ENERGY AND EMISSIONS IMPLICATIONS OF SELF-DRIVING VEHICLES

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ABSTRACT

Despite saving drivers time and decreasing the number of crashes, connected and self-driving or automated vehicles (CAVs) will increase vehicle-miles traveled (VMT) and thus congestion, at least for some time. This is due to the potential for current non-drivers (e.g. the elderly) to travel independently, empty-vehicles repositioning themselves, and greater land development at the periphery of regions. However, the adoption of these vehicles may have a greater impact on travel patterns, emissions, and energy usage.

In terms of travel distance, CAVs may increase VMT as a result of longer and more frequent trips. Persons without driver’s licenses may now experience greater mobility, thanks to the fully-automated driving performance. Empty-driving, when a self-driving vehicle travels with no passengers, will induce new VMT. CAVs may drive empty to find cheap parking lots or pick up another passenger. However, the introduction of dynamic ride-sharing (DRS) may manage this increased VMT by optimizing the correlated origin-destination pairs. Also, vehicle right-sizing strategies can match more efficient vehicles to the needs of passenger occupancy and baggage size. For example, a mixed fleet of single-seated, two-seated, and four or more seated CAV utilizing DRS strategies might be a possible solution to reduce the VMT and energy implications induced by CAVs.

In this paper, the energy implications of self-driving vehicles, for individual and shared use under different energy and technology scenarios are estimated. The existing findings and estimates of energy and emissions savings from CAV applications are synthesized and summarized. Some aspects of CAVs might result in energy savings, while some would result in greater energy consumption. Evolving VMT, congestion, and traffic management conditions considering evolving fleet conditions are anticipated to estimate magnitudes of emissions and energy savings from the various emerging CAV technologies. The change in users’ travel behavior might require 46% more energy use, and the improvement in driving details of CAVs would need up to 50% more energy compared to current state. However, multi-vehicle operation of CAVs would reduce up to 49% more energy, and electrification of power train would reduce up to 70% more energy than before. Through these findings, impacts of different technologies should be rank-ordered, and recommendations to public agencies, manufacturers, and other stakeholders should be provided to encourage lower emissions and more sustainable self-driving conditions in the United States.
KEYWORDS
Energy consumption; Energy and emissions; Connected and automated vehicle; Self-driving vehicle

INTRODUCTION
Early-stage CAVs currently exist throughout the U.S. and have a high likelihood to increase in number in the near future. These include vehicles with limited automation, such as the Tesla Model S, and vehicle-automation technologies, such as adaptive cruise control and lane keeping assistance. To ensure public safety while establishing a solid foundation for the development of self-driving vehicle technology, the National Highway Traffic Safety Administration (NHTSA) has announced guidelines for five levels of vehicle automation as an initial step for the safety and deployment of automated vehicles (AVs) (NHTSA, 2013). According to these guidelines, level 2 automation refers to the vehicle system that can control both steering and braking/accelerating simultaneously under some circumstances, while level 3 automation refers to the system on the vehicle that can perform all aspects of the driving task under some circumstances. Tesla vehicles can be classified as somewhere between level 2 and level 3.

Fully automated and self-driving vehicles would affect various areas in transportation. Drivers would experience less burden in their driving and spend their time riding in connected and automated vehicles (CAVs) for entertainment, business or even sleeping. The connected environment would reduce crashes among vehicles by actively exchanging driving information between vehicles and infrastructures. Self-driving vehicles would change not only the travel pattern, but also the economic structure, shape of urban cities, and eventually the lifestyle of U.S. citizens. Riders of self-driving vehicles would be less reluctant to go further than before, transportation workers - taxi and truck drivers - might lose their work place, and human and material exchange will become more active than before.

Among various changes that are anticipated, this paper focuses on energy and emissions implications from the adoption of self-driving vehicles. AVs might use more energy or save more energy than before. A smoother driving cycle would lower the energy consumption, while newly induced trips would increase the energy consumption in contrast to conventional vehicles. Self-driving vehicles would affect numerous areas related to energy consumption, while thorough analysis should be required to understand its implications. Since AVs have not yet reached full market penetration rate (MPR), the result provided in this paper is largely based on literature review and simulation results.

This paper is organized as follows: the existing literature related with CAVs is reviewed and each impact that would be influenced by the adoption of self-driving vehicles is categorized. Following this, a scenario analysis to understand the change in fuel consumption with respect to the increase of market penetration rate of self-driving vehicles is explored. Finally, the conclusion is discussed.

SELF-DRIVING VEHICLES IMPACTS
Complete adoption of AVs as part of the U.S. vehicle fleet would take decades, making AVs’ resulting impact on energy and emissions challenging to anticipate. In this section, a review of impacts influenced by the anticipated adoption of CAVs are analyzed to overcome the lack of existing knowledge regarding AV fleets. However, most of them provide a quantified estimate of each impact. Some impacts are anticipated to save the energy consumption, while others are expected to increase the energy consumption. These estimates may not comprehensively reflect the future, but they can be seen as a foundation to anticipate the outcome of CAVs.

This paper categorizes each impact into four categories as follows:

- The travel demand change category includes possible changes of users’ travel behavior as a result of AV implementation.
• The driving details category includes possible changes in vehicle performance, such as the change in acceleration / deceleration scheme, as well as the adoption of shared automated vehicles.

• The multi-vehicle operation category includes the interaction among multiple CAVs and infrastructures.

• The powertrain energy source category explains the outcome of a new power source – fueling the transition from gasoline-powered to electric vehicles – which could be applied to vehicle fleets in the future.

**Travel Demand Changes Category**

**Better Route Choice**

Drivers with CAVs might choose their travel route more efficiently as compared to drivers without a connected environment. Automated vehicles without the driving task might have improved route choice capability through immediate judgment of traffic conditions in real time. For example, CAVs might find the shortest path of their trip more effectively by knowing the traffic conditions through communication. They might optimize their path to satisfy certain objectives, such as finding the path with fewer stops. When route choice algorithms are combined with automated vehicles’ computing power, more effective trips can be made. For instance, SAVs can choose more effective routes that satisfy more passengers within the dynamic ride-sharing (DRS) scheme. The distance or travel time required for empty driving of an automated vehicle can be minimized by choosing the optimal route for it.

Route choice of CAVs will affect the traffic flow in both the individual level and system level. At the individual level, riders might travel more efficiently by choosing the best route required for their personal trip. At the system level, the congestion level can be lowered by dispersing each driver’s path to avoid congestion. Past research (Gonder et al., 2016; Guo et al., 2013), indicates the energy consumption would be reduced from enhanced route choice by as little as -5% to as much as -20%.

**Newly Induced Trips from Under-served Population**

CAVs can reduce or even eliminate the burden of driving task, so that non-drivers who were not able to drive can ride in CAVs without having difficulties. Specifically, elderly seniors and disabled persons with medical conditions would benefit from CAVs, and their mobility would not be restricted from driving tasks. By 2030, around 74 million seniors are expected to be living in the U.S., which comprises 26% of US population (Harper et al., 2016). Moreover, those who used public transit for their work trips tend to rely on automobiles after their retirement. If more CAVs make up the U.S. vehicle fleet, these groups will maintain this usage, or it may increase (Harper et al., 2016). This is because a driver’s license might not be required to ride in CAVs, since the required driving task is relatively low for CAVs as compared to conventional vehicles.

Improvement of accessibility is another factor that would induce new trips from this previously underserved population. Accessibility describes how well a certain place can be reached (Meyer et al., 2017), and with the capability of CAVs reduced driving task, originally underserved population would travel more easily than before. Thus, the trips from both seniors and disabled might rise with CAVs, and thus energy use and emissions would increase as well. Through the literature survey, this research estimates the increased energy consumption from newly induced trips to be between 10-14%.

**Shared Automated Vehicles – Increased VMT and Empty Driving**

Shared automated vehicles (SAVs) are automated vehicles shared among riders on demand. Car-sharing is available with conventional vehicles, such as car-pooling, but SAVs would expand this service more. SAVs might shift personal transportation choice from privately-owned vehicles to a service from shared vehicles used on-demand. Automated vehicles are more favorable for car-sharing than conventional vehicles. Automated vehicles might make users more accessible to the vehicle they need for travel. With
empty-driving capability, SAVs can act as an automated taxi that serve the users on demand.

However, empty driving might adversely affect the energy consumption rate of SAVs. Until passengers’ travel demand is met, SAV can drive without any passengers, and this additional driving will cause more energy consumption than before. The fleet size of SAVs would be smaller than that of conventional vehicles, because a single SAV can replace several conventional vehicles. However, the vehicle-mile-traveled (VMT) of SAVs would be larger than that of conventional vehicles. This is because SAVs serve more passengers with smaller fleet size, so that each SAV must drive more often than conventional vehicles. In the end, this research focuses on the probability of increased energy consumption caused by SAVs. Specifically, empty-driving of SAVs could increase the VMT, and result in increased energy consumption. It is inevitable that a certain proportion of SAV’s VMT would be empty-driving and minimizing empty-driving is essential for efficiency and fuel usage of SAVs. Past research (Loeb et al., 2016; Perrine et al., 2016) expects that the increased rate of energy consumption would be at least 6% and as much as 14% compared to current state.

**Long-distance Travel with AVs**

With vehicle automation, the driving task is reduced, and the vehicle takes over the role of driving. The burden required for driving would be reduced with CAVs, and riders of CAVs can focus on other interactions. For example, riders can play games, watch movies, chat with others, or even sleep during the ride. Consequently, the value of travel time with CAVs would be lower than that of conventional vehicles, and riders would be less reluctant to travel further than before. Thus, longer-distance travel, such as intra-urban, inter-regional travel, would increase with the adoption of CAVs. This paper assumes riders of CAVs can drive longer distances than drivers of conventional vehicles, and that the added distances are holistic including intra-urban, inter-regional, and even longer distance travel.

The increase of long-distance travel with CAVs will affect its competing travel modes, especially airline travel. It is expected that airline revenue would reduce to 53%, and travel to further distances with personal vehicles would increase to 9.6% (LaMondia et al., 2016). Inter-regional travel, such as travels with 500 miles or further distance, would increase further with the implementation of CAVs. As a result, the increased travel distance with CAVs would increase energy consumption and emissions in the ground transportation sector. However, airline travel would still serve travels for very far distances of 1000 miles or more (Perrine et al., 2016). The analysis results from previous literature (LaMondia et al., 2016; Perrine et al., 2016) expect the increased rate of energy consumption and emissions to be at least 6% to as much as 18%.

**Driving Details Category**

**Smotherer Driving Cycle**

Unlike the expectation from ‘Faster travel from improved driving skill’ section, CAVs might have a smoother driving cycle in contrast to conventional human-driven vehicles. This is because the control techniques of CAVs can be used to remove redundant driving cycles that are not favorable for the durability of the vehicle, fuel consumption, etc. For instance, by knowing downstream traffic condition, CAVs’ stop-and-go driving cycle while decelerating can be smoothed by better preparing for downstream conditions. During acceleration, CAVs can drive in a way to maintain its cruising speed, so that acceleration noise can be smoothed. Through interaction with traffic signals, the vehicle’s acceleration or deceleration can be smoothed to eliminate stopping using the information regarding signal cycles. Smoother driving cycle are analyzed to have lower emissions as compared to noisy driving cycles (Liu et al., 2017).

Another smoothing strategy for CAVs is to intentionally drive in eco-friendly way. Unlike the smoother driving cycle designed for effective driving mentioned above, the eco-friendly driving strategy can result in smoother driving cycle and reduced energy consumption and emissions. CAVs’ eco-driving ability can
be improved in contrast to human drivers, since control techniques can adjust the most efficient dynamic eco-driving skill while considering the traffic condition received from communication and sensors. It is known that dynamic eco-driving strategy of human drivers reduces the fuel consumption and lowers CO2 emissions (Barth et al., 2009). When such a strategy is accompanied with CAVs’ advanced control technique, energy savings can be greater than conventional human drivers’. This paper estimates the energy consumption from smoother driving cycle would decrease to be at least -10% to at most -20% of current state based on literature survey (Liu et al., 2017; Barth et al., 2009).

**Computer & Sensor Power Demands**

The computer and sensors required for automation of vehicles give better performance and driving experience to the driver compared to vehicles without automation. However, additional device and equipment for automation requires additional energy use. For example, air-conditioner (A/C) usually provides more pleasant and convenient driving environment when it is turned on, but the fuel economy would be decreased because of additional load required to run A/C. Steady-state air-conditioning in a sedan requires 1000w of energy loads, which results in 15% decrease in fuel economy compared to 500w base-line energy loads (Farrington & Rugh, 2000).

The energy use of CAV system will be different according to automation level, and it is challenging to expect how much energy would be required. In a life-cycle assessment analysis, CAV system is analyzed to have at most 4% more emissions during its life-time compared to vehicle without this system (Gawron et al., 2018). However, this estimate is based on life-cycle analysis, so that actual energy consumption on the road would be higher than this estimate.

In this paper, CAV system is predicted to use additional 1000w of auxiliary loads. This amount of auxiliary load is required to operate steady-state air-conditioning. It is also reasonable to assume a CAV system would use 1000w, since the power supplies installed on the desktop PC with high-performance CPU and GPU usually have around 1000w or more wattage. Based on this assumption, this paper estimates a CAV system would increase the energy consumption to at least 4% to at most 15%.

**Faster Travel from Improved Driving Skill**

One of the benefits of vehicle automation is the control technique obtained from advanced sensors, networking capability and artificial intelligence. Through the assistance or even full control of a vehicle from these techniques, the driving skills of CAVs will be improved in contrast to conventional human-driven vehicles. For instance, CAVs might be driving in faster speed with closer spacing to the leader vehicle, while ensuring safety.

With the increase of travel speed, capacity of the facility tends to increase. Thus, future road infrastructure with CAVs would have larger capacity compared to that of current state, and congestion would be lowered. Faster travel speed would ensure reduced travel time, thus riders of CAVs would benefit the improved traffic condition caused by CAVs. However, if the performance of power train and efficiency of fuel sources used in CAVs are equal to that of current vehicles, faster travel of CAVs would consume more energy, and thus emit more emissions. Through the literature survey (Lee et al., 2018; Brown et al., 2014), this paper estimates the change in energy consumption from faster travel of CAVs to be increasing at least 7% to at most 30% compared to the current state.

**Multi-vehicle Operation Category**

**Vehicle-to-vehicle (V2V) and Platooning**

V2V refers to communication through networking technologies, such as dedicated short-range communication (DSRC). The adoption of V2V technology enables velocity synchronization and closer spacing among vehicles, which will eventually lead to platooning of vehicles. Platooning can improve
string stability (Li et al., 2017; Talebpour et al., 2016) and increase capacity (Zhao et al., 2013), since vehicles will be driving with reduced acceleration noise and maintaining closer spacing with the vehicle in front of them. Apart from improved traffic flow, platooning can reduce fuel consumption and emissions through a smoother driving cycle (Gonder et al., 2012), the ability to send downstream traffic condition to vehicles in upstream (Li et al., 2015), and drag reduction (Alsabaan et al., 2013). Reduced acceleration noise in the driving cycle results in a smoother driving cycle with minor differences in the acceleration rate. Since vehicles in the upstream can receive the traffic condition downstream through V2V, upstream vehicles can adjust to the downstream condition better than before. Closer spacing among vehicles in the platoon will lead to reduced aerodynamic drag. These three aspects will lead to reduced fuel consumption and emissions in contrast to the vehicles without V2V platooning technique.

Through the literature survey, the energy and emissions reduction from V2V and platooning is estimated to be at least 7% to as much as 35% (Li et al., 2017; Talebpour et al., 2016; Zhao et al., 2013; Gonder et al., 2012; Li et al., 2015; Alsabaan et al., 2013). However, past research assumed that V2V was applied in the cruising situation of vehicles, where vehicles are platooning in a lengthy road, like highways. In fact, cruising traffic flow is rarely observed in non-highways, such as an urban network, so the estimates of V2V’s energy reduction should be modified. According to FHWA travel statistics, highway-travel in the U.S. comprises between 33% (interstate highway and expressway) and 55% (including major arterial roads) of all kilometers traveled in the US. (Wadud et al., 2016). Based on these statistics, this research applies the rate of highway travel to modify the energy and emissions reductions of V2V for the highway-traveling scenario. Therefore, the energy and emissions consumption rate from V2V implementation is assumed to be changing to at least -2% (=7%*33%) to at most -19% (=35%*55%) as compared to conventional vehicles. This estimate was derived from assuming all other travel that does not take place on the highway is non-highway travel and the intersection management technique will affect the travels achieved on those networks.

**Shared Automated Vehicles – Enhanced Fuel Efficiency**

Although SAVs may have adverse impacts on energy use as speculated above, they also have the potential to save energy when operated in an efficient way. Through vehicle right-sizing, SAVs can have various size options that fit the users’ demand. If vehicle size can be optimized to enhance fuel efficiency, SAV can save energy required for travel. With dynamic ride-sharing (DRS), passengers with similar origin-destination can share their travel by taking SAV ride together.

On-demand-travel of SAVs would increase the efficacy of trips, so that excessive use of energy can be minimized. The trips that are not required to match the rider’s demand, such as searching for a parking lot, can also be minimized to further reduce the energy consumption rate. Vehicle right-sizing can introduce smaller vehicles with smaller engines that still match the demand of riders and increase the energy savings. Passengers’ travel demand can be served with fewer vehicles by dynamic ride-sharing, and reduced emissions. Past research (Fagnant et al., 2014), estimates the change in energy consumption from SAVs to be as little as -5% to as much as -12% compared to current state.

**Vehicle-to-infrastructure (V2I) and Connected Intersection**

Vehicle-to-infrastructure communication or V2I is nearly analogous to V2V. However, V2I is communication protocol between vehicle and infrastructure, instead of communication between vehicles. Infrastructure with V2I communication include intersections, lane markers, and parking meters, but this paper constrains the target to connected intersection management with and without traffic signals. When smart intersections can be operated with automated vehicles, speed control of individual vehicles can be more easily compared to the existing speed advisory system, which carries uncertainty in the driver’s obedience of the rule. With the adoption of V2I to intersections, vehicles stop delay can be reduced (Lee et al., 2012; Niu et al., 2013a), vehicles will be eco-friendlier (Qian et al., 2011; Rakha et al., 2011; Niu et al., 2013b), and the vehicles in upstream can better adjust to the traffic condition in the downstream...
(Sanchez et al., 2006). Furthermore, autonomous intersection management (AIM) can be implemented, where traffic signals are not required (Carlino et al., 2013; Fajardo et al., 2011; Sharon et al., 2017). This type of intersection can manage the traffic by checking the trajectory of each vehicle and reserving the intersection to the target vehicle that should pass. In this way, collision between vehicles can be prevented, while minimizing stopping delay.

The expected energy and emissions reduction from V2I varies among the literature, but ranges between 13% to as much as 44% (Lee et al., 2012; Niu et al., 2013a; Qian et al., 2011; Rakha et al., 2011; Niu et al., 2013b; Sanchez et al., 2006; Carlino et al., 2013; Fajardo et al., 2011; Sharon et al., 2017). Similar to V2V, this reduction rate is modified with FHWA’s non-highway travel rate in the U.S., which is between 45% and 67%. Thus, the energy and emissions consumption rate from V2I implementation is assumed to be decreasing to at least -6% (=13%*45%) and at most -30% (=44**67%) as compared to conventional vehicles.

The limitations of V2I research conducted so far are 1) research is constrained to the implementation of a single intersection, rather than multiple smart intersections network-wide 2) interaction among different approaches of the intersection are often neglected and are constrained to a single approach. When these areas are covered through future research, the estimates for the fuel reduction rate from V2I can be derived more accurately.

Powertrain Energy Source Category

Electric and Hybrid Electric Vehicles

As technologies advance, energy and carbon-saving regulations take effect, and the public grows more concerned about mitigating climate change, there will be more vehicles equipped with electric motors in the future. Moreover, greater adoption of CAVs may well inspire greater adoption of electric and hybrid powertrains. Quarles et al.’s (2018) microsimulations of the U.S. passenger vehicle fleet (which recognize CAV technologies along with EV technologies) and others’ forecasts of the future (Loeb et al. 2017, Loeb et al. 2018, Chen and Kockelman, 2016) suggest that electric powertrains will be the majority of U.S. and global vehicle powertrains by 2050. CAVs’ empty-driving capabilities will allow EVs to self-charge without drivers. When charged inductively (or with a robotic arm), no human need be present for the refueling (unlike with diesel and gasoline). This is particularly valuable for electric SAV fleets (Loeb et al. 2017, Loeb et al. 2018), when travelers do not have to worry about the range of the SAV being sufficient for their trip request (since only sufficiently charged SAEVs would be sent their way) or worry about charging times (since charging happens only when vehicles are unoccupied, as in Loeb et al., 2018 and Chen and Kockelman, 2016).

With the advent of CAVs, the likelihood for adoption of electric motors or hybrid engines for powertrains might increase. Because electric vehicles do not have tail-pipe emissions, the emissions from vehicles would be reduced. Although power plants that generate electricity might carry more emissions because of their increased electricity demands, this research does not cover emissions from power plants, instead focusing on tail-pipe emissions and energy consumption from vehicles themselves. Past research (Hawkins et al., 2013; Al-Samari et al., 2017; Pitanuwat et al., 2015), suggests that the adoption of electric or hybrid vehicles would reduce the energy consumption of vehicles from -30% to as much as -70%.

Summary

In summary, improved driving performance would provide an enhanced driving experience to the users of AVs, while it might use more energy due to more active operation. If AVs are designed to have better fuel efficiency through control techniques, it might save more energy than conventional vehicles. Considering
all of these impacts, change in fuel type is expected to have the biggest impact on energy use. In the end, the change in energy consumption rate will affect the change in emissions implications of self-driving vehicles. The results of this literature review are summarized as in Table 1.

**TABLE 1 Summary of Impacts**

<table>
<thead>
<tr>
<th>Category</th>
<th>Impacts</th>
<th>Description</th>
<th>Energy Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Demand Changes</td>
<td>Better Route Choices</td>
<td>Route choice based on real-time traffic data from connected environment</td>
<td>-5% to -20%</td>
</tr>
<tr>
<td></td>
<td>New Trips from Under-</td>
<td>Motorized trips by limited drivers &amp; non-drivers</td>
<td>+10% to +14%</td>
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<td></td>
<td>served Populations</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shared Automated Vehicles –</td>
<td>SAVs traveling to next passenger, empty</td>
<td>+6% to +14%</td>
</tr>
<tr>
<td></td>
<td>Empty Driving</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>More Long-distance Travel</td>
<td>Longer distance travel caused from lower driving task of CAVs</td>
<td>+6% to +18%</td>
</tr>
<tr>
<td>Driving Details</td>
<td>Smoother Driving Cycle</td>
<td>More fuel-efficient driving cycles</td>
<td>-10% to -20%</td>
</tr>
<tr>
<td></td>
<td>Computer &amp; Sensor Power</td>
<td>Energy for sensors, on-board computing, vehicle control &amp; navigation</td>
<td>+4% to +15%</td>
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<tr>
<td></td>
<td>Demands</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Faster Travel from</td>
<td>Fast &amp; throughput-efficient driving cycle</td>
<td>+7% to +30%</td>
</tr>
<tr>
<td></td>
<td>Improved Driving Skills</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-vehicle Operation</td>
<td>V2V &amp; Platooning</td>
<td>Vehicle-to-vehicle connectivity &amp; platooning</td>
<td>-2% to -19%</td>
</tr>
<tr>
<td></td>
<td>Shared AVs &amp; Ride-Sharing</td>
<td>Fuel-efficiency from vehicle right-sizing &amp; dynamic ride-sharing (DRS)</td>
<td>-5% to -12%</td>
</tr>
<tr>
<td></td>
<td>V2I &amp; Smart Intersections</td>
<td>Vehicle-to-infrastructure connectivity &amp; smart intersection</td>
<td>-6% to -30%</td>
</tr>
<tr>
<td>Powertrain Energy Source</td>
<td>Plug-in Electric &amp; Hybrid</td>
<td>Drivetrain shifts from gasoline to electricity</td>
<td>-30% to -70%</td>
</tr>
<tr>
<td></td>
<td>Electric Vehicles</td>
<td></td>
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</tbody>
</table>

However, when classified by category level, changes can be observed more directly. Fig. 1 shows the most optimistic and most pessimistic change in energy consumption rate of each category. The travel category and driving category are more likely to use energy than other two categories. If an individual vehicle’s driving performance is improved, it is reasonable to assume that the vehicle would consume more energy than before. Likewise, passengers and travelers would have different travel patterns than before, which would lead to more trips with longer travel distances. Thus, it is reasonable to assume that travel and driving categories would be more likely to use more energy than current state.

For the operation category, energy savings is assumed. The operation category includes connection and communication among multiple vehicles and infrastructures that were not available with conventional vehicles. Enhanced communication ability would lead to improved interaction among vehicles and infrastructures, which can lead to more fuel-efficient driving. Energy source category is highly related to energy consumption rate, and this paper focuses on electrification of drive train and it is assumed to be the largest energy saving category in this paper.
FIGURE 1 Change in energy consumption according to each category

SCENARIO ANALYSIS

Due to the uncertainty surrounding AV implementation, it is difficult to predict the exact outcome caused from their adoption. Each impact may cancel out each other, or the range of change might be greater than what is expected by the literatures. To overcome this uncertainty, this paper conducts a scenario analysis to anticipate various scenarios that can be observed in the future. The change in energy consumption rate is analyzed with respect to the market penetration rate (MPR) of self-driving vehicles. Since electrification of power trains has shown the largest impact on energy use, its impacts are analyzed separately by including and excluding its impact in the model.

Energy Consumption with respect to Penetration Rate

Random sampling analysis was undertaken to overcome the uncertainty of future predictions. Considering all the impacts except from energy source change, random samples of each impact’s change in energy consumption were generated. The impact from electrification of power train is excluded to focus on the impact of CAV system. Assuming 100% MPR of CAVs, a total of 1000 samples of change in energy consumption rate are derived. Fig. 2 shows the histogram of this random sampling analysis.

When placing the current energy consumption rate at 100%, a lower value than 100% implies energy savings, while a larger value than 100% implies energy use. Fig. 2 shows that most of the random samples are smaller than 100% and the average decrease in energy consumption is 11%. Thus, energy savings is expected with the full adoption of CAVs in the U.S.
Extreme Electrification Effects with respect to CAVs’ Penetration Rate

The penetration of CAVs is expected to be gradually achieved rather than an abrupt increase. Thus, the energy consumption rate will be gradually changing with respect to the increase of market penetration of CAVs. To track this change in energy consumption rate, scenario analysis with respect to market penetration rate was achieved.

Energy consumption rate ($\%) = CAV\% \times (All \ effects) + (100 - CAV\%) \times (100)$

Eq. 1 shows the method of tracking the energy consumption rate with respect to the penetration rate of CAVs. The impact of conventional vehicles is assumed to be 100% (business as usual), while impacts of CAVs would have a lower or higher value than 100% as compared to conventional vehicles. The impact of CAVs is derived by taking the average value of random sample analysis for each penetration rate as achieved above. By deriving the weighted average with the penetration rate of CAVs (CAV%), the change in energy consumption rate can be tracked. To track the impact from power train electrification, two different analysis results are provided. One includes the impact from electric vehicles, while the other one does not have electric vehicles in its vehicle fleet.

Fig. 3 shows the average result, standard deviation, as well as the most optimistic and pessimistic result. As the MPR of CAVs increases, so does the standard deviation increase. This can be explained by the uncertainty of predicting the future, so that a larger error can be observed for future predictions. While the most pessimistic result shows an increase in energy use and the most optimistic result shows energy savings, the average value predicts that decreased energy consumption rate with respect to the increase of MPR is more likely. It is likely that emissions would decrease as well, since emissions would be proportional to the amount of energy spent in ground transportation.
The extreme effects from electrification of power train is analyzed in both 0% and 100% rate of electric vehicles (EVs) on the road. Decrease in energy consumption is expected without any EVs (Fig. 3-(a)), but the amount of decrease is larger when 100% of EVs are on the road (Fig. 3-(b)). The average decrease in energy consumption without EVs is around 11%, while it is around 55% decrease when all the CAVs are EVs. The range between pessimistic and optimistic estimates becomes smaller when EVs are included in the model, indicating more accurate prediction can be made. In conclusion, the adoption of CAVs would lower the energy consumption, and adoption of electric CAVs would further decrease energy reduction.

**CONCLUSION**

In this paper, possible outcomes from the adoption of CAVs are analyzed. Each impact would use or save the energy, resulting in varying impacts on energy and emissions implications. Through the literature review, this paper defined the types and effective range of these impacts. Scenario analysis supplements the uncertainty of predicting future results with the random sampling method.

With the adoption of CAVs, it is likely that fuel consumption rate would decrease. Impacts that would use or save energy are categorized and the possibility of change in power trains are considered as well. This paper assumed that emissions would be proportional to the amount of energy spent with CAVs, so that emissions would change similarly with respect to the energy consumption rate. CAVs’ sensors and computers would require more power and might prompt electrification of drivetrain. Electrification of power train in CAVs is expected to save at most 40% more energy compared to non-electric CAVs. The adoption of electric trucks, fast-charging technology, and lower rate of diesel-vehicles could further increase the energy saving from power train electrification studied in this paper. However, the impacts from CAVs could reduce the energy consumption even without electrification, so that CAVs would use less energy and emit less pollutants compared to conventional vehicles.

Since self-driving vehicles do not yet make up any of the US vehicle fleet, so this paper used random sampling methods to overcome the lack of real experimental data. However, future research should provide experimental data that can be observed with the adoption of CAVs. The change in energy consumption rate and emissions should be tracked in the long run with the adoption of CAVs, so that more accurate and realistic results can be provided.
AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Kara Kockelman; data collection: Jooyong Lee; analysis and interpretation of results: Kara Kockelman, Jooyong Lee; draft manuscript preparation: Kara Kockelman, Jooyong Lee. All authors reviewed the results and approved the final version of the manuscript.

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