NEAR-TERM IMPACTS OF AUTOMATED VEHICLE TECHNOLOGIES

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Glossary of Frequently Used Terms

Advanced Driver-Assistance System (ADAS): A system that uses some combination of sensing, decision-making, and control technologies to help the driver of a vehicle with some aspect of vehicle locomotion. This includes warning systems, such as lane departure warnings, as well as systems that can take direct control of a vehicle, such as lane keeping assistance (LKA).

Adaptative Cruise Control (ACC): An ADAS able to control vehicle acceleration and braking to keep a target speed while maintaining a target headway with any lead vehicle.

Cooperative Adaptive Cruise Control (CACC) or Platooning: An ACC system augmented by connected vehicle technology, whereby participating vehicles communicate information with each other to improve safety and velocity and/or reduce headway. This often improves fuel economy and is, by definition, a CAV system.

Lane Keeping Assistance (LKA): An ADAS that can control vehicle steering to keep a vehicle from leaving its lane.

Automated Vehicle (AV): A vehicle in which at least one component of vehicle control is being performed by a computer system or systems. AVs exist on a spectrum from levels 1 to 5, summarized in figure 1 of this report.

Connected Vehicle (CV): A vehicle able to either send or receive information to or from other vehicles or pieces of traffic control infrastructure while in use and to communicate received information to the vehicle's operator, whether human or computerized.

Connected and Automated Vehicle (CAV): An automated vehicle that is also a connected vehicle.

Vehicle to Vehicle (V2V): Communications among multiple vehicles.

Vehicle to Infrastructure (V2I): Communications between vehicles and traffic infrastructure systems, such as traffic lights.

Vehicle to "X" or Vehicle to Everything (V2X): An umbrella term that covers both V2V and V2I systems, as well as those that involve the communication of multiple vehicles with each other and with traffic infrastructure systems.

Abstract

This paper investigates the potential effects that automated vehicle (AV) technology may have on light-duty vehicle fuel economy in the coming decade. It also investigates how current fuel economy and emissions regulations may or may not encourage the development of AV technology to be as efficient as possible. This paper concludes by making recommendations on how current regulations may be amended to better encourage AV technology to be developed so as to improve fuel efficiency.

We find that, depending on how it is implemented and designed, near-term AV technology could increase fuel economy by up to 46% but could also decrease it by up to 14%. This variation reflects the range of different AV capabilities and implementations that have already been introduced or may be developed and brought to the market in the near future. We find that some of this range reflects design choices that could be influenced by regulatory incentives, such as off-cycle fuel economy credits. The current off-cycle credit program, however, is found not to appropriately incentivize improvements in AV fuel economy. This paper therefore suggests changes in the existing fuel economy and emissions regulation off-cycle credit program that would foster a streamlined and standardized testing environment for AV fuel economy and effectively encourage increases in AV fuel economy while decreasing emissions.

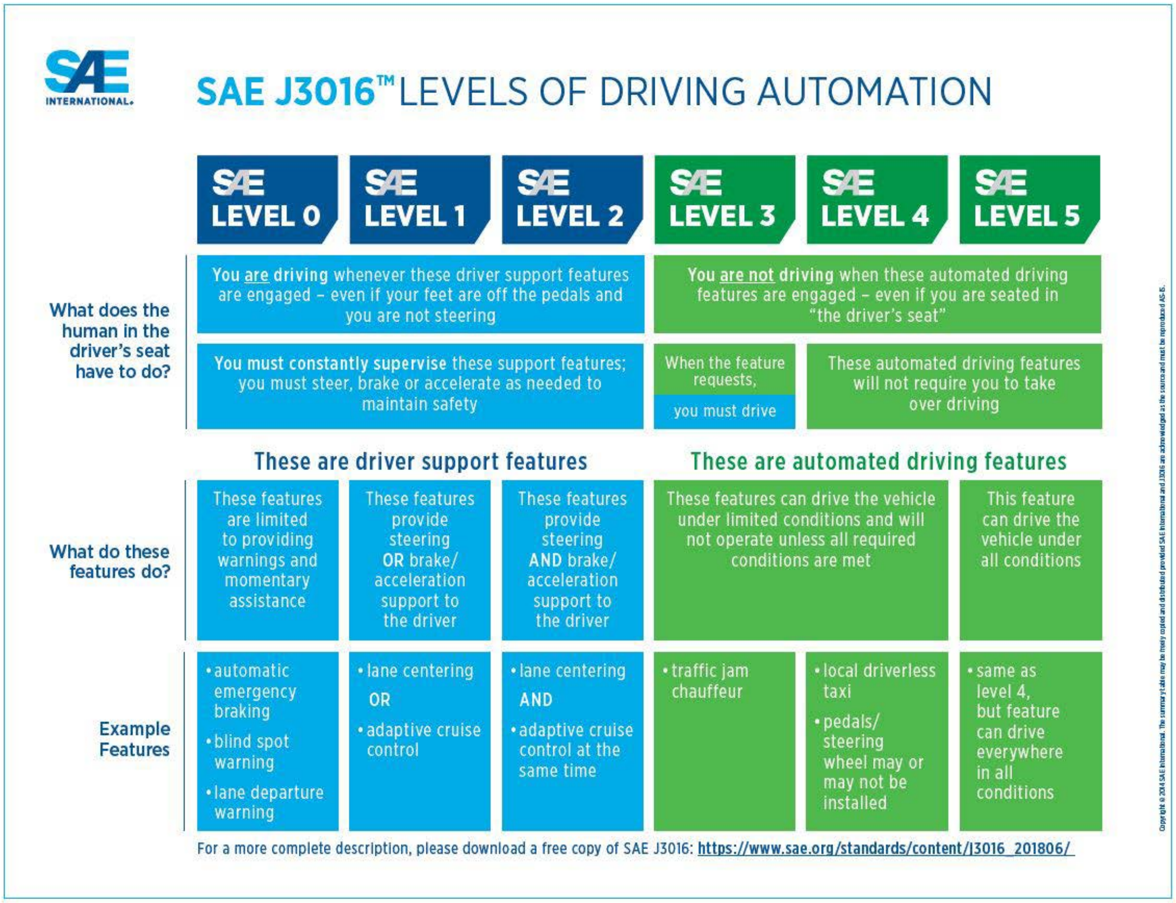
Introduction

Automated vehicle (AV) technology continues to be developed and commercialized. Despite often being thought of as a technology of the future, it is already widely deployed and encompasses many existing driver-assistance and safety features. Over a quarter of all new vehicles delivered to U.S. dealers in Q1 2020 had some automated features (Xie et al. 2020). These new technologies have significant implications for vehicle safety and fuel economy. Literature reviewed for this paper shows that current and near-future AVs, when using their AV features, could increase fuel economy by as much as 46% or decrease it by up to 14%.

Current AV technologies have largely been developed with safety impacts in mind, a marketable feature on its own. Despite the current rate of deployment of AV technologies, market growth, and the potential for significant impacts on vehicle performance, safety regulations for these technologies are still in development (NHTSA 2020). Moreover, there are no AV-specific provisions in existing fuel economy or emissions regulations. In both cases there is acknowledgment—by the regulating agencies themselves, industry, and academia—that the current regulatory framework does not adequately address AV technology (NHTSA 2020; Mersky and Samaras 2016; NAS 2021).

The National Highway Traffic Safety Administration (NHTSA) and SAE International both divide vehicles into the same six levels, based on the combination of AV technologies deployed and the capabilities of the vehicles they are installed in (SAE International 2018; NHTSA 2016). The criteria for the six levels of AVs are summarized in figure 1.

Level 0 vehicles, already outdated, have no persistent automation but at least one installed computer-controlled function that is able to provide limited or momentary assistance, such as electronic stability control (ESC) or cruise control (CC) (NHTSA 2016). ESC has been available since 1998 and has been installed on all new cars since 2012 (Kahane 2015; NHTSA 2007). Cruise control, while not mandated, has been standard on entry-level vehicles even longer. Many manufacturers have already introduced vehicles with level 1–2 AV technologies to the market; in these vehicles, humans share significant control of the vehicle with computers (NHTSA 2016; Monticello 2020). Level 3 AVs, in which the vehicle can occasionally control all aspects of locomotion but the driver must be ready to take control, have been demonstrated to be technically feasible on prototype vehicles but have not yet been released into the American market. Level 3 AVs are expected to enter the market in the early 2020s, but legal and liability concerns with temporarily removing driver responsibility for some critical safety functions and giving final responsibility to the vehicle itself (and potentially the automaker) make estimating market growth difficult (NAS 2021). While no manufacturer has certified a level 4 or 5 AV for mass market sale, lower-level AVs can significantly change the manner in which the vehicles are driven, and therefore can have an appreciable impact on fuel consumption (Mersky and Samaras 2016; NAS 2021). This paper investigates only level 1–3 AVs.



SAE INTERNATIONAL

SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You <u>are</u> driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You <u>are not</u> driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

For a more complete description, please download a free copy of SAE J3016: https://www.sae.org/standards/content/j3016_201806/

Figure 1. NHTSA/SAE's graphic explaining levels of automation. *Source:* SAE International 2018.

AV technologies are rapidly entering the market, and their effects on fuel efficiency can be substantial. Level 1 AV advanced driver-assistance systems (ADAS), such as adaptative cruise control (ACC), are common across most major manufacturers. By Q1 2020, 26% of all new car deliveries to dealers were equipped with at least level 1 AV technology such as lane keeping assistance (LKA) or ACC systems (Xie et al. 2020). Level 2 AV market share grew from 2% in 2018 to more than 10% in 2019 and is expected to grow further in the future (NAS 2021; Low et al. 2019). This can be seen in the increase in reviews of vehicles with automated features. Consumer Reports started rating level 2 AV systems in 2018, evaluating vehicles from three manufacturers (Olsen 2018). As of 2020, Consumer Reports had rated the performance of level 2 AV systems in 17 different brands (Monticello 2020). These systems are in vehicles from 7 of the top 10 global vehicle manufacturers (OICA 2018).[1] Consumer Reports reviews systems that have some combination of concurrently running ACC and LKA (Monticello 2020).

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[1] It is worth noting that Renault has a strong technology-sharing alliance with Nissan, which has a rated AV system, though it is not yet included on any Renault models.

There has also been much recent development in the space of connected vehicle (CV) technology. CV technology allows vehicles to send and receive information to and from other vehicles and pieces of infrastructure, such as traffic signals. This information can be used to inform the vehicles' controllers, human or otherwise, to improve safety (NHTSA 2017). CV technology is expected to eventually affect both human-driven vehicles and all levels of automated vehicle control. However, CV technology has not yet reached the levels of market penetration that AV technology has.

While consumer light-duty AV development has to date been motivated primarily by a desire to improve driver convenience, safety, and market desirability, the technology has a large potential to affect fuel efficiency as well. AV technologies allow computers to control a portion of the driving tasks, thus changing how vehicles move. Additionally, just as people can be trained to drive more efficiently, automated vehicles can be designed to drive more efficiently. Despite this, current fuel economy and emissions test protocols cannot account for the effects of technologies that change how a vehicle is controlled and consequently cannot capture the effects of AV technologies. Current fuel economy testing is highly prescribed and does not allow for much variance in test velocity. To comply with fuel economy standards, automakers can apply for so-called off-cycle credits, which can be granted to technologies that improve fuel economy but are not accounted for properly in the official testing. The options available in the off-cycle credit program, however, are ill suited to automated vehicles. While issues with fuel economy regulation are not unique to AVs, a 2021 report from the National Academies of Sciences, Engineering, and Medicine (NAS) found that "the current statutory authority and regulatory structure for fuel economy is rapidly becoming outdated" (NAS 2021). The same report notes how AVs uniquely challenge current regulations and goes into detail about the shortcomings of the current regulatory environment.

One challenge identified in estimating the impact of AVs and connected and automated vehicles (CAVs) on fuel economy is that these vehicles could cause widespread changes in driving behavior, which could lead to widespread changes in travel demand and traffic patterns, which in turn could affect fuel use. CAVs can therefore be understood to have both direct and indirect impacts on fuel consumption. The direct impacts are the changes in fuel consumption of individual AVs under the assumption that the surrounding traffic will be unresponsive or negligibly changed by these AVs. Indirect impacts include the changes in fuel consumption that may arise from changes in traffic patterns and travel behavior that occur in response to CV and AV adoption, the CAVs' and AVs' responses to those traffic changes, and so on.

Many papers have suggested that the indirect fuel consumption impacts of AVs and CAVs may be greater than the direct impacts (DOE 2020; Taiebat, Stolper, and Xu 2019; Auld, Sokolov, and Stephens 2017; Wadud, MacKenzie, and Leiby 2016; Fagnant and Kockelman 2015; NAS 2021). These indirect impacts can be divided into three broad categories: (1) a worsening of traffic flow at higher levels of AV adoption (NAS 2021). This effect can become significant at high levels of AV adoption, but initial adoption rates of early AVs are likely to be small, and more advanced AV and CAV systems correct this issue (NAS 2021). (2) Increased travel demand brought about if AVs or CAVs improve traffic flow and capacity. Such an increase in demand could offset or overpower any efficiency-derived decreases in emissions. While this may be a problem, fuel economy regulation should promote the adoption of more fuel-efficient vehicles. Undesirable increases in vehicle miles traveled (VMT) should be discouraged by separate policies that specifically target demand. While the structure of fuel economy regulations themselves is not the place to attempt to control demand issues, it is appropriate for the agencies to take into account the scale of this impact and, in the absence of other regulations, decide whether to allow AV off-cycle credits at all. (3) Increased travel demand due to level 4 and 5 AVs making it more convenient. We are not investigating these vehicles, so this effect is outside the scope of this paper.

As mentioned earlier, this paper focuses on AV levels 1–3—that is, light-duty vehicles that are or will be operated with significant human control and/or supervision. Level 4–5 AVs, in which human control and supervision are absent, and which can control a much broader array of functions simultaneously, will need a separate regulatory framework. This paper investigates the fuel consumption, energy usage, and emissions impacts that we expect to see from level 1–3 AVs technologies in the near term (i.e., by 2030). We investigate only the direct fuel economy impacts and highlight how the current fuel economy regulation framework can be updated to maximize the energy and emissions reductions of AV technology.

What AV Technologies Will Be Deployed by 2030?

AV technologies have been on the market for more than 20 years. Level 0 AV features, such as cruise control and electronic stability control, were already common before 2000, and the latter has been mandated in new light-duty vehicles sold in the United States since 2012 (NHTSA 2007). Level 1 AV technology includes adaptative cruise control systems, now common across manufacturers and model price ranges.[2] The first ACC system entered the market in 1995 (Xiao and Gao 2010; Verpraet 2018). As early as 1995, Carnegie Mellon University developed a prototype AV that, under trained supervision, was able to navigate interstate highways across much of the country with no human intervention 98% of the time, which could qualify it as a Level 3 AV (Anderson et al. 2016).

Current AV technologies on the market, however, are not able to handle all driving tasks, and this will be true of near-future AVs as well. The certification and release of fully automated passenger vehicles for sale to consumers are still far in the future, with the laws and regulations necessary to allow them still pending (NHTSA 2020; NAS 2021). What is becoming more common is the grouping of different AV technologies into packages that work together to handle navigation within predefined limits. Concurrent combinations of advanced driver-assistance systems such as ACC and LKA, for example, can enable effective supervised navigation within a single lane. Additional systems may allow for automated lane changes and intersection approaches. However, these systems are often limited by traffic conditions and location; for instance, ACC systems that function in free-flow freeway traffic often do not function, or are not certified by manufacturers, for stop-and-go or urban traffic. Any effective fuel economy regulation of AV technology must be

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[2] ACC systems control vehicle speed up to a user-set limit to keep constant headway. Drivers are required to control steering, pay attention, and take control if conditions are unsafe. Early systems required drivers to control brakes.

able to differentiate the capabilities and limitations of various combinations of these technologies.

Different combinations of ADAS working in unison can create discrete operating environments in which computer control will be the predominant determinant of vehicle dynamics. This paper describes these environments as discrete AV feature groups (AVFGs). We define a "discrete" AVFG as any group of technologies that produce similar divisions of responsibility for computers and drivers. Since resultant changes in fuel economy from AV technology adoption are based on how these technologies change vehicle locomotion, we argue that regulatory treatment must be based on functionality—that is, on AVFGs—and not on individual technologies, or ADAS. Regulating ACC and LKA assistance entirely separately from each other would ignore the very significant scenario of when they work together. The rest of this section will describe potential AVFGs, as well as the capabilities and limits of these combinations of technologies, and anticipate which ones will be widely available by 2030. These AVFGs are summarized in table 1. While more specific AVFG classification is possible, this paper tries to strike a balance between meaningful distinctions among AVFGs and the ability to estimate their effects from available literature. Appropriate classification for direct regulation may differ from the grouping this paper describes.

Table 1. Summary of defined AV feature groups (AVFGs)

AV feature group	Technologies combined	Operating conditions	AV levels	Literature review inclusion criteria
Single-lane freeway navigation	ACC and LKA	Free-flow freeway traffic, stay-in-lane only	Levels 2–3	• Freeway-only traffic conditions • Lane changes do not occur • General traffic conditions only • No V2X communication capabilities
Single-lane urban navigation	ACC, LKA, and intersection control device recognition[3]	Urban traffic, stay-in-lane only	Levels 2–3	• Urban-only traffic conditions • Lane changes do not occur • General traffic conditions only • No V2X communication capabilities
Full freeway navigation	ACC, LKA, and lane changing and merging capabilities	Full-on freeway navigation, possibly including entry and exit ramps	Levels 2–3	• Freeway-only traffic conditions • Lane changes may occur • Includes studies that investigate specific traffic conditions and not general traffic • V2V communication capabilities limited to location and velocity

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[3] These devices include traffic lights, stop signs, (no) right turn on red signs, and other signage or devices that control intersections.

What all of these systems have in common is that they are available primarily on light-duty passenger vehicles and are all non-connected, meaning that the vehicle is controlling itself on the basis of independently sensed road conditions and not from communication with infrastructure and/or other vehicles. Among the most advanced AV level 2 systems currently on the market is Tesla's Autopilot, which is advertised as being able to maintain nearly full control with supervision on freeways, including lane changes and merging, and speed and traffic signal control for urban conditions (Tesla 2021).[4] Given the current level of technological development and market deployment, it is safe to assume that by 2030 the deployment of level 2–3 AV technology will be common, with freeway ACC being a standard option on most vehicles and concurrent freeway ACC and LKA systems being available on most vehicles. This combination would allow automated vehicle control on freeways under free-flow traffic conditions, without lane changes and under driver supervision.[5] This combination of systems can be described as a "single freeway lane" AVFG. The "single freeway lane" AVFG would cover almost all of Consumer Reports' rated AV systems that function on freeways (Monticello 2020).

We also expect that if currently deployed systems do not cause major safety incidents, automated lane changing and merging technology will be commercially available and allow full freeway control, under human supervision, from the on-ramp to the off-ramp. As with the "single freeway lane" AVFG, this may work only under free-flow traffic conditions and driver supervision, potentially with drivers needing to indicate when lane changes are desired. This can be described as a "full freeway navigation" AVFG. Such technology is already available on limited premium vehicles, such as Tesla vehicles with Autopilot (Tesla 2021).

Urban navigation has different and additional requirements when compared with freeway navigation and is generally much more technically difficult to pull off safely. Urban traffic is often slower and more stop-and-go than freeway traffic. Lane markings may also be different. Some ACC and LKA systems that work under freeway conditions may not function safely under urban ones, which is why these ADAS are often designated for these conditions separately. Navigation on non-freeway roads also requires the ability to recognize intersection control devices and navigate through them. This last feature is a key difference because requiring human intervention for intersections decreases the significance of computer control and would suggest against any separate treatment for these technologies in fuel economy measurement protocols. As with AVFGs for freeway conditions, urban AV systems can be divided into "single urban lane" and "full urban navigation" AVFGs. A current example of the "single urban lane" AVFG on the market is

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[4] The Tesla Autopilot system has more total driver features and is able to operate in more road conditions, under human supervision, than any other AV system available to the mass market at press time. Some of these features are defined as "in beta" but are end-user accessible. Other mass-market automakers do not sell beta AV features. Autopilot capabilities under urban conditions exclude lane changes and turns.

[5] Automakers often restrict ACC and LKA systems to free-flowing freeway traffic—i.e., traffic that does not regularly see large velocity changes and does not regularly go below ~30 MPH. There are also systems on the market without specific speed or free-flow traffic limitations. We believe that any AV freeway test would assume that such conditions predominate (as under the EPA's Highway Fuel Economy Test) and allow these systems to be grouped together.

from Tesla, although the key intersection navigation features are still in beta mode (Tesla 2021). We find it likely that absent major safety events, this technology will migrate to more mainstream vehicles and become widespread by 2030. While "full urban navigation" has seen deployment in prototype vehicles and fleets, some of which allow public passengers on a limited pilot basis (Krafcik 2020), these have not yet been made available for U.S. consumer purchase, and no major manufacturer has yet announced and demonstrated this capability for near-future consumer mass-market deployment. We therefore believe it unlikely that it will be mature enough to reach widespread market deployment by 2030.

Connected vehicle technology is also expected to continue development and market growth in the near future. With a focus on safety, NHTSA put forward a Notice of Proposed Rulemaking on vehicle-to-vehicle (V2V) communications in 2017 (NHTSA 2017). It also issued a request for comments on standards for vehicle-to-everything (V2X) communications in 2018 but has yet to set any specific standards.[6] V2V standards are currently scheduled for finalization by 2025 (NHTSA 2017). However, NHTSA has not kept to a fixed timeline for development of these standards, through both the Obama and Trump administrations. The Federal Communications Commission has also moved to reappropriate some of the spectrum reserved for V2X usage to telecoms (Hawkins 2020). The lack of official U.S. standards and forward guidance continues to be a major impediment to the mass-market commercial development of V2V and vehicle-to-infrastructure (V2I) connected vehicles, especially light-duty passenger vehicles. International standards from SAE and the Institute of Electrical and Electronic Engineers (IEEE) can help set the stage for future innovation and act as guides for official regulations, but they cannot be a substitute for NHTSA action. Automakers need guarantees on the activities of their competitors, which only legally binding regulations can provide.

Market deployment of connected and automated vehicle systems without standards is even more difficult. CAV systems generally need to be able to seamlessly communicate among many different models and across manufacturers of not only vehicles but also infrastructure systems. A V2I intersection does not improve traffic if the vehicles are not compatible, and V2V systems obviously need a number of compatible vehicles within a certain range if they are to offer real benefits. Despite the potential benefits of CAV technology, we do not believe there will be significant light-duty advanced CAV adoption until NHTSA, or another federal standard-setting authority, provides standards for V2V and V2I systems. This makes significant deployment by 2030 unlikely.

What Are the Potential Fuel Economy Impacts of AV Technologies in 2030?

This section provides a range of potential fuel efficiency impacts for each AV feature group identified above. This allows us to determine (1) whether the fuel economy impacts could be large; and (2) whether these impacts are responsive to design decisions. For guidance, we conducted a brief review of peer-reviewed reports, as well as government and highly cited research lab reports, on the subjects of automated and connected vehicles. Results from the literature review were classified into the aforementioned AV feature groups by close

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[6] V2X refers broadly to a combination of V2V and vehicle-to-infrastructure (V2I) systems. V2I includes additional capabilities of traffic infrastructure, such as traffic lights, that would communicate with vehicles.

reading of the scenarios and limitations of the technologies tested. The criteria we used to decide if a study result was indicative of an ACFG are summarized in table 1. In many reports, authors did not explicitly mention traffic conditions or maneuver limitations, so we instead inferred them from scenario descriptions. For example, if the traffic scenarios never went below 40 MPH, we assumed freeway conditions. Most reports specifically investigated methods believed to improve fuel economy and estimated these potential improvements. A notable minority of reports investigated how fuel economy might decrease as a result of the application of these technologies. Additionally, most reviewed research reported only the fuel economy changes of these technologies when in use and did not estimate how frequently they could be deployed. These factors limited the utility of the literature in estimating the overall fuel economy impacts of these technologies.

The ranges of expected fuel economy changes are summarized in table 2 and discussed in detail in the subsections that follow. They include only the direct impacts that we defined in the introduction. This fits with current regulatory practice in which, "for a technology to be 'counted' under the credit provisions, it must make direct improvements to the performance of the specific vehicle to which it is applied" (NHTSA and EPA 2012). It is noteworthy not only that there is a large amount of uncertainty of the magnitude of each AVFG's impact on fuel economy, but also that the literature on each was found to support the possibility that fuel economy could either increase or decrease. The wide range of findings is partly due to differing scenarios, varying assumptions about vehicle characteristics, or the use of different fuel economy simulation software. But it is also due to different methods of implementing AVFGs. This underscores the benefit of incentives to encourage fuel economy in designing AVs, to ensure that fuel economy rises and does not fall. The following section discusses how light-duty vehicle emissions regulation could be modified to accomplish this.

It is notable that the majority of reviewed reports relied on computer simulations to ascertain both the changes in vehicle behavior and the resulting changes in fuel consumption. Most of these reports assumed, often implicitly, that the only difference between AVs and traditional vehicles that would lead to fuel consumption differences is the driving behavior of the vehicles. In actuality, AVs require additional components, which increase weight, power draw, and potentially drag (Gawron et al. 2018). Gawron et al. estimated the sum of these effects to be a 2–20% direct increase in power needs. While this seems extreme, the higher effects are seen only in the most extensive CAV systems, with more moderate AV systems increasing energy use by less than 4% (Gawron et al. 2018). Additionally, the 4% increase in fuel consumption still reflects a level 4–capable system, which may require higher power draw than the systems analyzed in this paper. Future developments may change this further, with increased safety plausibly allowing lighter vehicles or more power-efficient ADAS than are currently feasible (Anderson et al. 2016; NAS 2021). Refinements in design from prototypes to market vehicles may also reduce drag by incorporating additional equipment into the vehicles' design rather than adding them to the exterior of an existing design. It is reasonable to assume that near-term consumer market vehicles will see no more than the 2–4% increase in power draws seen in Gawron et al.'s scenarios.

Table 2. Expected in-use fuel economy impacts of each AVFG on conventionally powered vehicles

AV feature group	Expected in-use fuel economy impacts (not including increased potential power draw and drag)	Expected in-use fuel economy impacts (Including potential increased power draw and drag)
Single freeway lane navigation	–10% to +15%	–14% to +10%
Single urban lane navigation	–5% to +52%	–9% to +46%
Full freeway navigation	–10% to +20%	–14% to +15%

SINGLE FREEWAY LANE

On the basis of the reviewed literature for the "single freeway lane" AVFG, we find that this technology could decrease fuel economy by up to 14% or increase it by up to 10%. Most literature on these AV features focused on the potential fuel economy gains. A National Research Council report briefly investigated the potential fuel economy improvements from "automated highways" and "eco-driving" and found improvements of 4–10% (National Research Council 2013; Anderson et al. 2016).[7] Li et al. (2017) also investigated how ACC could be used in freeway conditions to optimize vehicle control for step-gear transmission vehicles and found potential fuel economy gains of 8.9%.[8] More recently, NAS released a report showing that current level 2 AV technology could increase fuel economy by up to 5% under freeway conditions (NAS 2021).

Relatively few reports consider both increases and decreases in fuel consumption possible from this technology. One such report is Mersky and Samaras (2016). This report investigated how the fuel economy of vehicles would change if they obeyed different sets of AV control functions[9] and followed behind a single vehicle running the EPA's freeway (HWFET) test velocity cycle.[10] They found potential increases or decreases in fuel economy of up to 2.2% for freeway conditions, though the authors noted that they lacked access to current and future proprietary AV rule sets and had to simplify rule sets for simulation purposes (Mersky and Samaras 2016).[11] He et al. (2020) found an even more significant potential fuel economy decrease of 2.6–17%, though these results were based on Italian, not American, driving patterns. These results were also based on a platoon effect, where some ACC vehicles were following other ACC vehicles. If we look only at an AV following a human-driven vehicle, the fuel economy could decrease 13.9% (He et al. 2020). If Italians drive more efficiently than Americans, then we could expect a smaller decrease in American fuel economy.

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[7] "Eco-driving" refers to human driving practices that improve fuel economy, or technologies that encourage these. An AV could, in theory, apply these perfectly and consistently.

[8] Step-gear transmission refers to non-continuously variable transmission.

[9] That is, the different potential rules that would control how the AV reacts to traffic.

[10] These are the main test conditions that the EPA uses for evaluating vehicle emissions on freeways.

[11] An AV rule set is the specific algorithm that an AV obeys, given its knowledge about the surrounding environment.

We find it plausible that the potential fuel economy gains lie within the range of the reviewed literature, as the more optimistic reports broadly agree with one another. Given that the greatest fuel economy losses were seen only in reviewed literature from overseas or in response to traffic level changes, we believe that a conservative estimate would place the range of fuel economy losses between those estimated by He et al. 2020 and Mersky and Samaras 2016. We therefore believe that "single freeway lane" AVFGs could decrease the fuel economy of equipped vehicles by up 10% when in use, or increase it by up to 15%. As this estimate is based on reports simulating vehicles and not adjusting power draw from additional components, we use Gawron et al.'s 4% moderate power draw estimate to calculate a decrease of not more than 14% or an increase of up to 10%.

SINGLE URBAN LANE

On the basis of the reviewed literature for the "single urban lane" AVFG, we find that this technology could decrease fuel economy by up to 9% or increase it by up to 46%.

The reviewed sources showed that ACC under urban conditions has much higher potential for fuel economy gains, primarily because freeway conditions already encourage many efficient driving practices. Wadud, MacKenzie, and Leiby (2016) summarizes four sources that investigate single-lane ACC performance under urban conditions (He et al. 2012; Mensing et al. 2013; Mensing, Trigui, and Bideaux 2011, 2012). Under heavy congestion conditions, increase in fuel economy were 54–200% (He et al. 2012; Wadud, MacKenzie, and Leiby 2016). Under more common conditions, increases in fuel economy of 11–52% were found to be possible (Wadud, MacKenzie, and Leiby 2016; Mensing et al. 2013; Mensing, Trigui, and Bideaux 2011, 2012). Lang, Schmied, and Del Re (2014), which compares cooperative ACC (CACC) to ACC systems under urban conditions, shows slightly more modest 5–25% increase in fuel economy (Lang, Schmied, and Del Re 2014). More recently NAS released a report showing that current level 2 AV technology could increase fuel economy by up to 5% under urban conditions (NAS 2021).

As with freeway conditions, fuel economy gains were not found to be guaranteed. In addition to freeway conditions, Mersky and Samaras 2016 investigated how the fuel economy of vehicles would change if they obeyed different sets of AV control functions and followed behind a single vehicle running the EPA's urban (FTP) test velocity cycle.[12] That report found potential decreases in fuel economy of up to 2.6% and potential increases of up to 4% (Mersky and Samaras 2016). While other reviewed reports did not show a similar decrease in fuel economy from ACC, Luo et al. (2010), an early report on the subject, compared an ACC system optimized only for safety to one optimized for comfort and fuel economy without decreasing safety and found that under urban car-following conditions, there was a potential increase of 15% in fuel economy when optimizing for fuel economy. On the basis of this literature, we expect that when "single urban lane" AVFG systems are in use, fuel economy could decrease by up to 5% or increase by up to 52%. As these estimates

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[12] These are the main test conditions that the EPA uses for evaluating vehicle emissions off freeways—i.e., under urban conditions.

are based on reports simulating vehicles and not adjusting for power draw from additional components, this could be adjusted to a decrease of up to 9% or an increase of up to 46%.

FULL FREEWAY NAVIGATION

On the basis of the reviewed literature for the "full freeway navigation" AVFG, we find that this technology could decrease fuel economy by up to 14% or increase it by up to 15%. Full freeway navigation includes car following (that is, ACC), but what separates it from the other AVFGs is the ability to perform additional maneuvers, such as switching lanes, passing slow-moving vehicles, and merging. Estimates of fuel economy changes from full freeway navigation are more complicated than for the other AVFGs because assumptions regarding the frequency of specific maneuvers will impact fuel economy. Additionally, research into the fuel economy effects of general AV freeway control is rarer than research investigating very specific, though common, scenarios such as freeway entries and exits. Rather than attempting to estimate the fuel economy changes of every possible maneuver and their relative frequency, we instead looked at general navigation and a sampling of specific maneuvers. As most time on freeways is generally spent in a single lane, the results from "single freeway lane" navigation were used as a baseline, with the results here being used to judge whether other maneuvers and scenarios may significantly modify the fuel economy results in a predictable direction.

A major component of any difference between "single lane" and "full freeway" navigation would be the assumed time spent in a single lane following a car and how many maneuvers the vehicle would initiate or respond to, such as merging onto the freeway, exiting the freeway, changing lanes, and responding to lane changes of leading vehicles. Jin et al. (2013) compared a connected *and* automated vehicle (CAV), while on a freeway on-ramp, to both AVs on a signal–controlled on-ramp and on a segregated, no-traffic-light, AV-only on-ramp. It found that AVs on a freeway on-ramp may reach fuel economy increases of 30% compared with those on the traffic-light–managed on-ramp (Jin et al. 2013). Another scenario that automated vehicles will have to face is reduced-speed zones, such as construction sites. Malikopoulos et al. (2019) investigated this scenario and showed a potential increase in fuel economy of up to 28% for AVs, though this was for 100% AV penetration and without lane changes. If aggressive human drivers react to an AV by cutting in front of it, fuel economy could potentially decrease.

Some sources simulated vehicles driving on a freeway while performing passing, merging, and other maneuvers, rather than investigating only specific maneuvers. These sources often assumed at least some limited CV capability and/or assumed some level of mass (C)AV adoption. That said, the lowest reported levels of (C)AV adoption showed similar increases and decreases in fuel economy when compared with simple "single freeway lane" navigation (Kamal, Taguchi, and Yoshimura 2016; Li and Wagner 2019). The reports investigating more specific traffic scenarios showed the potential for even higher gains in fuel economy, though these would be realized only when those scenarios arose. While large fuel economy gains were found to be possible for specific maneuvers, such as on-ramping, these are quite rare compared with car following and lane changing. The reviewed literature did not show much deviation in the range of potential fuel economy changes in studies that allowed lane changes versus those that simply followed a lead vehicle.

In the absence of a more comprehensive study showing all the specific freeway scenarios that AVs could be optimized for, and the relative frequency with which these scenarios will occur, we find that a range of fuel economy changes similar to that of the "single freeway lane" AVFG is possible, but with slightly higher potential gains in fuel economy. We believe that a decrease in fuel economy of up to 10% or an increase of up to 20% is likely for "full freeway navigation" when this feature group is in use. This estimate is based on reports simulating vehicles without adjusting for power-draw from additional components. Including this additional power draw could lead to a decrease of up to 14% or an increase of up to 15%.

THE EFFECTS OF HYBRIDIZATION AND ELECTRIFICATION

The impacts of AV technology on fuel economy are not independent of the vehicle's power train. In particular, regenerative braking already captures some of the losses in efficiency (from excessive braking) that AV technology may mitigate. An NAS report found that level 2 conventional AVs may reduce fuel consumption by 5% under urban and freeway conditions, while a hybrid would save only 4% under urban conditions and 3% under freeway conditions (NAS 2021). The results for battery electric vehicles (BEVs) were similar, with 4% savings seen for both urban and freeway conditions (NAS 2021). Reports on freeway AV systems similar to those reviewed above also showed more modest gains for hybrids (Mensing, Trigui, and Bideaux 2012; Wadud, MacKenzie, and Leiby 2016).

Other research does show the potential for greater gains in fuel economy from hybrids and BEVs, but these are dependent on additional technology that optimizes power train control and may have a level of dependence on CV technology to function consistently (NAS 2021; Karbowski et al. 2020). While the short-term EV and hybrid gains in fuel economy from automation are likely to be smaller than in conventionally fueled vehicles, AVs will still represent a significant opportunity for short-term fuel economy gains in hybrids and EVs. Over the longer term, CAVs will likely be able to take advantage of unique opportunities in EV power train optimization that are not easily obtainable from other technologies.

IMPLICATIONS OF POTENTIAL CHANGES IN FUEL ECONOMY

The "single freeway lane," "single urban lane," and "full freeway navigation" AVFGs are all expected to be available and adopted by a significant portion of the consumer light-duty vehicle market by 2030. All are also expected to be able to run without vehicle-to-vehicle communication. Any individual vehicle model's implementation of an AVFG is likely to change the fuel consumption patterns of the individual vehicles in predictable ways, even if there is great variability in the range of potential implications. Emissions regulations are meant to encourage greater fuel economy, but if changes in fuel economy from AVs are not accounted for in the regulations, then it is possible that manufacturers will implement these technologies without regard to fuel efficiency impacts. This could result in increased fuel consumption and emissions and in lost opportunities to save fuel and reduce emissions. It is therefore desirable that vehicle emissions regulations capture the impacts of such technologies and provide incentives for improvements.

The following section gives an overview of the current fuel economy and emissions testing environment and then presents our recommendations on how the off-cycle credit program specifically can be amended to account for AV technologies in a standardized way. We believe that V2X implementations will not be widespread in the light-duty vehicle market by 2030. Our recommendations therefore focus on the more immediate AV technologies and do not account for CAV implementation. Recommendations for CAV and V2X fuel economy regulation will require more research.

Accounting for the Impacts of AV Technology in Vehicle Fuel Economy and Emissions Regulations

THE CURRENT FUEL ECONOMY AND EMISSIONS TESTING ENVIRONMENT

The current standard light-duty vehicle fuel economy and emissions test procedures rely on testing fuel consumption and emissions for fixed velocity schedules on a dynamometer.[13] These procedures cannot detect the fuel economy impacts of technologies, including AV technologies, that change how the vehicle responds to the environment around it. The fuel economy and emissions programs do have a mechanism to recognize the benefits of technologies that are not detected under the test procedures: Manufacturers can apply for off-cycle credits, either as a fixed amount for pretested technologies, or by vehicle manufacturer petition, with supporting data, and subsequent agency review and approval. Automakers can apply any earned off-cycle credits to bring their vehicle fleet's total tested fuel economy into compliance with standards.

Under current regulations, there is a menu of preapproved credits, where specific off-cycle technologies are precertified for a certain number of credits to any equipped vehicle. This will not work for AV technologies, as AV implementations have too much variability in fuel economy effects, even among similar features, to utilize a fixed menu of credits. Gating menu credits with one or a small number of parameters, such as following distance, will not fix this, as such parameters do not lead to simple relationships that can reliably predict if fuel economy will improve (Mersky and Samaras 2016). The potential for decreased fuel economy also means that credits should not ever be guaranteed. Another option, using a more comprehensive, but still predefined, testing protocol such as the five-cycle test option, will not work as it still follows fixed velocities and cannot capture the changes in driving behavior that AVs introduce.

The final option is for manufacturers to petition for off-cycle credits with their own data and testing methodology. Normally automakers can claim that their technology is substantially the same as another's and use the latter's results to request off-cycle credits. This is not simple with AVs, however, because software control can and will be different across models. Automakers must either show that their AVs drive exactly the same as another's or propose a new test if their implementation differs. This could lead to multiple competing proposed tests for packages of technologies that produce similar levels of AV computer control but use different underlying technologies or produce different driving patterns. To effectively encourage fuel economy improvements, regulation must be predictable during

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[13] That is, vehicle speedometers must read specific velocities each second of the test, with one row of wheels on a treadmill-like device. The results from these "on-cycle" tests are the base results of emission testing. Any modifiers to the base vehicle emission ratings come from off-cycle credits. Different test cycles may prescribe different ambient temperatures, vehicle starting temperatures, and air-conditioning usage.

product development and consistent across manufacturers. This process should therefore be amended for AV adoption as described in the following section.

Without the opportunity to gain credits that properly reflect the impact of AV technologies, automakers have little incentive to design for fuel efficiency. They will design only for features that are regulated or advertisable, such as convenience, safety, comfort, and vehicle acceleration.[14] Designing for these features will not automatically improve fuel economy and may actually decrease it, as some of the reviewed studies suggested (Luo et al. 2010). Hence it is desirable that emissions and fuel economy regulations incentivize manufacturers to design AV systems with fuel efficiency in mind.

RECOMMENDATIONS

Our recommendations are based on the principle that the testing of fuel economy should be as standardized and consistent as possible. Whenever feasible, AV features should be grouped together and subject to the same tests. The AVFGs discussed above are examples of such groupings. This leads to four questions.

- How do you classify and divide AV features into groups that can be effectively evaluated by a single test?
- What AV feature groups should be eligible for off-cycle credits?
- How do you create the standardized test protocols?
- How should the results from the standardized test protocols be used for regulation and off-cycle credits?

The following recommendations attempt to help resolve some of the technical issues involved in AV fuel economy testing but leave certain critical questions unanswered. For instance, they do not define the specific divisions of AVFGs that should be used or the test protocols for such AVFGs. More research and technical work is necessary to move from these recommendations to actionable regulatory and testing rules.

Classifying and Dividing the Technology

Recommendation #1. For level 1–3 AV technologies, we propose that each discrete AVFG have only one agency-approved and pre-validated method of fuel economy testing and off-cycle credit awards.

- For example, all adaptative cruise control (ACC) systems that only control velocity should be grouped together.
- ACC features that work with lane keeping assistance (LKA) should be a separate AVFG.

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[14] EPA regulations restrict how automakers may communicate the fuel economy of their vehicles. Advertising fuel economy impacts that are not demonstrated in the testing used for EPA fuel economy stickers is one such restricted practice and may impede the marketability of AV features, all of which fall outside the scope of such testing.

- Vehicle-to-vehicle communication systems, when working with AV systems to allow maneuvers that humans could not perform safely, should likewise be classified separately.

Segmenting AV capabilities into discrete and definable groups is advisable for several reasons. First, it allows each AVFG to be tested by the protocol that is most applicable to its use; for instance, a test environment with curves will not work for an ACC system without LKA but may be useful when testing systems that do have it. Second, systems that are more capable are likely to be used more and should, therefore, receive credits based on this increased use, as described in recommendation 5.

Recommendation #2. Additionally, AVFGs should be separated by limits of certified, not effective, functionality, even if this leads to identical divisions of driver and computer control and responsibilities. Effective functionality refers to the situations that the system will work in, regardless of instructions to drivers on system limits. Certified functionality refers to the situations in which the system is certified by the manufacturer and communicated to the driver as safe to operate in. So even if a system can work, say, in urban centers, if it is not certified for or meant to be used there, then it will not be regulated for that use. There is a possibility of mismatch between effective and certified functionality if an AV system is not capable of gauging its own circumstances and relies on the driver, who may use it in unintended ways. The question of how to handle effective and certified capability mismatch, while important, best falls under safety regulatory authority, not emissions. Emissions regulations should therefore defer to any existent safety regulations for such divisions. If a system is ruled safe in urban centers, it should be assumed to have that capability for emissions regulations. While safety regulations are important, they are independent of and beyond the scope of this paper.

- Systems that work only in free-flow traffic on freeways should be considered separate from those that work only in gridlock conditions.
- Systems that can seamlessly switch between such modes should be considered a separate AVFG.

Determining Eligibility

Recommendation #3. Current regulations explicitly forbid awarding off-cycle credits for safety technologies, such as automatic emergency braking (NHTSA and EPA 2012). Such pure safety features should remain ineligible under any AV off-cycle credit program. Other AV technologies should only be eligible for off-cycle emission credits under one of two circumstances. The first is if the technology's primary purpose is to improve fuel economy, rather than to improve safety or convenience or provide another benefit. A good example would be CACC with reductions in inter-vehicle spacing. The reduction in headway is used primarily for fuel economy benefits. The second circumstance is if the ADAS has another primary purpose that can be accomplished at the expense of fuel economy. For example, while ACC implementations can be designed to increase fuel economy, ACC's primary purpose is convenience, and otherwise desirable ACC applications may decrease fuel economy. Including this second circumstance is necessary to ensure fuel efficiency is factored into these systems' designs.

Creating Standardized Test Protocols

Recommendation #4. The regulating agencies, EPA and NHTSA, should provide a list of AVFGs eligible for credits and develop standardized rules on how these AVFGs should be evaluated. The agencies should internally design fuel economy test protocols for each AVFG that capture, as closely to reality as possible, the effect of potential changes in vehicle behavior in the environments that the technology can be used in. Accomplishing this may require further investigation into current driving patterns, as has been recommended by many, including NAS (2021).

These protocols should be used to quantify the changes in fuel economy when these technologies are deployed, and these results should be used, along with usage estimates form recommendation 5, to award off-cycle credits. These protocols should take into account that AV systems involve additional weight, power draw, and potentially drag and should therefore require a test on the AV itself in a direct performance comparison with a non-AV vehicle under new conditions. The agencies should require that such comparison tests be carried out on comparable vehicles whose only difference is the absence of all AV features in one of them. Any other optional features that are present in the AV package should also be in the comparison vehicle.

The agencies should then publish the protocols for public comment. Agencies should start by identifying AVFGs that are already on the market and either design test protocols for public evaluation or solicit them. For future technologies, the agencies should standardize and publish procedures only for AVFGs expected to come into the market in the near future, within approximately 2–3 years.

Given that the creation, public comment, and promulgation process for new protocols would be time consuming, we suggest that the regulating agencies attempt to create a standard process that is applicable to multiple AVFGs. An example could be predefined test tracks or a process to create new velocity cycles, similar to those suggested by previous research (Mersky and Samaras 2016; Prakash et al. 2016). The agencies could use this as the basis for most test protocols, but may find circumstances in which other solutions are preferable. While many AVFGs have similar operating conditions and could be tested the same way, others are quite different from one another. Additionally, we should not assume that we can anticipate the needs of all AVFGs before they have even been prototyped. An overly standardized approach risks limiting unanticipated design options. While the agencies should have some plans to speed up the test design process, they should not be too restrictive in advance and should leave the option open to design new test protocols as needed.

Recommendation #5. For new AVFGs, the agencies should attempt to forecast what will be introduced into the market in the near future and also accept preliminary manufacturer petitions for technologies to be adopted in future model years. For any new AVFG, the agencies, or the petitioner, should have to provide information on the implementation, justify its difference from current and planned technologies, and open the proposed AVFG up to public comment. This process should be open for either prototype vehicles or those in development. In the latter case, preliminary test protocols can be set, to give guidance to automakers, while allowing for fine-tuning if final products differ significantly from what was expected.

The final test protocols should include both the vehicle testing methods and specific rules on how these results will be used to calculate credits. These credits should be based on regularly updated estimates or regularly updated empirical evidence of the extent of technology use, including, when possible, how often users actually choose to deploy them and, if significant, the implementation or technology's penetration rate. Depending on the specific usage conditions of an AVFG, its novelty, and potentially other factors, this data may come from preexisting estimates of traveling behavior that define when the AVFG could be used, the national household travel survey (potentially with a supplement dedicated to this task), manufacturer-provided data tracking existing feature use, or other resources.

Usage of the Test Results

Recommendation #6. Over the short term, these suggestions could potentially be implemented under the existing optional off-cycle credit program. As these technologies become more common, better understood, and more widely tested, we believe that the agencies should consider requiring that all common AVFG technologies be tested for fuel economy changes. The resulting changes, even if negative, should be applied to the vehicle's rated fuel economy on a mandatory basis rather than as an optional credit.

A testing mandate will ensure that applications that increase fuel consumption will be accounted for. Off-cycle credits will continue to not apply to safety features and therefore will not decrease vehicle safety. Potential automaker use of such credits can also be considered by policymakers when setting emissions and efficiency stringency standards.

Conclusion

Automated vehicle (AV) technology has the potential to drastically change the effective fuel economy of light-duty vehicles in the coming decade. Despite this, current fuel economy and emissions regulations are unable to effectively account for these changes or properly incentivize the adoption of AV technologies in a way that would improve fuel economy. A proper regulatory environment for AV fuel economy is vital as automaker choices in AV design and implementation can greatly affect the efficiency of vehicles, leading to not only a plausible future in which fuel economy could increase by up to 46%, but also one in which it could decrease by up to 14%. This paper therefore lays out clear recommendations on how the EPA and NHTSA can begin adjusting the existing off-cycle credit program to incentive AV fuel economy. AVs are already a reality on our streets and will only increase in complexity and market share as time goes on. Regulations must change to account for this and ensure that AVs are designed with efficiency in mind.

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