U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0002163
on
Energy-Efficient Technologies for Automated Vehicles (AVs)

Objective

The Advanced Research Projects Agency – Energy (ARPA-E) of the US Department of Energy is seeking information concerning the current state and future development of automotive technologies that can improve the energy efficiency of fully automated vehicles (AVs).

THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI. This RFI is not seeking or accepting applications for financial assistance, and a response to this RFI will not be viewed as a binding commitment to develop or pursue the ideas discussed. No material submitted for review will be returned.

Please carefully review the **REQUEST FOR INFORMATION (RFI) GUIDELINES** below and note in particular: the information you provide will be used by ARPA-E solely for program planning, without attribution. ARPA-E will not publish a public compendium of each response received. ARPA-E has no obligation to respond to those who submit comments, or to provide any feedback on any decision made based on the responses received. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this RFI. **Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential**.

Energy Impact and Motivation

The US Energy Information Administration reports[1] that transportation accounts for 28% of all energy consumed in the United States, and the automotive sector is responsible for 82% of transportation energy usage – thus, 23% of total energy use in the US. The efficient and safe movement of passengers, goods, and services is of paramount importance to the US economy. As a part of its ongoing program funding portfolio since 2009, ARPA-E has supported the research, development, and commercialization of a range of technologies designed to reduce the energy burden of automotive transportation.

For many years, the automotive industry has been developing and implementing a range of vehicle energy efficiency technologies, including engine downsizing and boosting, vehicle light-weighting, aerodynamic improvements, rolling resistance reduction, engine efficiency improvements, waste heat recovery, auxiliary and parasitic load reduction, transmission improvements, hybridization, and electrification. Over the past several years, there has been an increasing number of new fully electric vehicle models introduced (EVs), although current adoption rates in the US new vehicle market are below 3%[2]. It is clear that for the next decade or more, the new vehicle market will continue to constitute a mix of propulsion technologies, with EVs and potentially hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) garnering an increasing market share over time.

Automotive transportation is on the verge of a further significant disruption through the development and deployment of advanced automated driving systems and automated vehicles (AVs). AVs have the potential to reduce future automotive transportation energy demands significantly, through the deployment at scale of intrinsically safe, down-sized and lighter-weight fully automated vehicles with high efficiency powertrains. In the absence of significant vehicle down-sizing and down-weighting, however, there is the potential for a significant increase in the energy usage of the future AV fleet, if the total vehicle fleet vehicle miles traveled (VMT) increases dramatically[3]. The implementation of energy-efficient, down-sized (or 'right-sized') AVs and powertrains is contingent upon those vehicles

[1] https://www.eia.gov/energyexplained/?page=us_energy_transportation
[2] https://afdc.energy.gov/data/10567
[3] See for example, Brown A., Gonder J., Repac B. (2014) An Analysis of Possible Energy Impacts of Automated Vehicles. In: Meyer G., Beiker S. (eds) Road Vehicle Automation. Lecture Notes in Mobility. Springer.

being proven to exceed some pre-determined level of safety such that the general car-using public accepts them as sufficiently safe[4]. To this end, in 2018 the US Department of Transportation (DOT) published an assessment of the development of AVs, entitled "Automated Vehicles 3.0 Preparing for the Future of Transportation"[5].

In 2016, ARPA-E initiated the NEXT-Generation Energy Technologies for Connected and Automated on-Road Vehicles (NEXTCAR) Program[6], a $35 million R&D program aimed at utilizing vehicle connectivity and automation (at the SAE J3016 L1-L3 levels)[7] to produce a 20% improvement in the energy efficiency of conventional and hybrid electric cars and trucks. ARPA-E, as an energy research and development funding agency, is interested in technologies that build on the NEXTCAR Program and in supporting the development of automotive energy efficiency technologies that can reduce the energy consumption of AVs when they are deployed at scale in the US vehicle fleet. Under the ARPA-E NEXTCAR Program (2017-2020), 11 individual project teams – spanning light-duty (7), medium-duty (2) and heavy-duty (2) vehicle applications – have developed and implemented new advanced vehicle dynamic and powertrain control technologies that improve the energy efficiency of 2016-2017 baseline (L0) vehicles. In a number of cases, the fuel- or energy-efficiency of the NEXTCAR vehicles have been improved by an aggregate of 20% or more. These new energy-efficiency technologies employ a combination of vehicle connectivity (that provides a preview and characteristics of the upcoming route, indications of traffic density and speed, signal phase and timing, etc.) and L1-L3 levels of vehicle automation (to facilitate cooperative adaptive cruise control, speed harmonization, eco-approach and departure, and platooning etc.) to achieve their fuel and energy efficiency gains. These gains have been obtained for a range of powertrain configurations in conventional and hybrid electric vehicles, and for a variety of vehicle duty cycles, driving operations, and driving maneuvers.

[4] The trucking industry could also see significant disruption from AV and automated driving system development, and many observers posit that heavy-duty AVs will be widely deployed sooner than automated passenger cars due to the compelling economic motivation behind truck automation (through removing the requirement for a driver, or at least reducing driver workload). For the purposes of this RFI, where AVs are mentioned, they should be considered to include light-, medium- and heavy-duty vehicles, as appropriate.
[5] https://www.transportation.gov/av/3
[6] https://arpa-e.energy.gov/?q=arpa-e-programs/nextcar
[7] https://www.sae.org/standards/content/j3016_201401/

Among the fuel- and energy-efficient vehicle technologies that have been effectively implemented at the L1-L3 levels of automation in the NEXTCAR Program are:

- vehicle eco-routing,
- eco-driving,
- the use of preview or look-ahead information for such maneuvers as traffic intersection eco-approach and departure,
- drive-cycle smoothing,
- real-time hybrid energy flow optimization, including the real-time control and optimization of internal combustion engine (ICE) operation, exhaust after-treatment, electrification sub-system (motors, inverters and batteries), and auxiliary loads (such as HVAC), and
- platooning (primarily in heavy-duty truck applications).

A further consideration in the application of L1-L3 vehicle automation technologies is that there is a wide range of timescales of look-ahead or preview data that is useful and necessary for vehicle efficiency optimization, ranging from seconds to minutes to hours of pertinent information. This information includes the actions of vehicles immediately ahead in traffic, the behavior of other surrounding traffic, the phasing and timing of upcoming traffic signals, weather and environmental conditions on the vehicle's route, and an indication of congestion along the chosen route. The synergistic interaction of look-ahead data and real-time HEV power flow optimization has also been facilitated by L1-L3 automation and vehicle connectivity (for a range of HEV architectures).

It is apparent from both simulation studies and actual conventional (L0) vehicle testing that there exists a strong trade-off between elapsed trip-time (travel time) and energy expenditure for the operation of a vehicle between any origin and destination. It has been found in the NEXTCAR Program that in many cases allowing a small increase in trip-time can result in appreciable vehicle energy savings for L1-L3 vehicles too. It is of interest to ARPA-E to know whether trip-time requirements may be relaxed in the operation of future L4-L5 AVs – in the absence of a human driver, will the vehicle occupants not notice small increases in trip-time or travel time that can result in appreciable energy savings for a given trip?

Energy-efficient Technologies for AVs

ARPA-E is interested in the development, application, and ultimate commercialization of energy-efficient vehicle technologies beyond those developed under NEXTCAR. Specifically, ARPA-E is interested in those technologies that utilize connectivity (including vehicle-to-vehicle or V2V, vehicle-to-infrastructure or V2I, and vehicle-to-everything or V2X) and L4-L5 automation to obtain significant further energy efficiency improvements, beyond those achievable and already obtained using L1-L3 automation. While there are a number of infrastructure- or roadway-based energy-efficiency technologies that could augment future vehicle (or fleet) energy efficiency, for the purposes of this RFI, ARPA-E is solely interested in connectivity- and automation-enabled vehicle-based technologies. Further, while cooperative vehicle behavior at the largest scales, or transportation system optimization or fleet management, are worthy energy efficiency technologies in their own right, ARPA-E is solely interested in the control and optimization of the behavior of individual (or "ego") vehicles, or the interaction of those individual vehicles in small, ad-hoc groupings.

Regarding connectivity, it is assumed for the purposes of this RFI that a range of vehicle connectivity technologies will be available for or on future vehicles, including suitable V2V and vehicle-to-cloud (V2C) hardware and software (this may include dedicated short range communication or DSRC and 5G connectivity systems). Of interest to a study of future vehicle efficiency is an assessment of **what information is needed to obtain additional vehicle energy efficiency improvements and what useful information will be available in real-time on future vehicles**. Future L4-L5 capable vehicles will also experience significant additional energy consumption beyond the energy required for propulsion due to their enhanced sensing, computation, and communication requirements. To operate and perform safely and adequately, AVs will require the use of a multitude of additional on-board electrical and electronic hardware including sensors, actuators, and computational hardware, as well as the required firmware and software. This hardware and software will allow for machine vision, data fusion, full (V2X) connectivity, mapping, localization, routing, path planning, decision making capability, logic, vehicle dynamic control, and artificial intelligence capability (presumably to include machine learning). The required hardware and accompanying software will reside in a range of vehicle components, sub-systems, and systems with capabilities far beyond those required today for L0 vehicles – all of which will be required to work effectively and reliably in concert to give those vehicle their automated driving capability. These systems will operate on a wide range of timescales, and will require information with look-ahead or preview from milliseconds, to seconds, to minutes and potentially hours. For effective, safe operation an AV will be required to have complete knowledge of everything of consequence around itself, including all obstacles, vehicles, and road infrastructure over a broad range of length-scales, too.

To assess the true energy consumption of future AVs (designated as the total energy required to perform some useful function, such as driving across some relevant driving cycle or route, or to perform a certain set of driving maneuvers, in units such as passenger miles per gallon gasoline equivalent, or kWh/mile, or energy used per ton-mile of freight transported, as appropriate), the total net energy consumed by an individual vehicle must be considered. The total primary energy budget for that vehicle must be taken into account: this includes the motive power required to move the vehicle and its occupants and/or goods from the designated origin to the final destination; the energy required to provide the full on-board electrical energy used for sensing, computation, and communication; as well as the total off-board energy required for the operation of that same vehicle (including for communication and cloud-based computation, for example). Significant reductions in the energy consumption of both the on-board and off-board computing for L4-L5 AVs will likely occur in future automotive development, and the energy efficiency improvements that ARPA-E seeks are in addition to, and beyond those likely improvements in sensing, computation, and communication.

In order to assess the true advantage that any particular energy efficiency technology offers for future AVs, a full analysis of the baseline vehicle primary energy consumption or efficiency must be undertaken in each case[8], and the effect of different vehicle driving cycles, vehicle operation, vehicle vocation, and variable rates of penetration of the developed technologies on the net vehicle energy efficiency must all be considered.

[8] For the NEXTCAR Program, for each project the baseline vehicle was taken to be a comparable, unmodified MY2016 or 2017 (L0) vehicle.

The Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E's consideration to inform the possible formulation of future research, development, and commercialization programs intended to reduce the energy burden of future automotive transportation, specifically with regard to the deployment of high-efficiency AVs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI on a non-attribution basis. This RFI provides the broader research and development community with an opportunity to contribute information, views and opinions regarding the state of the art and the future development of highly energy-efficient vehicle technologies for L4-L5 AVs. Based on the input provided in response to this RFI and other considerations, ARPA-E may decide to issue a FOA. If a FOA is published, it will be issued under a new FOA number. No FOA exists at this time. ARPA-E reserves the right to not issue a FOA in this area.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop or pursue any project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI. No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this RFI. All responses provided will be taken into consideration, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the e-mail address ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on September 16, 2019.** ARPA-E will not review or consider comments submitted by other means. Emails should conform to the following guidelines:

- Please insert "Response for RFI for FOA DE-FOA-0002163" in the subject line of your email, and include your name, title, organization, type of organization (*e.g*. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), *etc*.), email address, telephone number, and a brief statement of the area of expertise of your organization in the body of your email.

- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Please include your name, your organization name and "Response for RFI for FOA DE-FOA-0002163" at the top of the first page of your PDF submission.
- Responders are strongly encouraged to include data and quantitative information as appropriate in their responses.

ARPA-E is interested in finding out about energy-efficient technologies that can be applied to the control and operation of fully automated vehicles (highway-capable SAE J3016 L4 and/or L5 vehicles that meet all applicable Federal Motor Vehicle Safety Standards), so as to ensure that the full energy efficiency potential of these vehicles can ultimately be realized. **Specifically, ARPA-E is interested in the development of technologies that can improve the energy efficiency (and/or fuel efficiency) of AVs with full L4 and L5 AV driving capabilities.** Technologies or concepts that ARPA-E is interested in finding out in response to this RFI include:

- For a given vehicle powertrain configuration (which may include conventional ICE, hybrid, plug-in hybrid, battery electric, or fuel cell powertrains), what emerging vehicle dynamic and/or powertrain control technologies are there that can improve the net energy efficiency of L4-L5 AVs?
- Is an energy efficiency increase of 30% for an L4-L5 vehicle over a comparable L1-L3 vehicle feasible?
- What real-time information (obtained on-board or off-board via connectivity) is useful and/or required for L4-L5 vehicles to improve their energy efficiency to the maximum extent possible? How can this information be obtained and/or be made available to individual vehicles (through V2X connectivity)?
- Are there any emerging cooperative vehicle behaviors that can improve the energy efficiency of AVs? Are there any emerging infrastructure-based connectivity or automation technologies (i.e.

technologies that do not reside on individual vehicles) that can further improve the energy efficiency of AVs?

- What amount of on-board versus off-board computation is required for the control and optimization of future AVs? How can the total on-board and off-board energy requirements for vehicle sensing, computation, and communication be minimized?

For the purposes of this RFI, ARPA-E is interested in technologies that are applicable to one or more of light, medium, or heavy-duty vehicle applications. It is anticipated that the energy-efficient vehicle technologies recommended in response to this RFI will be predominantly software-based (and potentially open-source), scalable, and adhere to industry best practices, including functional safety requirements. ARPA-E is interested in information and/or insights on both existing and emerging technologies in AV energy efficiency at high levels of automation, across a range of vehicle applications while meeting all prevailing FMVSS standards.

Further Questions:
ARPA-E encourages responses that further address any subset of the following questions of relevance to the respondent and encourages the inclusion of references to important supplementary information.

- Aside from the AV control technologies discussed above (eco-routing, eco-driving, eco-approach and departure, drive-cycle smoothing, real time hybrid energy flow optimization and platooning), what other specific energy-efficiency technologies might be applicable to the operation of L4-L5 AVs (including ego vehicles or small cohorts)?
- What AV energy efficiency technologies (predominantly vehicle-based) require further development?
- What capabilities are required by those organizations seeking to develop these technologies?
- What capabilities does the respondent’s organization have? What capabilities would an ideal team have in order to research, develop, and ultimately commercialize, these AV energy efficiency technologies?

Areas that are very important for AV development but that are specifically **NOT OF INTEREST** for this particular RFI include:

- Specific vehicle safety technologies (beyond those required to optimize vehicle energy efficiency as discussed above),
- Cybersecurity,
- Vehicle-to-grid (V2G) technologies,
- Component development or testing, except where that testing is in the context of measuring the energy efficiency of AVs,
- Policy considerations of AVs and their deployment,
- Regulation or regulatory considerations of AVs and their deployment,
- Economic considerations (beyond the cost of technology development),
- Human behavior (beyond AV operating considerations such as an analysis of travel time or trip-time versus energy efficiency),
- Methods to promote vehicle sharing or to increase vehicle occupancy rates, and/or
- Ethical or moral considerations of AVs and their deployment.