Automated Vehicle Fuel Efficiency Town Hall

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Abstract. AV and CAV technologies are already affecting on-road energy usage and in the future may drastically change vehicle energy usage and efficiency. The Efficiency Town Hall, at ARTS2021 showed the importance of the question of how to balance individual vehicle efficiency with systemic transportation efficiency as well traffic and demand management. The Town Hall also showed that these questions can no longer be considered a problem for the future, solutions must be found for the vehicles entering the market now. Connectivity will also be key in ensuring that AV technology delivers consistent energy reductions. Finally, regulations which can capture the effects of CAVs and incentivize energy efficiency must be promulgated to ensure that AVs are designed with efficiency and energy reduction in mind.

Keywords: Autonomous vehicles · Connected vehicles · Energy · Demand · Energy efficiency · Energy consumption · Energy policy

1 Introduction

Breakout sessions B301 and B307 at the Automated Road Transportation Symposium 2021 (ARTS2021) were part of a double feature sponsored by AMS30(3), the Transportation Research Board (TRB) Subcommittee on Energy and Demand Implications;

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AMS30, the TRB standing committee on Transportation Energy and ACP30, the TRB standing committee on Vehicle-Highway Automation. The double session focused on understanding the technical and regulatory hurdles of implementing efficiency regulations for automated vehicles, a topic that has yet to be tackled in other symposia. Vehicle automation is often promoted to increase safety and convenience, however little discussion often surrounds the associated energy and environmental implications of this new technology class.

A robust representation of professionals from industry groups, government agencies and regulators, academics, national laboratories, and public interest groups convened to open the lines of communication between regulator, stakeholders, and researchers. Presenters delivered twelve (12) presentations of 15–20 min with two (2) 45 min moderated panel Q&A at the end of each session. The B301 morning session featured seven (7) presentations followed by a panel discussion that focused on energy demand analysis of automated vehicles and enabling technologies that promote energy efficiency. The B307 afternoon session featured five (5) presentations followed by a panel discussion focused on understanding the challenges of developing a regulatory framework to regulate automated vehicle energy efficiency.

The ultimate goal of the sessions was to expose technical and policy research, promote data sharing and develop forward guidance and research needs statements around the themes of (1) understand the true financial cost of implementing Automated vehicles (AVs) energy efficiency regulations – or the environmental costs associated with delaying and (2) exposing the "bleeding-edge" energy efficiency enabling technologies/research and analysis. The symposium outcomes described hereinafter regarding the importance of balancing individual vehicle fuel economy with system-wide energy use/reduction objectives will ultimate be monitored by the TRB subcommittee on Energy and Demand Implications AMS30(3) and future breakout sessions at the Automated Road Transportation will be tailored to ensure this discussion is continued and adapted to the changing landscape.

2 Summary of Presentations

The following section summarizes a selection of the research presented during the conference breakout session. Each presentation's section summarizes the findings and/or methods, where applicable, of one of the presentations. Presentations included original research, summaries of literature and syntheses reviews, reports from regulators and government agencies, and reports from industry groups. A list of all presentations, including those summarized in this chapter, and slides for each can be found in the conference proceedings.

2.1 Autonomous Vehicles and Off-Cycle Emission Credit Testing

Avi Chaim Mersky, American Council for an Energy Efficient Economy

2.1.1 The Growing Impact of Automated Vehicles

Automated vehicle (AV) technology continues to be developed and commercialized and are already widely deployed and encompass 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, while the market share of Level 2 AVs has grown from at least 2% of all new vehicles to at least 10% in just 2018–2019 [1–3]. Research by ACEEE suggests even more advanced AVs will be significant components of the US vehicle fleet by 2035 [4]. Vehicle fuel efficiency and emissions are both highly sensitive to how the vehicle is controlled and, therefore, automation. AV efficiency is also highly variable. A review of recent literature by ACEEE showed that AV features, likely to be available on mass market vehicles, could reduce vehicle efficiency by as much as 14% or increase it as much as 52% [4].

2.1.2 The Need for Autonomous Vehicle Efficiency Regulations

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. These procedures cannot detect the fuel economy impacts of technologies, including AV technologies, that change how the vehicle responds to the environment around it. While there is a mechanism to recognize the benefits of technologies that are not detected under the test procedures: the process is labor intensive for both automakers and the regulatory agencies and the results are not guaranteed. Both factors act as a cost that reduces the incentive to improve AV efficiency. Hence it is desirable that emissions and fuel economy regulations incentivize manufacturers to design AV systems with fuel efficiency in mind.

2.1.3 How Autonomous Vehicle Fuel Efficiency Should Be Regulated Now

Our recommendations apply only to level 1–3 AVs. We believe that highly or fully autonomous vehicles must have their fuel efficiency be tested as a single unit, rather than applying credits to specific features. We propose that the regulating agencies, EPA and NHTSA, define discrete AV Feature Groups (AVFG) that describe a set of unique operating conditions and capabilities. 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. Certification should be based upon manufacturer instructions, unless and until NHTSA starts issuing requirements for AV safety certification.

The regulating agencies should provide a list of AVFGs eligible for credits and develop standardized rules on how these AVFGs should be evaluated. The agencies should publish the rules for public comment. 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 and, if significant, the technology’s penetration rate.

Over the short term, these suggestions could potentially be implemented under the existing optional off-cycle credit program. Over the longer term, we believe that the agencies should consider requiring that all AVFGs 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. This will ensure that applications that increase fuel consumption will be accounted for. AV efficiency improvements can also be considered by policymakers when setting efficiency standards.

2.1.4 Future Work

Our recommendations reflect on an existing regulatory environment that is concerned with the direct effects of technology on an individual vehicle's fuel economy. The impact of AVs is both dependent on surrounding traffic and also changes traffic conditions. These systemic impacts need to be better understood and the regulatory agencies should ensure that they do not encourage technologies whose systemic detriments are greater than their individual benefits. AVs may also change the total demand for travel. While existing efficiency and emission are not intended to tackle such impacts on energy use, regulators and policy makers should create policies to ensure that AVs do not increase total emissions, even if increase vehicle efficiency.

2.2 National Academies Light-Duty Fuel Economy Report: Findings on CAV Technology Energy Impacts

Therese Langer, American Council for an Energy Efficient Economy

The recent National Academies of Science Engineering and Medicine study *Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles—Phase 3* (https://www.nap.edu/catalog/26092) examined vehicle efficiency technologies likely to be available in 2025–2035 [5]. The committee relied on information gathered from industry meetings and site visits, public information sessions, expertise of committee members, and the literature. The study, sponsored by U.S. DOT's National Highway Traffic Safety Administration, was mandated by Congress in Energy Independence and Security Act of 2007. [This presentation summarized the study's findings on the energy impacts of connected and automated vehicle (CAV) technologies; recommendations on associated policies were discussed in Sect. 2.4].

The study distinguished energy issues for lower level CAVs (SAE Levels 1–3) from those of fully autonomous (Levels 4 and 5) vehicles, focusing in the former case on effects of the technologies on the fuel economy of individual vehicles. For autonomous vehicles, there is a much wider array of potential energy effects, based on these vehicles' implications for car ownership decisions, mode choice, vehicle miles traveled, and other issues that go beyond the technology's effects on the vehicles themselves.

The study summarized cost and effectiveness of three CAV technology packages.[1] Key findings and caveats included that low levels of automation (Level 2) can provide fuel savings of up to 8% through optimizing velocity and minimizing acceleration events, though the savings depend strongly on driving conditions and powertrain type. Adding

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[1] See Table 8.6 of the National Academies study.

connectivity to increase the system's prediction horizon and optimizing power train controls allows fuel savings of as much as 20%, with the greatest benefit achieved in plug-in hybrid vehicles on trips exceeding the battery range. These estimates do not represent savings on standard test cycles, however, nor do they reflect energy effects of any changes to traffic flow the CAVs may produce. All-electric vehicles will see the lowest efficiency gain but will benefit from other synergies with CAV technologies.

The committee estimated direct manufacturing costs of the Level 2 package at $1,520 and Level 2 with power train controls and connectivity at $2,410, with modest declines in the costs of both packages over the next 15 years. The fully autonomous vehicle (Level 4/5 with connectivity) was estimated at $7,210–$17,210, depending on lidar unit specifications, but was projected to decline to $2,545–$4,683 by 2035. Since CAV technology adoption is largely driven by benefits other than fuel savings (safety, mobility, convenience), these costs should not be attributed entirely to fuel savings in the context of a cost-effectiveness assessment of technologies for regulatory purposes.

For autonomous vehicles, the committee highlighted a recent national laboratory meta-analysis of the literature, which bounds likely energy impacts of full adoption of autonomous vehicle between a 40% reduction and a 70% increase in energy use [6]. While power draw of these higher level CAV systems can be substantial—on the order of 2 kW—the draw for a fixed vehicle capability will decline rapidly over time as electronic systems evolve. However, total electrical load of these systems may remain significant as their functionality increases, due especially to growing computing requirements.

The study found that connectivity is unlikely to be widely deployed in 2025 but could reach high adoption levels by 2035 if public infrastructure is updated to collect, process, and distribute data, and if useful, affordable connectivity services are available. Autonomous vehicles' share of the market in 2035 is likely to fall in the 0–40% range, with ride hailing and delivery fleets accounting for 40–60% of those sales.

2.3 National Academies Light-Duty Fuel Economy Report: Policies to Promote CAV Technology Energy Savings

Therese Langer, American Council for an Energy Efficient Economy

Among the recommendations of the recent National Academies of Science Engineering and Medicine study Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles—Phase 3 were several on federal agency actions to promote energy savings from connected and automated vehicle (CAV) technologies. [For a brief description of the National Academies study, see Sect. 2.3 on energy impacts of CAVs.]

For lower levels of vehicle automation (SAE Levels 1–3), the study considered primarily effects of these technologies on fuel economy and greenhouse gas emissions of individual vehicles and implications for vehicle standards. The study found that CAV technologies enable, but do not ensure, substantial fuel efficiency improvement over current vehicle technologies. Today's vehicle test procedures generally cannot detect any CAV technology fuel efficiency benefits, so these technologies could only help manufacturers comply with fuel economy standards through the off-cycle credit program.

While off-cycle credits could promote adoption of CAV technologies, the agencies will need to exercise caution in awarding such credits due to the complexities of evaluating CAV energy impacts. In particular the committee recommended that 1) off-cycle credits be available for CAV technologies only to the extent they improve the fuel efficiency of the vehicle on which they are installed (and not through changes in traffic flow, for example), and 2) any credits be based on realistic assumptions regarding technology adoption on other vehicles or infrastructure. Moreover, given that some CAV technologies are becoming commonplace, once their energy impacts have been adequately quantified the agencies should consider their potential benefits in setting the level of the standards.

With regard to quantifying CAV technology impacts for purposes of compliance with vehicle standards, the committee noted that allowing these vehicles limited departures from the standard cycles during testing would permit some CAV technologies' fuel efficiency gains—and losses—to be measured. More generally, the committee found the problem of estimating CAV technology energy impacts to be symptomatic of a larger issue in the fuel economy standards program, namely the divergence between vehicles' fuel economy as captured in testing and their performance in the real world. The study underscored the opportunity and need to rely more on real-world data to assess vehicles' performance, noting that "vehicles currently being produced/sold in the U.S. market can record fuel consumption over specific periods of time, which provides the capabilities for verifying performance and could enable a shift from the test-cycle-based approach of estimating emissions to an approach of directly measuring emissions."

In the case of fully autonomous vehicles, the study noted that the maximum feasible fuel economy standards for these vehicles in fleet use could be more stringent than standards for personally owned vehicles, and that an all-electric mandate should be considered for autonomous fleet vehicles. However, achieving positive energy outcomes through adoption of autonomous vehicles will require a much more extensive policy approach. Agencies should consider actions to guide system effects of autonomous driving, including policies to promote vehicle sharing and ensure these vehicles' complementarity to less energy-intensive modes. Additional research and policies are needed to advance the simultaneous achievement of the safety, economic, environmental, and equity benefits which autonomous vehicles can provide.

2.4 Impact of Vehicle Automation on Energy Consumption[2]

Jihun Han, Dominik Karbowski, Jongryeol Jeong, Namdoo Kim, Julien Grave, Daliang Shen, Yaozhong Zhang, Aymeric Rousseau, Argonne National Laboratory

Connectivity and automation technologies offer the potential for improving vehicle efficiency through energy-focused controls. Under the SMART 1.0 (Systems and Modeling for Accelerated Research in Transportation) Mobility Laboratory Consortium [6], we developed various automated driving controllers, e.g., "speed-only" optimization [7], "speed + powertrain" co-optimization [8]. The speed + powertrain algorithm co-optimizes speed and powertrain to achieve maximum efficiency. Using RoadRunner, a new simulation framework for research energy-efficiency and driving

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[2] This material is based upon work supported by the U.S. Department of Energy, Vehicle Technologies Office, under the Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Laboratory Consortium, an initiative of the Energy Efficient Mobility Systems Program.

automation, we performed a large-scale simulation study applying the algorithms and demonstrated up to 22% savings when utilizing traffic signal information through V2I (Vehicle-to-Infrastructure) communication.

However, the algorithms need to be deployable on real-time control units and provide the energy savings on real vehicles without safety issues (e.g., traffic rule violations, rear-end collisions). To this end, we have developed an XIL (anything-in-the-loop) workflow that includes: creating a digital twin of a real vehicle and environment, developing an automatic building process from full simulation to a mix of simulation and hardware, developing a methodology for interactions between a real vehicle and a simulated environment, developing an automatic quality-check process for control functionality verification, etc. The XIL workflow accelerates the experimental testing process, enables testing of various control algorithms and quantification of their impact on energy consumption, while ensuring high test-to-test repeatability and accuracy.

We improved the speed-only optimization algorithm to perform well in a broad range of situations using RoadRunner, and implemented it in the real vehicle to automatically drive in an energy-efficient way. Finally, we tested the automated driving controller for 22 scenarios (total 280 km) and applied it to two powertrains (GM Electric Bolt and Blazer). Scenarios defined by a combination of route and controller features (e.g., V2I communication on/off, preceding vehicle speed prediction on/off) include various situations such as traffic light approach, speed limit change, and traffic. The controlled ANL on-dynamometer tests validated all functionality and performance of the automated driving controller and led to a successful on-track (3.72 km) demonstration at ACM (American Center for Mobility) [9]. Experimental test results showed that energy savings from V2I communication become greater (up to 30%) for single intersection approach and departure situation on empty road, as the remaining time to the next green light is longer. In scenarios with traffic, energy savings are increased (about 11%) as the penetration rate of V2I communication increases (0%, 50%, and 100% in 2 vehicle scenarios). A vehicle without V2I following the virtual preceding vehicle equipped with V2I communication also saves energy (about 10%). Moreover, more accurate and longer prediction of the preceding vehicle's driving behavior (e.g., braking-stop-wait-departure at a red traffic light) can generate smoother trajectories and more energy savings (about 7%). Note that these energy saving values are computed with respect to the controller without V2I communication (not a human driven vehicle).

In future works, we would like to validate energy impacts for real-world representative scenarios designed well by data. Moreover, we could test advanced controllers (e.g., enabling multi-traffic light approach, speed + powertrain control) to gauge their further energy saving potentials through ANL xIL workflow.

2.5 Automated Vehicle Policies for Equity and Clean Air

Jeffrey Lidicker, California Air Resource Board

2.5.1 Background

The State of California has been actively tracking and researching Automated Vehicles (AVs) as initial information indicates that AVs may influence emissions dramatically. A recent study by Dr. Merksy indicates that AVs can, depending on how well they are programmed to eco-drive, reduce vehicle emissions by as much as 40%, or increase them by up to 14% [4]. A study by Dr. Hardman et al. indicates that 36% of drivers using available partial automation features reported "more long distance travel" and 40% reported "more driving during periods of congestion" [10]. The study estimates that, for Teslas only, due to partial automation an average of 4,884 additional miles are driven per year per vehicle. Lastly, a study by Dr. Wadud et al. estimates that energy consumption and emissions from AVs could be cut in half, or double depending on the particulars of how they are operated [11]. Certainly, if AVs were to double energy consumption or emissions, this would derail California's emissions reduction goals [12].

In 2018, a multi-agency workgroup was formed in California to ask these policy questions. Over 10 state agencies participated in the workgroup.[3] The workgroup produced an AV Principles for Healthy and Sustainable Communities document [13]. Although the document was adopted by the Governor and subsequently posted to the Office of Planning and Research website, it does not officially represent the position of the participating agencies or commissions. It exists, however, for policy makers from local, state, and federal agencies to use as a resource. The AV policy document lists eight guiding principles.

2.5.2 AVs as Shared-Use Vehicles

With respect to energy consumption and therefore emissions, it is preferable for AVs to be shared-use vehicles instead of privately owned. If AVs enable a high percentage of shared trips, say 85%, then there would be essentially a de-facto VMT fee in place without any new legislation, new authority, or government run administration and reporting system. These shared ride fees are based on a combination of time and distance along with a built-in peak pricing mechanism, which would be an optimal VMT reduction policy. Other attributes of this policy are better utilization of vehicle capital and reduced parking demand that enables better utilization of high-value real estate.

2.5.3 AV Rides as Pooled Rides

Maximizing the average number of passengers in an AV will reduce vehicle miles traveled but not passenger miles traveled. The higher the penetration of shared-use vehicles, the

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[3] Participating agencies included but are not limited to: CalEPA, CalSTA, Caltrans, CARB, CDPH, CEC, DGS, DMV, Go-Biz, OPR, and SGC. Also participating was the CPUC.

more opportunities for pooled rides. Other benefits of pooling include lower prices that improve transportation equity and fewer empty miles traveled. For example, a policy designed to increase the use of pooling is the California Clean Miles Standard, in which shared-ride services must meet grams of CO_2 per passenger mile traveled targets [14]. Thus, the more they pool, which reduces VMT but not PMT, the easier it will be to meet the targets. Companies that have developed and continue to develop pooling services are Via, Lyft, and Uber.

2.5.4 AV's as Low-Emission Vehicle

Any policy that can motivate AVs to be low-emission or zero emissions will produce fewer emissions than one that runs on fossil fuels. For example, the proposed California Senate Bill 500 would require all light-duty AVs be zero-emission by 2031 [15].

2.5.5 Right-Sized AVs

Rightsizing is a term that implies that, on average, the number of available seats in a car is equal to the number of passengers on a particular trip. Thus, if a city has 85% of trips by single-passenger travelers, then 85% of the vehicles used for trips would be one-seaters, and so on. Policies that discourage driving with empty seats will reduce emissions overall. Rightsizing might even reduce congestion as four single AVs may fit in the same space as a large SUV at a red light. In 2015, Dr. Greenblatt at LBNL estimated that vehicle rightsizing could reduce energy consumption, and therefore, emissions as much as 45% [16]. AVs would be necessary to achieve optimal rightsizing.

2.5.6 Integrate AVs into Multimodal Systems

Imagine if all AV policy was dictated only by profit and AVs had no bicycle racks on them, were programmed to pass bicycles very closely, and were not allowed to take anyone to or from a transit station or let anyone out of the vehicle when stuck in gridlock. These policies might improve profits for ride providers but would likely discourage the use of multi-model transport systems such as trips that make use of more than one mode: bicycles, transit, walking, and AVs. Instead, imagine AV policies that encourages the use of transit and trips with more than one mode. Examples of such policy are the CA Clean Miles Standard regulation that offers compliance credits for ride hailing companies to integrate transit into their mobile applications [14], and the company Via that has been partnering with transit agencies to provide on-demand transit in settings where fixed route transit isn't providing good access [17].

2.5.7 Shared AVs in Planning Polices

The sixth and seventh guiding principles are closely related. The sixth one encourages land-use policies that leverage shared AVs in ways that encourage infill rather than sprawl. For example, cities can leverage shared AVs to reduce the need for parking requirements freeing up land for a myriad of other uses such as housing or greenspace. Reducing parking requirements for buildings would also reduce housing costs and availability, which could improve equity metrics in non-transportation ways.

The seventh guiding principle applies to complete and livable streets - the spaces between the land or city blocks. Policies that can leverage shared AVs to prioritize people, other modes, and overall health and safety. For example, AV policies can motivate AVs to be polite to pedestrians and bicyclists making streets safer for pedestrians and other forms of active transportation. Other policies can allocate curb space for shared AV ride or freight drop-off and pick-up, so that loading and unloading passengers and freight do not block traffic lanes reducing traffic congestion. Due to advantages of AVs, perhaps only two traffic lanes are needed instead of three so that more street space can be used for people, other modes, and beautification. Parklettes are another example of a benefit allowed by the combination of city policy and the reduced demand for parking afforded by AVs. Parklettes provide a higher quality of life and increased revenue for restaurants among other benefits.

2.5.8 Transportation Equity and AVs

AVs present an opportunity to improve equity in transportation by increasing access or mobility with lowed transportation costs. Several features of AVs can lower operating costs such as removing the cost of a driver and spreading fees across multiple passengers when pooling rides. Capital costs can also be lowered due to higher utilization of shared vehicles for a lower cost per mile. Together, these two types of AV cost reductions improve the feasibility of on-demand transit that can expand service availability into disadvantaged communities and offer the potential of mobility for the disabled and elderly at the same price as for anyone else. However, without AV policies that ensure private companies provide services to everyone everywhere, and not just where the highest profit margins are, the opposite could happen.

2.5.9 Conclusion

The potential for AVs to improve transportation access for all, including for disadvantaged or disabled and elderly communities, is unprecedented. AVs can also improve health and safety by reducing accidents, reducing vehicle emissions, and encouraging active transportation. However, without government policies, these improvements may not happen.

2.6 Energy Efficiencies of Trucking Automation Now and into the Future

Rick Mihelic, North American Council for Freight Efficiency

The conversation on automation starts by understanding that automation is a journey, not a destination. Continuous improvement is the nature of heavy truck technologies. Freight efficiency is about moving more freight with less energy *and less cost*. Cost and energy are intertwined. Commercial trucks are businesses. They need to be profitable.

The future is easy to predict, after it has happened. History is replete with technology marvels that did not fare so well in the market. We are in the midst rapid and diverse changes in trucking technology. Zero and net zero solutions are ramping up. All have infrastructure needs. Automated and connected vehicle technology is just part of the story. And digital data and data mining is coming with all of these. This transition is being driven both by market and regulatory forces.

Nearly every day we see new AV companies and products in the news. These vehicles are on the road in limited numbers already, and more are coming. Why are AVs coming? There are multiple factors that can be grouped under the headings people, market, and accidents. Human employees bring with them a wide range of overhead factors. The market demands moving more freight than we have drivers. Competition requires all companies to minimize costs while maximizing profits. The convergence of all these factors, shown in Fig. 1, is the opportunity for AVs.

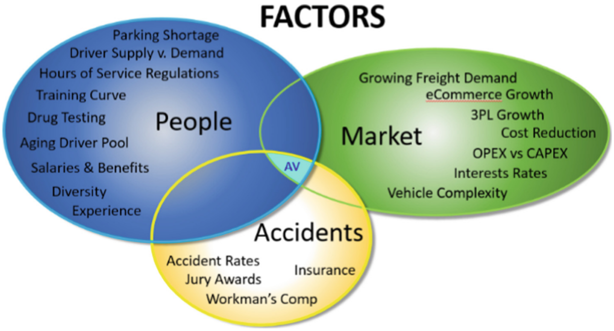

Fig. 1. Factors driving AV development and adoption

Every technology has tradeoffs, advantages, disadvantages, and unknowns. While AVs lower operating costs, they increase capital costs. AVs can increase daily volume of freight moved, but 24/7 operation brings with it a range of infrastructure challenges. While AVs promise to lower the number of accidents, the severity of the accidents that do occur could be more severe. These are just some examples.

The big question is always how much improvement? The answer is very context sensitive. It depends. Physical testing and analytical models range in real world performance from negative improvement to 0%, 5%, 10%, 20% and more. NACFE has quoted research showing that technology makers tend to over-estimate their products capability by as much as 3 times. While consumers of that technology tend to underestimate that same performance by as much as 3 times. Reality is usually somewhere in between. Not as good as the manufacturer's vision, not as bad as the fleet's expectations. In the end, both want the technology to work well. But there are no average fleets, no average drivers, no average trucks, no average routes, no average loads. Your savings may differ. There are no SAE standards yet for evaluating fuel economy in traffic conditions.

The savings also need to be in context of the entire freight system. A holistic view is the Total Cost of Ownership, or TCO perspective. It is common to look at operating costs on only a per truck basis. In stable periods this is about 1/3 of operating cost is due to the equipment, 1/3 due to the driver and 1/3 due to fuel. One argument for automated trucks reducing operating costs. But there is more to that.

Trucking has always needed more people, across the board. It is not just drivers. Its technicians, back-office people, supervisors. Competition for workers has grown, and quality of life factors are weighing more on job choices. Automated vehicles present an opportunity to add freight capacity.

Many factors are contributing to the shortfall in trucking people. In talking to fleets, in many cases it is not a lack of applicants. It is a lack of "qualified" applicants**.** The emphasis is on experienced, skilled drivers. Automated trucks are expected to fill this void.

So how do AVs help solve freight issues? Look at a 24-h day example. On an actual one-day truck route a particularly good driver and truck achieved 10.6 mpg and on a 637-mile route in an 11 h driving period. An automated truck does not need to stop for breaks, this gives it some advantage also in net fuel economy, allowing it to arrive earlier. It is then free to be reassigned after refueling to a new route.

What does this mean over a week? The human driver can get 3,185 miles with five similar deliveries. The automated driver in this case can do 8,918 miles and 14 deliveries. This is about three times the capacity of the single driver. This is just one example. There are a lot of duty cycles, routes and trips. Some drivers go back and forth A to B to A. Some have multiple stops A-B-C-A. Others may rarely get home, picking up new loads and routes at each stop, an A-B-C-D-E-F-. And the distances vary a lot.

So, what are the ramifications and trade-offs. An autonomous vehicle may make nearly three times the deliveries per week. But that extra mileage is not free. It brings with it increased maintenance. Shorter trade cycles. Need for more rapid capital. Regarding accident rates, they are based on miles driven per vehicle. Increasing the miles by a factor of three increases the opportunity for accidents to occur, while the technology is working to try to reduce the accident risk. The delivery network also must be able to accommodate 24/7 operations. And software is not free.

Automation is also in context of parallel movement towards zero and near zero emission vehicles. Some are competing for money and resources, some are enabling AVs.

So, what if the driver is not in the vehicle? Where does truck design lead? Moving more freight may be possible with larger trailers. While staying inside today's legal lengths. And what if we combine a number of technologies? We could see automated road trains.

AVs have the potential to help move more freight efficiently. How much depends on a holistic view of the freight system. For the near term, they will supplement not replace traditional vehicles. There are tradeoffs and unknowns with all new technologies. The market will prove out AV technology over time.

2.7 Infrastructure Assisted Automated Driving on Highways

Gábor Orosz, University of Michigan

Connected road infrastructure (CRI) can dramatically improve transportation system-level energy efficiency, productivity, and emission by exploiting connected and automated vehicle (CAV) technologies. This is expected to lead to significant improvement in the efficiency of passenger and freight transport (measured in mile/hour/kWh) even for low penetrations of CAVs. As illustrated in Fig. 2, achieving such high efficiency of road transportation relies on the tight integration of connected automated vehicle

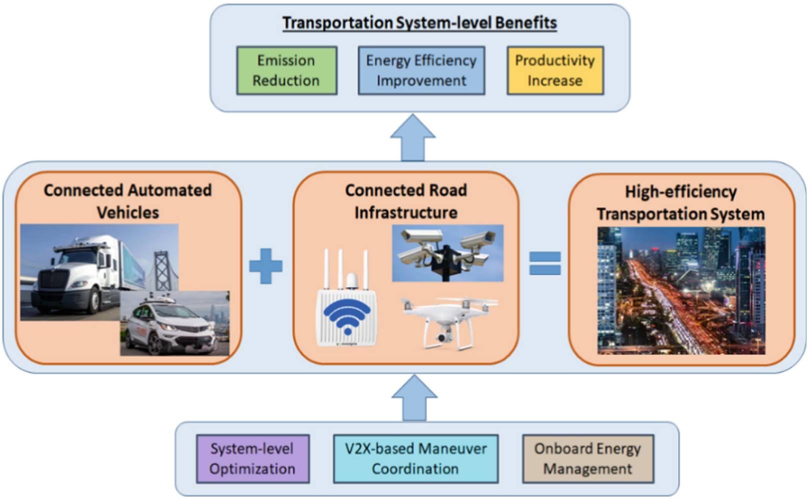

Fig. 2. Information flow of the integrated system

(CAV) technologies with connected road infrastructure (CRI) technologies. In particular, information collected via fixed-base and airborne cameras and vehicle-to-everything (V2X) communication shall be processed and aggregated by the CRI in order to merge the benefits having basic information about all non-connected vehicles and in-depth information about connected vehicles. Such information can enable CAVs to perform infrastructure-assisted automated driving: they can move through traffic faster and while using less energy delivering goods and passengers in a highly reliable manner. These actions can also be integrated with the onboard energy management systems of the CAVs in order to maximize energy efficiency at the component level. Since these CAVs also heavily influence the rest of the traffic they can lead to dramatic improvements of transportation system-level energy efficiency and significant reduction of emission even for low CAV penetrations. The arising highly efficient transportation system shall allow unprecedented growth of productivity with small investment to the infrastructure.

In case of a CAV, the efficiency improvements arise mainly from having access to lane specific real time traffic predictions for the next few miles ahead via V2X communication. These improvements are shown to be significant compared to the baseline scenario of having purely sensor-based automation [18–20]. Such strategies rely on technologies that make such information available for CAVs and on algorithms that allow these vehicles to achieve such improvements with high reliability.

A section of highway I-275 near Ann Arbor, MI is illustrated Fig. 3 where our team is currently deploying elements of the proposed infrastructure in collaboration with the Michigan Department of Transportation. This infrastructure will provide us with an unprecedented opportunity to monitor and predict road traffic. Historically, traffic data has been collected using fixed-base cameras mounted on roadside columns, and a set of those are already available along I-275. We are augmenting these with airborne cameras and with V2X communication devices that communicate to each other via 5G communication. This infrastructure enables us to collect high precision trajectory data from

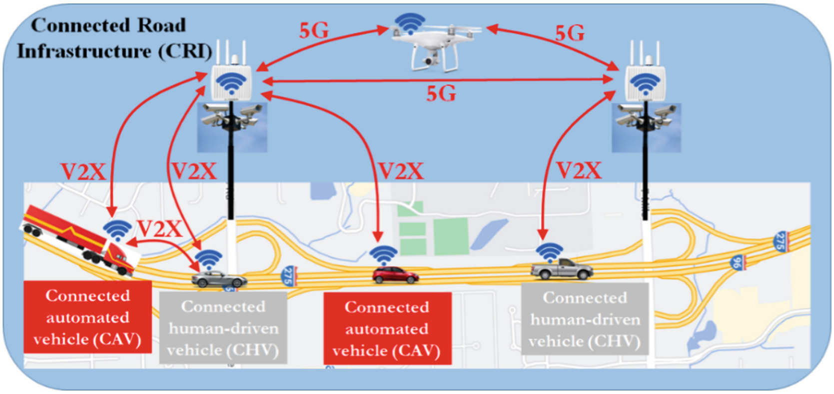

Fig. 3. Physical layout of the connected road infrastructure (CRI) supporting connected automated vehicles (CAVs) on highway I-275

passing human-driven vehicles, some of whom are equipped with V2X communication devices making them connected human-driven vehicles (CHVs). To minimize latency camera data will be fused with V2X data using edge computing on road-side units provided by Commsignia. As even the trajectory of a single CHV can provide prediction, this methodology will be able to accommodate different penetration levels of connectivity. The established CRI is able to communicate lane specific real time traffic predictions to the passing CAVs via V2X, enabling CAVs to select their lanes and longitudinal speed in order to maximize their efficiency.

Real-world traffic data collected on highway I-275 can also be used offline to design the connectivity-enhanced controllers while utilizing high fidelity vehicle models. This allows us to optimize the longitudinal controllers (engine, transmission, and brake) as well as the lane selection algorithms before implementing them on real hardware. Following such virtual development, we will utilize a Navistar class-8 connected automated truck, developed within DOE's Supertruck program, which is equipped with a real time controller giving access to the states of the engine, transmission, brakes, etc. Integrating the real time controller with a V2X onboard unit, we will make the truck capable of utilizing traffic predictions by the V2X road-side units at the Navistar Proving Ground. This will allow us to test the proposed algorithms in a safe environment. Finally, the truck will be tested in the real world on highway I-275 utilizing the real time lane specific traffic predictions provided by the deployed CRI. The developed technologies will be extended to trucks with higher level of automation with the help of Plus.ai and to different vehicle classes with help of General Motors enabling the team to evaluate the efficiency improvements of CAVs across a variety of vehicles with different drive types.

2.8 Improving the Energy Efficiency of Connected and Automated Vehicles: Results from ARPA-E's NEXTCAR Program

Marina Sofos, Department of Energy ARPA-E

The U.S. Department of Energy's Advanced Research Project Agency–Energy (ARPA-E) developed and initiated the NEXT-Generation Energy Technologies for Connected and Automated on-Road Vehicles (NEXTCAR) Program in 2016 with the aim of utilizing connectivity and SAE L1-L3 vehicle automation to achieve a 20% savings in the energy consumption of conventional and hybrid electric cars and trucks. Under the NEXTCAR Program, eleven individually awarded project teams, in collaboration with 13 OEMs, suppliers and partners, developed and implemented new advanced vehicle dynamic and powertrain control (VD&PT) technologies utilizing 2016–2017 L0 baseline vehicles.

The first part of this talk included an overview of the achievements of the NEXTCAR Program for each of the technologies developed and evaluated on light-duty and medium-duty vehicle applications (a sub-set of 9 projects). Adding functionality to existing advanced driver-assistance systems (ADAS) integrated into L1-L3 vehicles allowed for readily attainable energy efficiency improvements of 20% for a range of vehicle propulsion technologies, including internal combustion engine vehicles (ICEs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). Furthermore, it was shown that real-time powertrain optimization is facilitated by information obtained via connectivity across a range of time-scales. Results also showed a strong trade-off between elapsed trip-time and energy expenditure for typical vehicle operation. Finally, the power consumption of the sensing and computational systems required for connected and automated vehicle operation constitutes a major parasitic load (i.e. more than 1 kWe for each vehicle under the NEXTCAR Program) that needs to be considered in future vehicle designs.

The second part of this talk gave a preview of the second phase of the NEXTCAR Program that launched in 2021. Phase II builds on the goals of the original Program with a specific focus on light-duty passenger vehicles, a 30% reduction in energy consumption, and taking vehicles to Level 4 of automation, where a vehicle is able to perform all driving operations on its own with optional human override. The overall objective being to develop technologies (including those developed under the original Program) that will address potential runaway energy usage caused by higher levels of automation.

3 Conclusions

Automation technologies have long been promoted for their benefits in terms of improving safety and convenience for the end-user. However, it is also starting to become well understood that automation can decrease the barrier to mobility and the increased accessibility may be followed by an increase in travel demand which will yield higher annual vehicles miles traveled (VMT). Therefore, it is imperative to consider the energy efficiency of automated vehicles in order to counteract the potential increase in VMT they may cause.

The first overarching conclusion drawn from the presentations and the open panel discussions relates to need for policy and regulations to be developed and adopted to ensure that CAVs are designed for energy efficiency. Existing efficiency and emission regulations are not sufficient to capture the effects of CAVs and CAVs are not guaranteed to reduce emissions per VMT without conscience automaker design choices. Additionally, for the reasons stated above, increased in VMT are expected with increasing penetration of automation technologies and without intervention, there is little reason for automotive manufacturers to ensure energy efficiency of vehicles remains as high as possible or that increases to VMT do not lead to negative externalities in excess of any benefits from automation.

The second overarching conclusion drawn from the presentations and the open panel discussions relates to balancing the individual vehicle-level efficiency again system level efficiency improvements which is more desirable. An individual vehicle can achieve a hyper-localized maximum energy-efficiency. Correspondingly, the deployment of several of these highly efficient AVs should increase the energy efficiency of the overall system network, given all other variables remain constant. The reality though can be much different, given that AVs may not act like human-driven vehicles [21, 22] and as such their driving behavior may cause localized increase in traffic congestion. Thus, while the individual vehicle level efficiency is improved, the overall transportation system level energy efficiency can be degraded. Balancing, or potentially sacrificing individual vehicle-level energy efficiency may ultimately achieve a higher total system-level energy efficiency if traffic congestion can be mitigated.

The third overarching conclusion drawn from the presentations and the open panel discussions relates to balancing vehicle energy-efficiency and safety. Vehicle automation technologies have come a long way to improve safety and it is conceivable that in the far future, a significant portion of physical present-day vehicle safety requirements will be “virtualized” or “internalized” in the deepest layers of the operating logic of AVs. This will allow vehicles to be optimized for light-weighting and aerodynamic efficiency which will in-turn improve the vehicle energy-efficiency. For the near future, there will always be the question of when will safety in AVs reach the point to where we can downsize or eliminate certain crash-safety features (heavy sub-frames, large crumple zones, high should er lines, etc.) An additional point of consideration that requires striking the same balance and falls outside the vehicle relates to the safe following distance of two vehicles. In the case of co-operative and adaptive cruise control (CACC), decreased headway time can decrease the aerodynamic drag however, it can also significantly affect vehicle safety as the required stopping distance is violated. Ultimately, automation technologies will enhance safety and due consideration must be given as to how, where and if, vehicle safety is compromised in the name of vehicle energy-efficiency.

4 Next Steps

The Efficiency Town Hall showed the need for both further research and for new regulatory actions. Significantly more research is needed into how highly automated (L4/5) vehicles will affect traffic patterns and travel demand. Research is also need into what parts of automation (decreased cost of travel time, or changes in ownership models) will lead to these changes, as the policy levers to mitigate undesirable results may differ, depending on underlying causes. More research is also needed into how AVs both will and could affect transit demand. Panelists agreed that decreased transit demand would be an undesirable outcome, but research suggests that this outcome is not guaranteed. More research is needed into AV and transit interactions.

While new regulations are necessary to ensure AVs are designed for energy efficiency, more work is necessary to determine what these regulations should be, how they would even test energy efficiency and how they would balance individual vehicle performance vs. systemic effects on traffic and energy consumption. Significantly more research is needed into AV fuel economy testing, real world driving patterns and AV effects on traffic, as well as how lessons learned from simulations and physical studies can be applied in a regulatory space.

Finally, both more research and policy discussions are needed into the subject of crashworthiness of highly AVs. Vehicle light weighting represents an enormous opportunity to reduce energy usage and vehicle cost, but can only be done when AVs are "safe enough". Little agreement exists on where this point is and whether it is achievable only in purely autonomous environments, or if it can be achieved in mixed, AV and human, road systems.

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