_{t \in T} (1 + r_t^{i,j}) \right) \right) \quad (4)$$

$$\sum_{i \in I, j \in J} \left(\left(VMT_0^{i,j} \prod_{t \in T} (1 + s_t^{i,j}) \right) * \left(FC_0^{i,j} \prod_{t \in T} (1 + q_t^{i,j}) \right) \right) \quad (5)$$

Based on the EPA Motor Vehicle Emission Simulator (MOVES) model values for U.S. national averages, the fraction of VMT on city and highway roads at peak and non-peak hours are estimated.

The analysis considers that the average fuel economy of LDVs to be 26.9 miles per gallon. Particularly, the analysis uses the relationship between city/highway fuel economy values with the combined fuel economy for the computation of the average city and highway fuel economy.

Additionally, it is assumed that traffic congestion occurs during peak hours and free flow driving occurs during non-peak hours. The analysis accounts the adjustment factors that have been suggested to calculate differences in fuel consumption (or GHG emission) under congestion and free flow driving and applies those adjustment factors in order to compute fuel economy and fuel consumption values during peak and non-peak hours. **Table 2** shows the assumptions of VMT in percent, fuel economy and fuel consumption for a baseline conventional vehicle under various road types and time of day [16].

The preceding formulations (Eqs. (1)–(5)), along with the assumptions from **Table 2**, yield the fuel consumption per mile impacts of various vehicle automation technologies at a national level, as shown in **Figure 4**. The effects are distinguished by partial and full automation CAVs [16].

In **Figure 4**, it can be seen that the adoption of full automation CAVs may have significant productive energy impacts. Typically, the increased fuel savings due to various categories are as follows: for vehicle/powertrain resizing, fuel saving is 0%–50%; for drive profile and traffic flow smoothing, it is 6.5%–16%; for platooning, it is 3%–5%; for intersection V2I/I2V communication, it is 2%–4%; and for collision avoidance, it is 0.2%–2.2%.

In the paper [17], the researchers have presented a methodological approach for refining this wide range of estimated fuel consumption.

The researchers have utilized a framework that accounts for energy impacts at the vehicle level, projected adoption levels, and changes in VMT in order to estimate national level fuel consumption impacts of CAVs. And they have considered several scenarios [17]

Road type/time of day	VMT %	Fuel economy (U.S. MPG)	Fuel consumption rate (U.S. GPM)
Highway, peak hours	18	29.7	0.0337
Highway, non-peak hours	27	35	0.0286
City, peak hours	22	21.4	0.0467
City, non-peak hours	33	25.2	0.0397

Table 2. VMT percent, fuel economy, fuel consumption assumed for conventional vehicle by road type and time of day [16].

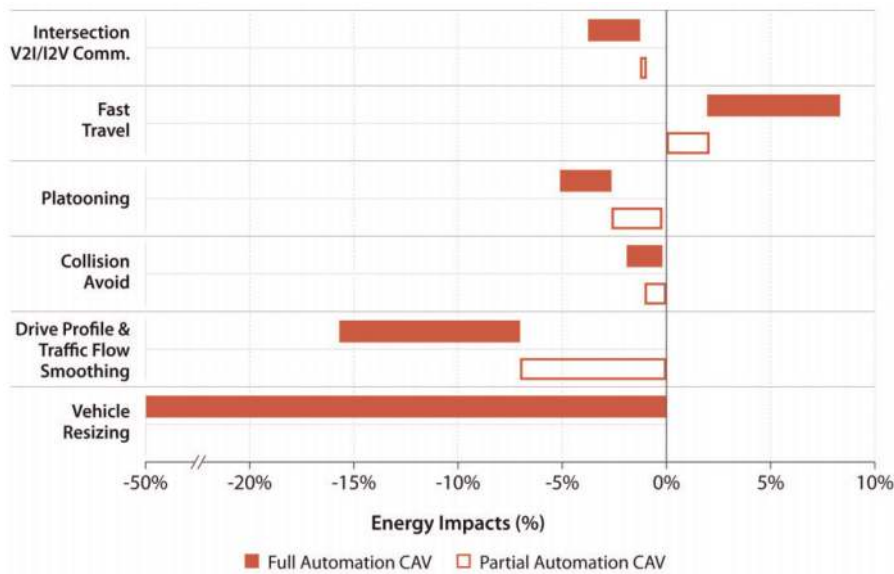


Figure 4. Vehicle-level fuel consumption per mile impact under various vehicle automations [16].

- BASE-AEO is a scenario that is based on EIA’s Annual Energy Outlook (AEO) 2017 Reference case;
- BASE-ADOPT is a scenario that is based on AEO 2017 inputs with projected vehicle sales shares from NREL’s Automotive Deployment Options Projection Tool (ADOPT);
- CACC-AEO is a scenario with Cooperative Adaptive Cruise Control (CACC) penetration projections applied to the BASE-AEO case;
- CACC-ADOPT is a scenario with CACC applied to the BASE-ADOPT case;
- AutoTaxi-AEO is a scenario with automated taxis penetration projections applied to the BASE-AEO case; and
- AutoTaxi-ADOPT is a scenario with automated taxis applied to the BASE-ADOPT case.

Figure 5 shows U.S. total LDV fuel consumption for various scenarios (i.e., BASE-AEO, BASE-ADOPT, CACC-AEO, CACC-ADOPT, AutoTaxi-AEO, AutoTaxi-ADOPT) for a certain time period from 2015 to 2050 [17].

In **Figure 5**, it can be depicted that AutoTaxi scenarios (i.e., AutoTaxi-AEO, AutoTaxi-ADOPT) will have considerable energy impacts in compared with BASE use cases (i.e., BASE-AEO, BASE-ADOPT) in the future. For instance, by 2040, the US total LDV fuel consumption of CAVs decreases by 5% in case of AEO and 5.5% in case of ADOPT.

The paper [18] is based the well-established ASIF framework, which expresses transport carbon emissions in terms of the major drivers. The formulation for carbon emissions (E) can be stated in the following equation: [18].

$$E = A * S * I * F \quad (6)$$

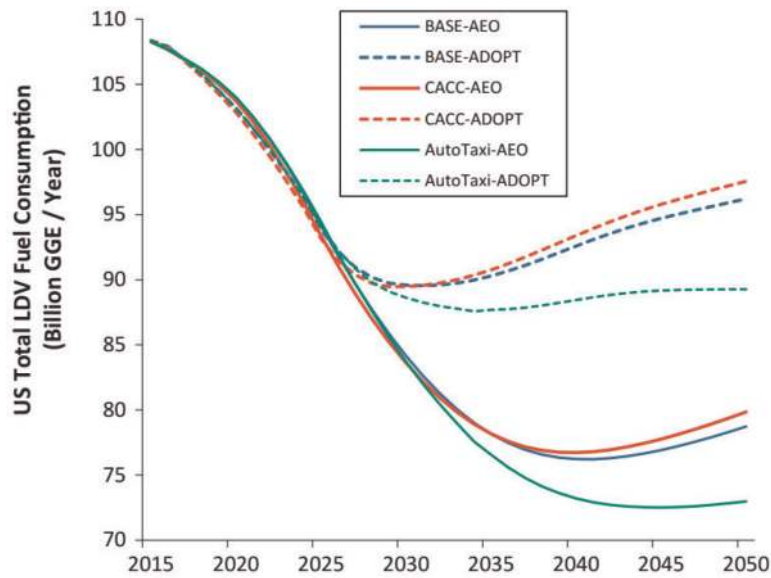


Figure 5. U.S. total LDV fuel consumption scenarios for a certain time period from 2015 to 2050 [17].

where, A is activity level; S is modal share; I is energy intensity; and F is fuel carbon content.

The ASIF framework functions as a tool to organize various anticipated mechanisms through which vehicle automation may affect energy consumption and carbon emissions. Each driving factor on the right hand side of Eq. (6) can be considerably affected by the use of vehicular automation and thus fuel consumption and carbon emissions. **Table 3** illustrates a concise version of presumed mechanisms for energy impacts of automated vehicles (refer to [18] for details).

Figure 6 illustrates estimated ranges of possible energy impacts of vehicle automation in respect of various mechanisms [18].

Mechanism	ASIF element	Direction of effect	Automation level	Penetration level
Congestion mitigation	I	-ve	1-4	Moderate to high
Eco-driving	I	-ve	1-4	Any
Platooning	I	-ve	2-4	Any
Higher highway speeds	I	+ve	1-4	Moderate to high
De-emphasized performance	I	-ve	3,4	Any
Improved crash avoidance	I	-ve	2-4	Very high
Vehicle right-sizing	I	-ve	3,4	High to very high
Increased features	I	+ve	3,4	Any
Demand due to travel cost reduction	A,S	+ve	1-4	Any
Demand from New user groups	A,S	+ve	3,4	Any
Changed mobility services	A,S	-ve	3,4	Any
Potential for low-carbon transition	F	-ve	3,4	High

Table 3. Presumed mechanisms for energy impacts of AVs [18].

It can be seen that several mechanisms may yield substantial reduction in energy use and carbon emissions, while others may have negative impacts. For instance, utilization of eco-driving, platooning, congestion mitigation, de-emphasized vehicle performance, lower crash risk, vehicle right-sizing, car-sharing and on-demand mobility, and reduced infrastructure footprint of automated vehicles may contribute to the improved energy efficiency of AVs. However, the increase in VMT due to lower travel costs, new user groups (youth, elderly, disabled), higher highway speeds, and increased vehicle features may increase the carbon footprints of AVs.

Table 4 provides abridged version of automation scenarios along with estimated ASIF multipliers for each effect. The scenarios vary in terms of levels of vehicle automation, effectiveness of the above-mentioned mechanisms in altering energy intensity, the degree of travel cost reductions, and the magnitude of travel demand [18].

The authors have conducted scenario analysis that shows vehicle automation may reduce energy use and GHG emissions by half in best-case scenario, or double them in a worst-case scenario, depending on the effects that come to dominate. Consequently, the outcomes depend on which scenarios prevail and proactive policy making is essential to steer the technology toward energy efficiency.

Overall energy and environmental implications of CAEVs in future will depend on following influencing mechanisms:

- Energy-saving algorithms and vehicle design.
- Vehicle operation (i.e., eco-driving).
- Platooning.
- Electrification using renewable energy resources.
- Changed mobility services.
- Vehicle utilization.
- Travel-cost implications.

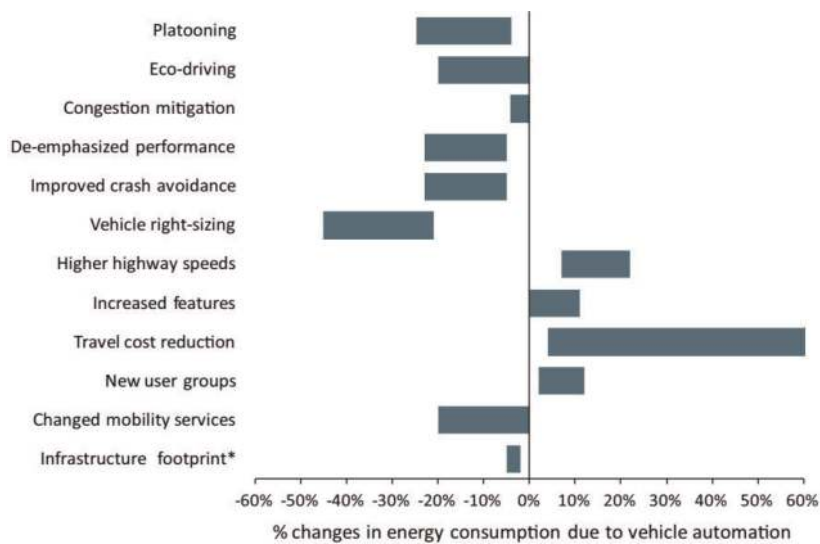


Figure 6. Estimated ranges of energy impacts of vehicle automation in respect of various mechanisms [18].

	Mechanism	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy intensity	Platooning	0.75	0.86	0.75	1.00
	Congestion	0.96	1.00	0.96	1.00
	Eco-driving	0.80	0.95	0.80	1.00
	Performance	0.77	1.00	0.77	1.00
	Crash avoidance	0.95	1.00	0.95	1.00
	Right-sizing	0.55	1.00	0.55	1.00
	Highway speeds	1.00	1.00	1.20	1.20
	Increased features	1.00	1.00	1.10	1.10
Travel demand	Generalized cost	1.56	1.09	1.89	1.49
	Newer user group	1.07	1.00	1.11	1.11
	Car-sharing	1.00	1.02	0.80	1.00

Table 4. Automation scenarios along with estimated ASIF multipliers for each effect (abridged version) [18].

- Congestion mitigation.
- Information and communication technology (ICT) infrastructure.
- Government policies and laws.

Cybersecurity in CAEV networks is one of the active research areas [19–22]. Cybersecurity of CAEVs is essential for smart and sustainable development of a low-carbon city, since it may provide safety and social stability as well as economic sustainability.

Provisioning security and privacy in low-carbon smart mobility is crucial as without secure communications between CAEVs and remote systems may yield susceptibility to malicious attacks. For instance, compromised global position system (GPS) data affects the localization of CAEVs that may lead to traffic instability and/or hazardous accidents. Similarly, information shared among CAEVs in cooperative driving should be protected from any cyberattacks not only to guarantee road traffic safety but also to preserve privacy of CAEVs and other participating entities.

Current researches on CAEVs focus to identify cyber threats and vulnerabilities as well as to design strategies for preventing damages caused by these cyberattacks. Cyber threats and attacks studied include passive attacks such as eavesdropping, interception attack, traffic analysis and active attacks including impersonation attack, spoofing attack, replay attack, Sybil attack, jamming attack, message tampering [22]. Basically, requirements for cybersecurity solutions for CAEV networks may range from authentication, non-repudiation, integrity, to confidentiality.

Several open issues that should be addressed in future include [22]: in-vehicle security; security challenges in low-carbon smart cities; safety and security countermeasure consistency; and safe and secure mixed traffic systems.

6. Conclusion

The connected autonomous electric vehicle (CAEV) will be an important part of the coming revolution in sustainable low-carbon mobility. They can result in major

reductions in GHG emissions from transportation and are at the forefront of this rapid transformation in transportation. The CAEVs have the great potential to operate with even higher vehicle efficiency, if they are charged using the electricity generated from renewable energy sources that will significantly reduce emissions as well as dependency on fossil fuels.

This book chapter provides the energy synergy of combining vehicular automation, vehicle electrification, and vehicular connectivity along with appealing on-demand mobility services. It also furnishes understanding of the potential environmental implications of CAEV technologies. Using several studies, the chapter highlights the analysis of environmental impacts including GHG emissions due to the transportation as well as improvement of vehicle efficiency.

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Conflict of interest

The authors declare no conflict of interest.

Acronyms and abbreviations

Some of the useful acronyms and abbreviations used in this book chapter:

ICE	internal combustion engine
GHG	greenhouse gas
ZEV	zero-emission vehicle
AV	autonomous vehicle
CAV	connected and autonomous vehicle
CAEV	connected and autonomous electric vehicle
V2V	vehicle to vehicle
V2I	vehicle to infrastructure
VMT	vehicle mile traveled
MaaS	Mobility-as-a-Service

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