NEXT-Generation Energy Technologies for Connected and Automated on-Road-vehicles (NEXTCAR) Program Overview

B. PROGRAM OVERVIEW

1. SUMMARY

The ARPA-E NEXT-Generation Energy Technologies for Connected and Automated on-Road Vehicles (NEXTCAR) Program seeks to fund the development of new and emerging vehicle dynamic and powertrain (VD&PT) control technologies that can reduce the energy consumption of future vehicles through the use of connectivity and vehicle automation. Potential vehicle energy improvement technologies may include, but are not limited to, advanced technologies and concepts relating to full vehicle dynamic control, powertrain control, improved vehicle and powertrain operation through the automation of vehicle dynamics control functions, and improved control and optimization facilitated by connectivity. These improvements will include the reduction of the fuel and/or energy consumed by future individual vehicles undergoing either human operation or semi- or fully-automated operation, either in isolation or in cooperation with other vehicles. Vehicle connectivity and automated operation hold significant promise to improve safety by reducing vehicle accidents and traffic fatalities in the US, but the full energy efficiency improvements enabled by the adoption of these technologies have not yet been tapped. Reducing the energy intensity of automotive transportation aligns directly with the ARPA-E mission areas of reducing energy imports, improving the efficiency of energy usage and reducing energy-related emissions, while promoting US innovation and competitiveness.

The NEXTCAR Program seeks to fund the development of new VD&PT control technologies for reducing the energy (or fuel) consumption of Light-Duty (LD), Medium-Duty (MD) and Heavy-Duty (HD) on-road vehicles. Future fuel and emissions standards such as Corporate Average Fuel Economy (CAFE) standards[1] for LD vehicles and NHTSA/EPA Phase 2 fuel efficiency and GHG emissions standards[2] for MD and HD vehicles will require substantial fuel efficiency improvements in the vehicle fleet. (*An explanation of a number of the terms, concepts and acronyms that will be used in this FOA is given in Appendix 1)*.

A large portion of future expected fuel efficiency improvements for all LD, MD and HD vehicles will be achieved through the commercialization and implementation of a mix of well-established fuel 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, electrification and hybridization. Vehicle fuel economy testing for regulatory purposes does not yet adequately take into account real-world (or "off-cycle") driving behavior or the potential efficiency advantages offered by vehicle connectivity or automation, or by cooperative vehicle operation. The energy efficiency improvements that the NEXTCAR Program seeks are in addition to, and beyond, any currently expected future vehicle fleet fuel efficiency improvements that will be required or driven by Federal or State regulations (CAFE and NHTSA/EPA Phase 2 fuel efficiency standards) [2].

The ARPA-E NEXTCAR Program seeks transformative technological solutions that will enable at least an additional 20% reduction in the energy consumption of future connected and automated vehicles (CAVs), compared to vehicles without these VD&PT control technologies. For the purposes of this Program, the technologies to be developed will be required to demonstrate a 20% reduction in energy consumption when implemented on a 2016 baseline vehicle. In fact, a reduction of 20% in the fuel consumption of the LD vehicle fleet in 2016 alone would result in a reduction of US primary energy consumption by 3.0 quads and a reduction of 0.2 gigatons of CO_2 emissions per year. The technologies contemplated in this Program include solutions that consider powertrain optimization as a part of the vehicle fuel or energy efficiency improvements of future CAVs. Solutions that only take into account vehicle-level longitudinal (or vehicle dynamic) control or driver behavior optimization without regard for optimized powertrain operation are unlikely to achieve the energy efficiency goals sought by this Program. *In essence, the co-optimization of vehicle-level (vehicle dynamic) and powertrain-level operations is sought in order to minimize the energy consumption of future vehicles.* It is expected that Applicant teams may be composed of researchers and developers from a broad range of disciplines spanning automotive vehicle control, powertrain control and transportation analytics, to allow for the development of these advanced energy efficiency optimization technologies for future CAVs. ARPA-E is interested specifically in the ultimate commercialization of the

[1] http://www.nhtsa.gov/fuel-economy

technologies that it supports, because it is recognized that commercial implementation is essential to achieving the energy efficiency potential of these technologies.

2. BACKGROUND

Over the next few decades the automotive vehicle fleet (LD, MD and HD vehicles) will remain predominantly powered by internal combustion engines (ICVs), while the numbers of hybrid electric vehicles (HEVs), fuel cell electric vehicles (FCVs) and battery electric vehicles (BEVs)[2] will continue to increase. The fuels used will presumably continue to include gasoline, diesel fuel, electricity (for BEVs and plug-in HEVs, or PHEVs), hydrogen, natural gas and biofuels. For the purposes of the ARPA-E NEXTCAR Program, no preference is expressed for any particular fuel or energy source for propulsion. Well-established methods of reducing individual vehicle fuel or energy consumption, such as hybridization, electrification, fuel shifting or alternative fuel substitution, weight reduction, aerodynamic drag reduction, rolling resistance improvements, waste energy recovery and parasitic load and friction reduction, will certainly be widely used by the automotive industry to achieve future required LD, MD and HD vehicle fuel efficiency standards; however their further development or demonstration is specifically <u>not</u> of interest in this Program. Also, the emphasis of the NEXTCAR Program is on reducing the energy consumption of individual vehicles, and not that of the overall transportation system (through such means as transportation system network optimization) or transportation mode shifting.[3]

The focus of the NEXTCAR Program is on developing vehicle and powertrain controls that use increased information available via connectivity to reduce individual vehicle fuel or energy consumption, with or without the intervention of a human driver.

A range of improved powertrain control techniques will be made possible in the near future by the increase in useful information available on-board vehicles through connectivity such as V2V (e.g. look-ahead data), although it is clear that certain further improvements in powertrain controls will occur even without the use of this additional technology. It is envisioned that in the future, the total reduction in energy consumption of an individual vehicle will be due to some combination of

- improved on-board powertrain controls (with improved real or virtual sensing and/or the use of V2V, V2I and V2X connectivity and real-time optimization),
- improved vehicle-level dynamic controls (using real or virtual sensing and/or the use of V2V, V2I and V2X connectivity),
- the utilization of new control system inputs from external sources, external optimization, or surrounding collaborating vehicles, and
- ultimately, the ability to operate in a fully automated mode, thereby removing the effect of the human driver from the vehicle and powertrain control systems.

From a control point of view, vehicles currently operate in isolation as a collection of single ‘selfish’ entities, even in dense traffic. Developments in connectivity and automation will allow vehicles in the future to operate in a range of cooperative modes with other surrounding vehicles. While such cooperative behavior has been the subject of much recent research, the full potential of improved powertrain control (as opposed to improved vehicle longitudinal or dynamic control) on the resultant composite energy efficiency of a cohort of vehicles undertaking cooperative vehicle behavior[4] has not yet been fully explored. *The focus of the ARPA-E NEXTCAR Program is on increasing the energy efficiency of each individual vehicle in the automotive fleet, through the improvement of vehicle dynamic and powertrain (VD&PT) control, by utilizing emerging technologies and strategies in sensing, communications, information, decision-making, control and automation.*

As noted above, future vehicle fuel economy standards already promulgated will by necessity result in the reduction of energy consumption by individual vehicles in the vehicle fleet. Noting that transportation currently accounts for 28% of the US primary energy usage, the ARPA-E NEXTCAR Program is aimed at investigating technologies that may provide *additional* opportunities for vehicle energy efficiency improvements beyond the base case expected across the next two or three decades. The technologies proposed in the NEXTCAR Program are required to be capable of meeting the prevailing

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[2] See, for example, The Outlook for Energy: A View to 2040, ExxonMobil, 2016. Available from: http://cdn.exxonmobil.com/~/media/global/files/outlook-for-energy/2016/2016-outlook-for-energy.pdf

[3] ARPA-E has previously funded technology solutions to minimize energy consumption in America’s surface transportation network <u>without</u> having to improve current infrastructure or vehicle efficiency via the *TRANSNET* Program. https://arpa-e-foa.energy.gov/Default.aspx?Archive=1#FoaIda65ecb06-eb2c-43e5-8b96-bd902efff4e8

[4] Cooperative vehicle behavior requires connectivity and at least partial automation capability.

regulated vehicle emissions levels at the expected time of their commercial deployment, and must ultimately result in equivalent (or at least acceptable) vehicle performance, utility, total cost of ownership and operation, functionality, drivability, power and energy storage density, reliability and maintainability.

2.1 THE CURRENT STATE OF THE ART OF AUTOMOTIVE VEHICLE OPERATION AND CONTROL

The most common LD, MD and HD vehicles today (at vehicle automation Level 0 – with no automated vehicle control features) are mostly either ICVs, or are HEVs, PHEVs or BEVs. These vehicles rely on a human driver to provide active high-level dynamic control of the vehicle through the actuation of accelerator pedal, brake pedal, and steering input (and sometimes gear selection). In turn the actual instantaneous powertrain operation is thereafter controlled by an electronic engine or powertrain controller that ultimately dictates the real-time powertrain power output, powertrain output speed, and by default, the vehicle fuel or energy efficiency and regulated gaseous exhaust emissions (if any). In L0 vehicles, the human driver relies on visual inputs of road and traffic conditions (and traffic signage and signals) and an innate requirement for instantaneous vehicle speed and power, to govern the most immediate selection of the vehicle dynamic commands (accelerator, brake and steering). Concurrently the driver utilizes visual input and sensations of displacement in 6 degrees of freedom (3 axes of displacement, yaw, pitch and roll, along with their resultant accelerations and rates of change of acceleration, or 'jerk') in an almost entirely reactive fashion to dictate any required modifications to the vehicle control inputs. External informational inputs, such as those derived from navigation systems, are normally used by the driver in an ad-hoc and advisory fashion.

Automated vehicle operation is viewed today predominantly as the ultimate vehicle safety enhancement, although the utility of automation in enhancing mobility and reducing environmental impacts has also been acknowledged. Fully automated vehicle operation will in the future allow for higher individual and collective vehicle driving speeds (and hence greater traffic throughput on existing roads) with vastly reduced collision and crash rates, and thereby free up the drivers' or occupants' time for other pursuits. Today, L1 vehicles (employing the automation of a single control actuator such as the accelerator in the case of adaptive cruise control, or ACC), L2 vehicles (two controls automated – ACC and steering for lane keeping, for example) and L3 vehicles (capable of automated operation but still requiring a human driver to take over full control if required) currently exist, and are anticipated to become the norm in the future. It is important to note the distinction between advanced driver assistance systems (ADAS) as implemented in L1, L2 and L3 vehicles, and fully automated operation (L4 vehicles) – the latter will require significantly higher levels of fidelity and bandwidth in sensor inputs, machine vision, connectivity, data fusion and higher levels of computation and real-time decision-making for the safe control of longitudinal and lateral vehicle dynamics alone. See Figures 1 and 2 for logic flow diagrams for L0 and L3-L4 vehicles, respectively.

L4 vehicles (fully automated and driverless) have the potential to lead to a significant reduction in individual vehicle energy usage as safety enhancements will ultimately allow for significant decreases in vehicle weight for the same vehicle functional utility. Conversely, as fully automated vehicle operation becomes the norm, total Vehicle Miles Traveled (VMT) by the automotive fleet has the potential to increase dramatically (the energy rebound effect), thereby offsetting much of the energy efficiency gain due to weight de-compounding on an individual vehicle basis[5]. For example, the reduction in energy intensity (classified as a positive energy outcome) by light-weighting and powertrain/vehicle size optimization is approximately equal to the increase in use intensity (classified as a negative energy outcome) caused by more travel[6]. *The optimization of the operation or energy efficiency of L4 vehicles is beyond the desired scope of the NEXTCAR Program, which emphasizes applications from L0 to L3 levels of automation.*

Due to well-established patterns of vehicle ownership, reliability and replacement, the incumbent LD vehicle fleet largely turns over in a 10 to 15-year time frame[6], thus requiring that for the next few decades at least, L4 vehicles will have to co-exist on the road with L0-L3 vehicles of higher vehicle weights and reduced levels of safe operation capability. This timeframe is also certainly consistent with the expected longevity of the internal combustion engine-equipped ICVs, HEVs and PHEVs, thus ensuring that at least part of the future fleet will continue to have fuel-consuming engines of varying power capabilities. The reduction of the energy consumption of the entire future vehicle fleet will contribute to our national energy security, economic security and climate change mitigation.

[5] Gonder et al. NREL Research and Thoughts on Connected and Automated Vehicle Energy Impacts. Remarks at EPA Mobile Sources Technical Review Subcommittee Meeting, December 2014. Available from: http://www.epa.gov/sites/production/files/2014-12/documents/gonder_120914.pdf

[6] http://www.rita.dot.gov/bts/. Available from: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_26.html_mfd

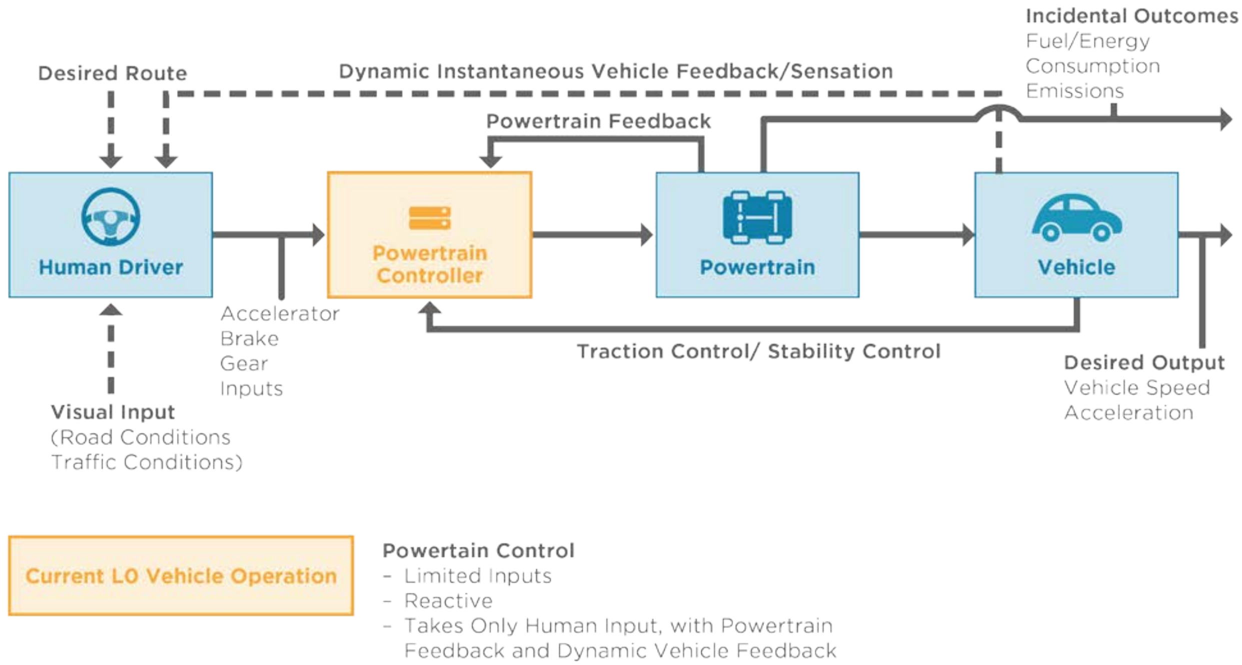

Figure 1: Vehicle dynamic and powertrain control and actuation logic flow diagram for a L0 vehicle.

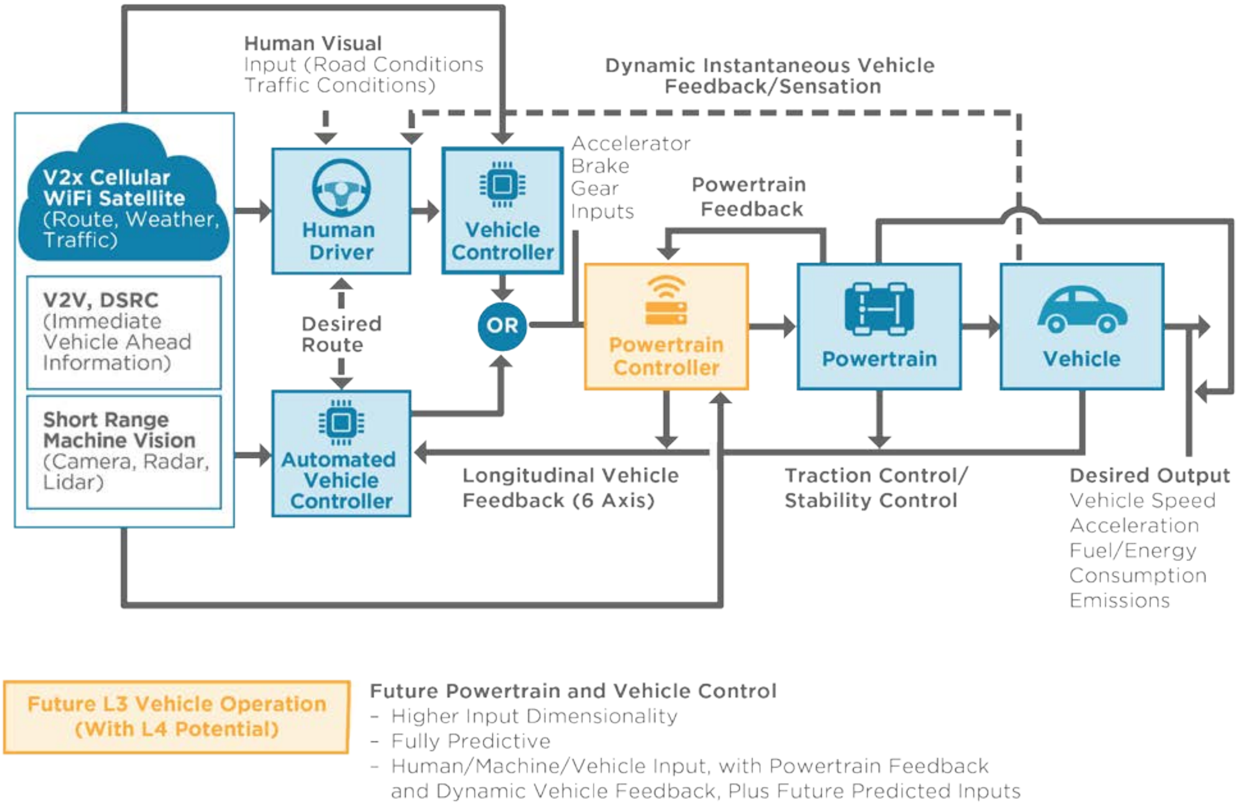

Figure 2: Vehicle dynamic and powertrain control and actuation logic flow diagram for future L3-L4 vehicles. Under the NEXTCAR Program, connectivity will allow the use of additional information inputs to the vehicle and powertrain controllers.

2.2 CURRENT TRENDS IN POWERTRAIN CONTROL

Conventional powertrain control at present is almost exclusively reactive and backward-looking, with limited provision for the incorporation of sensor-based feedback except for crude or indirect measures of combustion efficiency and/or exhaust emissions. As a result, powertrain operation is frequently rendered non-optimal with regard to fuel and energy consumption minimization, and considerable opportunity arises for energy efficiency optimization, with the required computation either performed on-board in real-time or on an off-line basis.

The advent of vehicle connectivity allows for the use of additional, exogenous inputs for improved real-time vehicle and powertrain control. In the near future, in addition to offering advanced levels of collision avoidance and crash prevention, V2V communications (such as DSRC) will facilitate extensive automated collaborative operation between neighboring vehicles – for platooning, cooperative ACC (CACC) and speed-harmonization for congestion mitigation, for example. This connectivity, and the resultant exchange of information, is mainly anticipated by the industry to be between vehicle controllers, as opposed to between powertrain controllers. V2I communications will further allow vehicles (and their on-board controllers) to interact with the road infrastructure, to allow for efficient traffic flows at intersections and traffic signals, for example. Untapped opportunities exist for the efficiency enhancement of future vehicles through optimization of powertrain operation, including real-time powertrain calibration and optimization via connectivity (that allows for over-the-air updates of off-line optimized control software and powertrain calibrations, for example). V2V communication, in addition, effectively equips each vehicle with foreknowledge or a preview of its own future actions, as DSRC gives immediate warnings of the actions and intentions of the vehicles directly ahead in traffic. This knowledge can potentially be used to create a specific time-based trajectory of optimized powertrain control references to minimize the fuel or energy consumption of each individual vehicle across some finite future time horizon, for example, in addition to providing optimal instantaneous vehicle speed (and acceleration) commands for L3 or L4 automation.

The creation or addition of additional high-value information that can be made available through V2X for use in powertrain control systems may also enable significantly higher individual vehicle efficiency through combustion optimization (in the case of ICVs or HEVs), energy storage optimization (in the case of HEVs and BEVs), and route optimization and optimized vehicle dynamic performance for all vehicles. For ICVs or HEVs, the addition of "perfect" information on fuel chemistry, engine and after-treatment conditions, weather and environmental conditions, traffic conditions ahead, and perhaps driver behavior (for example), could lead to meaningful enhancements in the energy efficiency of each and every vehicle under a range of operating conditions and use cases.

One promising enabling technology underlying future vehicle and powertrain control is the development of model-based control algorithms and systems – this will allow powertrain control to be fully predictive and forward-looking, and enhance the effect of real and virtual feedback, as well as utilizing a range of additional information available through connectivity. With this increased information, model-based control using real-time optimization has the potential for useful efficiency gains for individual vehicles, and hence by extension, the entire vehicle fleet. For example, connectivity might allow a vehicle to "know" with some certainty about its future operation across some planned route with respect to the anticipated profiles of acceleration, deceleration, braking (or regeneration) and grade climbing. This look-ahead or preview information can be used in conjunction with the vehicle and powertrain control models to optimize the vehicle energy efficiency over a portion of a trip, or indeed in the case of the availability of "perfect" information, over a full, extended trip. VD&PT control technologies that leverage this information, implemented on either a single vehicle basis, or across a cohort of cooperating vehicles, or even the entire vehicle fleet, could lead to significant fleet energy efficiency improvements.

2.3 REAL-WORLD OPERATION VS. REGULATORY DRIVE CYCLES

It is widely acknowledged that regulatory drive cycles used for statutory exhaust emissions and fuel economy measurements are not truly representative of real-world driving, particularly with respect to reproducing typical rates of acceleration and sustained cruise speeds. In fact, in 2005 the EPA conducted a study to compare real-world driving data from instrumented vehicles in Kansas City to the EPA drive cycles (the earliest of which were developed in the 1960s and 70s).[7] Results from this study concluded that the then relatively new US06 cycle (used since 2008 for fuel economy measurement) is a little too aggressive while the UDDS "city" cycle (used since 1972) is not aggressive enough as compared to actual driver behavior. Rather than develop new drive cycles that would quickly become outdated as driver behavior changed further, the EPA developed a modified weighting procedure to combine results from existing drive cycles to produce a representative average for apparent on-road fuel consumption. This weighting procedure was then reflected in the 2008 EPA 5-cycle approach currently used for fuel economy regulation.

While Federal drive cycles have not been modified in recent years even while vehicles have on average become significantly more powerful and are driven more aggressively, much research has been done to develop naturalistic drive cycles, often through a combination of real-world driving data and statistical analyses. For instance, Lee et al.[8] developed a process to characterize PHEV trip characteristics from a limited data set using a stochastic process and statistical analysis. Others have used comprehensive national data sets, such as the National Household Travel Survey (NHTS), or global positioning system (GPS) technology to collect large sets of real-world driving data from which to determine representative real-world operation. Earleywine et al.[9] took this approach and collected GPS data from 783 vehicles operating in Texas to evaluate real-world driving profiles and compare them against EPA drive cycles. They found that UDDS and HWFET cycles provide a limited representation of real world driving, primarily due to the more aggressive driving and higher accelerations evident in the real world. ARPA-E acknowledges the limitations of regulatory drive cycles in reflecting actual vehicle energy consumed under real-world driving operation and as a result *the NEXTCAR Program will utilize testing and validation over a more appropriate set of real-world driving and dynamic operational scenarios (see Section I.D of the FOA).*

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[7] U.S. Environmental Protection Agency, Fuel economy labeling of motor vehicle: revisions to improve calculation of fuel economy estimates, Office of Transportation and Air Quality, Report EPA420-R-06-017, 2006.

[8] Lee et al. Stochastic modeling for studies of real-world PHEV usage: driving schedule and daily temporal distributions, IEEE Transactions on Vehicular Technology, V.61 (4), 2011.

[9] Earleywine et al. Simulated fuel economy and performance of advanced hybrid electric and plug-in hybrid electric vehicles using in-use travel profiles, Vehicle Power and Propulsion Conference (VPPC), IEEE, 2010.

3. MOTIVATION

According to the EIA's Annual Energy Outlook 2015[10], in the United States the existing LD vehicle fleet of roughly 235 million vehicles will travel approximately 2,800 billion miles in calendar year 2016 at an average actual vehicle fuel consumption of 23.0 miles per gallon (mpg) gasoline equivalent. For regulatory compliance purposes the average new vehicle in model year (MY) 2016 will be assigned a CAFE after credits of 33.4 mpg, while their actual on-road, real-world fuel efficiency is projected to be 26.3 mpg. As previously discussed, the discrepancy between assigned (regulatory) fuel economy for CAFE purposes and the adjusted actual real-world fuel economy values are primarily due to the fact that vehicles are typically operated on the road by human drivers at higher speeds and loads (mainly due to higher rates of acceleration) than those covered in the laboratory regulatory cycles used for fuel efficiency determination. Moreover, it is not currently anticipated - due to typical industry and regulatory lead times - that future fuel economy regulations in the 2025 timeframe will take into account the potential benefits of emerging connectivity and automation technologies on individual vehicle fuel consumption. In other words, future testing for the purposes of regulation as currently anticipated is unlikely be capable of accounting for the fuel or energy consumption reductions that will be made possible through individual vehicles making use of connectivity for optimization, or through the effect of multiple vehicles employing automation to cooperate in their collaborative driving behavior for the purposes of reducing their collective fuel or energy efficiency.

As a consequence, it is assumed for the purposes of the NEXTCAR Program that any technology employing connectivity and automation that offers a 20% improvement in the energy efficiency of an individual MY 2016 vehicle today, will likewise offer a (roughly similar) 20% improvement in the energy efficiency of the comparable new vehicle in 2025, even if the future vehicle is significantly more efficient *ab initio,* as explained in Section I.B.2 of the FOA. The energy efficiency improvements to be achieved in this Program will be tested and validated over a range of real-world driving scenarios that are not explicitly captured in current (or future proposed) regulatory fuel efficiency tests (see Section I.D of the FOA).

Table 1: Fuel Cost and Technology Payback Analysis by Vehicle Class (VMT, fuel efficiency and fuel costs are notional and approximate).

	Vehicle Class		
	LD	**MD**	**HD**
VMT (mi/yr) (2015)	12,700	35,000	68,000
Fuel Efficiency (mpg) (2015)	27.0	10.0	5.3
Fuel Type	Gasoline	Diesel	Diesel
Fuel Cost ($/gallon) (2015)	$ 2.50	$ 2.50	$ 2.50
Fuel Cost ($/yr) (2015)	$ 1,176	$ 8,750	$ 32,075
20% reduction ($/yr) (2015)	$ 235	$ 1,750	$ 6,415
Current 3 year payback ($)	$ 706	$ 5,250	$ 19,245

Table 1 shows an analysis of vehicle annual fuel costs and the characteristic payback time for a notional advanced technology that offers a 20% reduction in vehicle energy consumption. Considering typical annual VMT by vehicle class, typical fuel consumption rates by vehicle class, and assuming a nominal $2.50 fuel cost per gallon for both gasoline and diesel fuel (roughly the 2015 calendar year average), it can be seen that a 20% energy consumption reduction for LD vehicles, over a 3-year period, results in a $706 energy cost reduction. The same analysis for MD and HD vehicles shows $5,250 and $19,245 fuel cost savings over 3 years respectively – which are both significantly higher than the LD case due to the much lower fuel efficiency of those vehicles and the far higher VMT rates that they undergo on an annualized basis. One conclusion of this analysis is that a nominal $1,000 incremental cost for an added technology that results in a 20% fuel consumption reduction in a LD vehicle incurs a 4.25-year payback period, while a $3,000 technology in HD vehicles is repaid in a mere 6 months of operation.

As previously discussed, the motivation for the development and implementation of vehicle connectivity and automation by the automotive industry has been up to this point primarily for road traffic safety considerations, and the ramifications of

[10] http://www.eia.gov/forecasts/aeo/

these technologies on vehicle or fleet energy consumption has not yet been fully understood or demonstrated. Table 2 shows a summary of recent work on the use of connectivity and automated operation in a number of different real-world operating scenarios with estimates of the resulting reductions in vehicle fuel or energy consumption. Note that Table 2 is not intended to provide a comprehensive review of the state-of-the-art but is provided solely for informational purposes. It should be acknowledged further that the US Department of Transportation (DOT) Applications for the Environment: Real-Time Information Synthesis (AERIS) Program[11] has funded and championed many of the vehicle efficiency studies in this area to date.

Table 2: Examples of vehicle efficiency studies aimed at fuel consumption reduction applicable to CAVs. In most cases, the energy consumption optimization was applied at the vehicle dynamic level with no direct control or coordinated optimization of the powertrain operation.

Reference (Study Type)	Technology or Application	Fuel Consumption or Energy Reduction Potential (%) Summary
Rakha[12] (Simulations)	Eco-routing (network-wide).	3.3% and 9.3% fuel consumption reduction with 4.8% and 3.2% increase in average travel time for Cleveland (OH) and Columbus (OH) networks, respectively.
Rakha[13] (Simulations)	Eco-cruise control (single vehicle).	9.7% fuel consumption reduction with 1.4% increase in travel time and 17.5% fuel consumption reduction with 7.9% increase in travel time for NYC-LA route.
Gonder[13] (Simulations)	Route-based control for HEVs.	2-4% reduction in fuel consumption.
Gonder et al.[14] (Simulations and Testing)	Effect of driver behavior on single vehicle fuel consumption.	30% fuel consumption difference between the most aggressive driver and an energy conscious driver in city driving conditions. 20% difference in highway conditions.
HomChaudhuri et al.[15] (Simulations)	Energy management of connected HEVs using a decentralized hierarchical control structure (two-level controller).	HEV fuel consumption improved from 32.4 mpg to 50.5 mpg (average of a group of 10 vehicles). Energy consumption reduction of 56%.
Mandava et al.[16] (Simulations)	Use of arterial velocity planning algorithms for providing dynamic speed advice to driver.	Energy saving potential of 12-14%.
Lammert et al.[17] (Testing)	Platooning effects on fuel consumption of Class 8 vehicles as a function of speeds, following distance and gross vehicle weight (GVW).	Leading truck fuel consumption savings were between 2.7% to 5.3%. Trailing vehicle fuel consumption savings ranged from 2.8% to 9.7%.

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[11] http://www.its.dot.gov/aeris/

[12] Rakha, H. Overview of VTTI's environmental connected vehicle research activities. Available from: http://www.its.dot.gov/aeris/pdf/12_VTTIsEnvironmentalConnectedVehicleResearchActivities.pdf

[13] Gonder, J. Route-based control for Hybrid Electric Vehicles, SAE 2008-01-1315, 2008.

[14] Gonder et al. Analyzing vehicle fuel saving opportunities through intelligent driver feedback, SAE2012-01-0494, 2012.

[15] HomChadhuri et al. Hierarchical control strategies for energy management of connected hybrid electric vehicles I urban roads, Transportation Research Part C, V.62, 2016.

[16] Mandava et al. Arterial velocity planning based on traffic signal information under light traffic conditions, IEEE Transactions on Intelligent Transportation Systems, 2009.

[17] Lammert et al. Effect of platooning on fuel consumption of class 8 vehicles over a range of speeds, following distances, and mass, SAE International Journal of Commercial Vehicles, V.7(2), 2014.

Ozatay et al.[18] (Simulations and Testing)	Dynamic Programming (DP) algorithm to provide optimal speed trajectory to a driver using traffic and geographical information.	12.6% and 7.4% fuel economy improvement in highway and city driving, respectively.
Ozatay et al.[19] (Simulations)	Generation of optimal velocity trajectory for a given road grade profile versus constant speed cruise control. Results obtained from an analytical solution matched with those from DP algorithm thus enabling real-time onboard implementation.	10.4% improvement in fuel economy by both solutions when compared to constant speed cruise control. Calculation times were 16.2s and 0.05s for DP and analytical solutions, respectively.
Qi et al.[20] (Simulations)	Real-time energy management for PHEVs using DP and Q-learning based blended real-time energy management system.	12% fuel consumption reduction as compared to binary mode control strategy, however 2.9% higher fuel consumption as compared to the DP solution.
Xia et al. [21] (Simulations and Testing)	Eco-approach using Signal Phase and Timing (SPaT).	An average of 14% fuel consumption reduction was achieved.
Barth et al.[22] (Simulations)	Eco-approach and departure at signalized intersections.	5-10% fuel consumption reduction at uncoordinated signal corridors. Coordinated corridors alone result in about 8% fuel savings with an additional 4-5% fuel savings from eco-approach and departure.
Wu et al. [23] (Simulations)	Optimal velocity trajectory is generated with the knowledge of vehicle location, roadway characteristics and real-time traffic information and used to determine battery charge depletion control.	10-15% fuel consumption reduction as compared to binary mode control strategy.

Table 2 above indicates the type of each study and whether the energy efficiency achieved for each individual technology was validated in Simulation or via real-world Testing (either on-road or on a chassis dynamometer) or both. As Sciarretta et al.[24] point out, there is a dearth of real-life test validation data for many proposed advanced vehicle energy efficiency strategies. Also, significant effort is needed to realize and implement these strategies in real-time on-board vehicles due to the complex nature of the control strategies required, and the real-time computational effort required. In many cases the controls problems have an innate multiple-input-multiple-output (MIMO) structure which is not amenable to closed-form solution. Dynamic programming (DP) algorithms have been proposed as a useful methodology to solve some of these complex real-time vehicle control and optimization problems, but these algorithms are not yet capable of allowing real-time predictions under the computational time constraints posed by city driving conditions. Sciarretta et al. have reviewed several analytical solutions for onboard vehicle dynamics optimization for eco-driving and reported a 14% reduction in energy consumption for a BEV. Similarly, onboard vehicle dynamics optimization of truck operation resulted in a fuel consumption

[18] Ozatay et al. Cloud-based velocity profile optimization for everyday driving: A dynamic-programming-based solution, IEEE Transaction on Intelligent Transportation Systems, V.15(6), 2014.

[19] Ozatay et al. Analytical solution to the minimum energy consumption based velocity profile optimization problem with variable road grade, 19th World Congress, The International Federation of Automatic Control, V.19(1), 2014.

[20] Qi et al. Novel blended real-time energy management strategy for plug-in hybrid electric vehicle commute trips, IEEE Transactions of Intelligent Transportation Systems, 2015.

[21] Xia et al. Field operational testing of Eco-approach technology at a fixed-time signalized intersection, IEEE Transactions of Intelligent Transportation Systems, 2012.

[22] Barth et al. Eco-approach and departure at signalized intersections: preliminary modeling results. Available from: http://www.its.dot.gov/aeris/pdf/UCR_eco-approach_final2.pdf

[23] Wu et al. Development and evaluation of an intelligent energy-management strategy for plug-in hybrid electric vehicles, IEEE Transactions of Intelligent Transportation Systems, 2014.

[24] Sciarretta et al. Optimal ecodriving control, IEEE Control Systems Magazine, October 2015.

reduction of up to 6% with a less than 2% penalty on the trip time through the use of online DP optimization. It must be noted that most often in these test cases, driver behavior is not modeled and hence is not taken into consideration in the optimization scenarios. As a result, many of the cases given above represent optimistic assessments of the achievable fuel consumption by assuming that the driver (human or automated) follows the optimal speed profiles exactly as generated by the optimization techniques (a known shortcoming of dynamometer-based driving and testing, for example).

Another significant technical gap that exists in this area is the co-optimization of vehicle dynamics and powertrain systems, which is an additional area of interest of this Program. It is envisioned that, as a part of the control system, a variety of useful additional *exogenous information* will be made available to vehicles through V2X connectivity, beyond that which is currently available. This additional information could include parameters such as traffic information (traffic density, route congestion, signal information etc.), topology (road curves, road grade etc.), weather (temperature, humidity etc.), road surface conditions (coefficient of friction etc.), fuel quality (heat of vaporization, knock resistance as indicated by octane number etc.) and others. A range of *endogenous information* is already available on-board vehicles, and this includes information such as powertrain states (engine state, battery state of charge, transmission states etc.), after-treatment states, fuel quality (in the case of flex-fuel vehicles), HVAC operation and other parasitic loads (available via real or virtual sensing) that is valuable for powertrain optimization. The combined use of these two types of information opens up a plethora of VD&PT optimization opportunities for real-time energy consumption and emissions reduction. The optimal velocity, torque and acceleration profiles as obtained by the 'higher-level' vehicle dynamic controller can be communicated to the 'lower-level' powertrain optimizer so that the latter can calculate the optimal reference set-points for fuel-system, air-handling, ignition, exhaust management, after-treatment, energy storage and electric drive sub-systems that can be met by the powertrain controller with minimal tracking error, to maximize the resultant vehicle energy efficiency. *ARPA-E sees a tremendous opportunity in this technical area that is currently void of any fully-deployed solution that utilizes cooperation across the vehicle longitudinal dynamics and powertrain optimization domains, utilizing connectivity for information and varying levels of automation for vehicle control.*

Early developmental examples of such vehicle- and powertrain-level cooperative solutions include the Bosch Electronic Horizon[25] and AVL Connected Powertrain™ [26]. For example, the Bosch Electronic Horizon, with the addition of limited exogenous information, predicts 5%, 6% and 8% CO_2 emissions reduction potentials for ICVs, HEVs and PHEVs, respectively, in real-world drive cycles using route and topographical information. In the case of ICVs, the energy consumption reduction is obtained from powertrain optimization purely using start-stop and coasting systems. In HEVs, the combustion engine and electric drive are co-optimized for further efficiency enhancements, including the optimization of regenerative braking strategies. An interesting example cited in Ref. 27 is that of eco-routing with and without diesel particulate filter (DPF) regeneration where the efficiency results can be different for the two scenarios as catalyst regeneration accounts for a significant penalty in fuel consumption. A similar approach whereby the powertrain operation is included within the energy efficiency optimization loop for the operation of a Chevrolet Volt PHEV can be found in the work of Gonder et al.[27]

Recently, ARPA-E released a Request for Information (RFI) on energy efficiency optimization for connected and automated vehicles[28]. Based on the responses received, there was a general consensus that the operation of L0-L3 vehicles with connectivity and "perfect" information for VD&PT control and optimization could lead to a 5-20% energy consumption reduction at the vehicle level. For L0-L3 vehicles, it was agreed further that advanced driving assistance systems (ADAS) and powertrain optimization with predictive features (using information obtained through both on-board sensing and external connectivity) would improve vehicle fuel or energy efficiency appreciably. The need for robust and adaptive algorithms for embedded vehicle and powertrain control technologies was also recognized in the responses.

It is further apparent that the time-scales for the information available via connectivity that is necessary for powertrain optimization may vary between vehicle and powertrain control sub-systems and the type of deployed CAV application. For example, a look-ahead time window of 5 to 15 seconds might be appropriate for the optimization of powertrain control while vehicle-level eco-routing would need a much longer time horizon (e.g., 5-15 minutes). Even at the powertrain level, there is

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[25] Bulander, R. Powertrain optimization using a comprehensive systems approach, 36th International Vienna Motor Symposium, 2015. Available from: http://www.bosch-presse.de/presseforum/download/BroschuereA5_Wiener_Motorensymposium_2015_EN.pdf

[26] Prenninger, P. Integrated open development platform. Available from: http://www.a3ps.at/site/sites/default/files/downloads/5_20141211_a3ps_workshop_prenninger_adas_overview_avl02.pdf

[27] Gonder et al. Connectivity-enhanced route selection and adaptive control for the Chevrolet Volt, 21st World Congress for Intelligent Transportation Systems, 2014. Available from: http://www.nrel.gov/docs/fy14osti/ 60960.pdf

[28] https://arpa-e-foa.energy.gov/Default.aspx?Archive=1#FoaId0853ef67-002d-4773-b11d-064b9168ae70

a multiplicity of time-scales, as the fuel system of an ICV has a characteristic response time-scale of milliseconds, while the air-handling dynamics (filling of a manifold, turbocharger and exhaust gas recirculation or EGR dynamics) display time-scales of 1-2 seconds or more. Exhaust catalytic after-treatment systems have even longer typical time-scales due to transient thermal and chemical effects that can range from seconds to minutes. The optimized control of a PHEV may require a much longer time-scale, such as the entire trip time, in order to allow for a fully balanced battery state of charge (SOC). The identification of suitable sampling rates (for the data acquired via connectivity), controller computational times and data transmission rates that are appropriate for each vehicle sub-system is a necessary part of the successful integration of vehicle and powertrain control strategies. HEVs and PHEVs by definition incorporate both a fuel-consuming system (such as an ICV) and an energy storage system (ESS) (typically electro-chemical in nature). It is widely acknowledged that the overall efficiency of a hybrid vehicle can vary significantly as a result of the integrated effect of the relative energy flows from the engine and to or from the ESS (during propulsion or regenerative braking). It is anticipated that connectivity will allow for the incorporation of a range of new high-value information into the optimization calculations and cost or objective functions that determine the optimal energy flows and splits under real-world driving operation. In fact, connectivity and partial or full automation may allow the full (and hitherto unfulfilled) energy savings potential of hybrid vehicles to be captured under a range of real-world driving scenarios, thereby improving the economics of their purchase, payback and use.

The vision of the ARPA-E NEXTCAR Program is to reduce the energy consumption of a status-quo (2016 baseline) light-, medium- or heavy-duty vehicle by at least 20% by taking advantage of connectivity and automation (of up to L3 capability), without explicitly requiring extensive powertrain architecture or vehicle hardware modifications. Moreover, the connectivity and automation technologies required for the implementation of the NEXTCAR technologies developed in this Program will be assumed to be available on the future target vehicles. Applicants may choose to employ advanced real (or virtual) sensing, as demanded by their powertrain and vehicle controls architecture, as long as all the incremental hardware, controls and software modifications meet the system cost target of the FOA as shown in Section I.E. It is acknowledged that the technical solutions developed in the NEXTCAR Program could ultimately be extended to future L4 vehicles, which themselves provide further potential for energy consumption and emissions reductions (mainly due to the effect of extensive light-weighting and by removing the effect of the human driver). *However, purely L4 applications are considered beyond the immediate scope of this Program.*

C. PROGRAM OBJECTIVES

The overall objective of the NEXTCAR Program is to develop optimized, coordinated vehicle dynamic and powertrain (VD&PT) control technologies that will improve the energy efficiency of each individual vehicle in the future automotive fleet, by utilizing emerging technologies and strategies in sensing, communications, connectivity, information, decision-making, control and automation. In essence, the co-optimization of vehicle-level (vehicle dynamic) and powertrain-level operations is sought in order to maximize future reductions in vehicle energy consumption.

The vision of the ARPA-E NEXTCAR Program is to reduce the energy consumption of a status-quo (2016 baseline) LD, MD- or HD vehicle by at least 20% by taking advantage of connectivity and automation (of up to L3 capability), without explicitly requiring extensive powertrain architecture or vehicle hardware modifications.

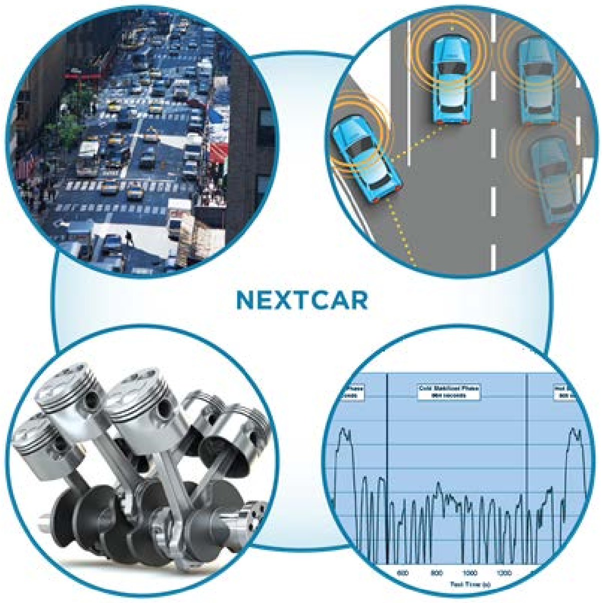
The proposed VD&PT control technologies are required to be capable of meeting the prevailing regulated vehicle emissions levels at the expected time of commercial deployment, and must ultimately result in equivalent (or at least acceptable) vehicle performance, utility, total cost of ownership and operation, functionality, drivability, power and energy storage density, reliability and maintainability, without compromise. The ultimate goal of this Program is the future commercialization and deployment, at scale, of energy efficiency optimization technologies for the future vehicle fleet that take advantage of advances in vehicle connectivity and automation (where the vehicle connectivity and automation technologies required are assumed already to exist). Given below are specific objectives of the NEXTCAR Program:

- **Reduce energy consumption:** The primary objective of the NEXTCAR Program is to fund the development of deployable VD&PT control technologies that can achieve, through the use of connectivity and automation, at least a 20% reduction in the energy consumption of LD, MD and HD vehicles under real-world operation, when compared to a 2016 baseline vehicle. Vehicle efficiency improvements should be achieved with minimal or no powertrain or vehicle hardware improvements or modifications beyond those offered by the 2016 baseline vehicle. The total cost of the technology improvements (both hardware and software) must meet the cost metric as outlined in Section I.E of the FOA. It is assumed that the connectivity and automation systems required for the implementation of the

NEXTCAR technologies either currently exist or will be deployed by the time of commercialization of these new VD&PT control technologies.

- **System target cost:** There are limits prescribed on the final commercial cost of the proposed NEXTCAR VD&PT control technologies at varying production scales for the LD, MD and HD markets. ARPA-E is interested in cost-effective solutions for minimizing fuel consumption, which will accelerate Original Equipment Manufacturer (OEM) acceptance and increase the fleet penetration of CAVs**. The anticipated NEXTCAR target system cost excludes the additional cost of any hardware and software required to provide the connectivity and/or automation required for its implementation in the target vehicle.** It is to be assumed, for the purposes of assessing costs (with justification where appropriate) that all of the required hardware and software that is needed to enable connectivity and automation is (i) currently available, or (ii) likely to be available before 2025, or (iii) available on-board the target vehicle at no additional or incremental cost.
- **Emissions:** The proposed vehicle technology must be compliant with all applicable emissions regulations for that vehicle class at the time of deployment, which is expected to be in the 2025 and beyond timeframe.
- **Target vehicle utility:** The NEXTCAR Program will only fund the development of technologies that either meet, or show the potential to meet, all applicable Federal Motor Vehicle Safety Standards (FMVSS) and other Federal and State safety and exhaust emissions requirements. As a result, the technologies, when deployed, should be compatible with all vehicle regulatory drive cycle and customer performance requirements, including acceleration, top speed, gradeability, startability, operating temperature range, NVH, and driveability. In this Program, it must be demonstrated that the proposed vehicle technology does not result in any degradation of the performance of the 2016 baseline vehicle with respect to the performance and emissions parameters and characteristics listed above.
- **Collaborative vehicle and powertrain solution:** One objective that the ARPA-E NEXTCAR Program aims to achieve is to enhance the collaboration between the vehicle dynamics control, transportation analytics and powertrain communities to formulate solutions for minimizing the energy consumption of future CAVs. To date, ARPA-E recognizes that there have been two independent approaches for improving vehicle energy efficiency (or reducing energy consumption): a purely connectivity-driven approach (such as the one undertaken under the auspices of the DOT AERIS Program) and a regulation-driven approach, such as CAFE and NHTSA/EPA Phase 2 fuel-efficiency and GHG emissions regulations. ARPA-E seeks integrated solution approaches that can leverage the efforts of the aforementioned research communities working together in unison. In schematic form, Figure 3(a) shows the status-quo of independent vehicle and powertrain level research, and Figure 3(b) shows the vision and the objective of the ARPA-E NEXTCAR Program in bridging the gap between the two independent approaches.

a)



b)

Figure 3: (a) Status-quo showing two separate and independent efforts for improving vehicle energy efficiency and (b) the NEXTCAR Program vision for maximizing vehicle energy efficiency through a cooperative effort from all communities.

It is acknowledged that the prediction of human driver behavior (for both an individual target vehicle and for neighboring vehicles) is an important artifact that can impact any solution for minimizing vehicle energy consumption; however, this is not an area of interest under the NEXTCAR Program.

D. TECHNICAL CATEGORY OF INTEREST

The ARPA-E NEXTCAR Program seeks to fund the development of technologies that **reduce future vehicle energy consumption by developing new co-optimized vehicle dynamic and powertrain control and optimization techniques, facilitated by the use of connectivity and vehicle automation**.

ARPA-E is specifically interested in supporting the development of new and emerging VD&PT control technologies that employ vehicle connectivity to extend beyond the automation of *vehicle dynamic control* functions, to the *powertrain control* level, for the purposes of reducing overall vehicle energy consumption.

APPLICATION SCENARIOS FOR TECHNOLOGY DESIGN, DEVELOPMENT, TESTING AND VALIDATION:

The VD&PT control technologies to be developed must apply to the operation of a single vehicle in isolation (undergoing operation on uncongested roadways, as well as in traffic) as well as to the operation of the same vehicle in a group of collaborating vehicles (under a range of traffic conditions). **The technologies to be developed should be appropriate for, and simulated and tested across, a range of CAV operating applications (listed in column A of Table 3). The range of appropriate operational factors that should be considered for either the simulation or testing of the technologies is shown in column B, while a description of the field testing and validation requirements of the proposed VD&PT control technologies is shown in column C below.**

Table 3: Example CAV applications and test factors that are pertinent to the VD&PT control technologies to be developed under the ARPA-E NEXTCAR Program.

(A) CAV Applications	(B) Simulation or Testing Factors	(C) Field Testing and Validation
• Platooning/ Cooperative Adaptive Cruise Control (CACC) • Speed Harmonization (SPD-HARM) • Eco-Approach and Departure at Signalized Intersections • Eco-Routing • City Driving and Highway Cruise Operation • ……	• Technology Penetration Rate • Level of Congestion • Lane Utilization Scheme • Facility Type • Number of vehicles in the cooperating cohort • …..	• Field testing must include VD&PT control technologies addressing at least two CAV applications, and more than one simulation or testing factor

Table 3 is not intended to be a fully comprehensive or prescriptive list of vehicle operational applications and simulation and testing factors, and it is up to the Applicant to expand on the information listed in the Table, or to state where deviations from those recommended applications, simulation or testing scenarios are justified.

The CAV applications[29,30] listed above are defined as follows for the purposes of this FOA:

- **Platooning/Cooperative Adaptive Cruise Control (CACC) Application**: This cooperative energy-saving behavior is enabled via V2V for a platoon of vehicles, wherein the lead vehicle informs the following vehicle(s) of its instantaneous location, speed, and acceleration, allowing the follower(s) to follow the leader safely with smaller inter-vehicle spacing. The follower(s) can safely and quickly respond to speed and acceleration changes by the vehicles ahead, thereby reducing the risk of rear-end collisions and string instability[31]. This application enables platooning, in which a train of vehicles cooperate to reduce their combined aerodynamic drag, and hence energy consumed. This type of application can be considered an example of cooperative vehicle behavior in which the total fuel or energy consumption of the cohort of vehicles is reduced compared to the sum of the energy usage of the individual vehicles operating alone.
- **Speed Harmonization (SPD-HARM) Application:** The speed harmonization application determines optimal vehicle speeds based on traffic conditions and the state of the surrounding roads. The purpose of speed harmonization is to vary the speed of traffic on roadways that approach areas of traffic congestion, bottlenecks, incidents, special events, and other conditions that affect traffic flow. Speed harmonization of a collection of vehicles assists in maintaining traffic flow, reducing unnecessary stops and starts, and maintaining consistent vehicle speeds to reduce congestion. This application utilizes V2I communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate an appropriate response plan and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to CAVs. Speed recommendations are sent to an in-vehicle display for driver-operated vehicles or are used to automatically adjust speed (via ACC for example) for automated (L1-L4) vehicles.
- **Eco-Approach and Departure at Signalized Intersections Application (Eco-AND):** This application, located in a vehicle, collects signal phase and timing (SPaT) and Geographic Information Description (GID) messages using V2I communications as well as data from nearby vehicles using V2V communications. Upon receiving these messages, the application calculates each vehicle's optimal speed to allow it to pass through the next traffic signal unimpeded on a green light or to cause the vehicle to decelerate to a stop in the most energy efficient manner (using regeneration, for example, in the case of HEVs). This information is then sent to the longitudinal vehicle dynamics control system in each vehicle in support of partial automation operation (L1-L3).
- **Eco-Routing Application:** This application determines the most energy efficient route, in terms of minimum fuel or energy consumption and/or emissions, for individual vehicles. This application is similar to current navigation

[29] http://www.its.dot.gov/aeris/
[30] http://www.its.dot.gov/dma/
[31] Swaroop, D.V.A.H.G. String stability of interconnected systems: an application to platooning in automated highway systems. PhD Dissertation, University of California- Berkeley, 1994.

applications, which determine the route based on the shortest path or minimum trip time. Eco-routing can also recommend routes that result in the lowest total fuel or energy consumption or emissions based on historical, real-time, and predicted traffic and environmental data, by incorporating energy usage in the calculation of a cost, objective or optimization function, for example.

- **City Driving and Highway Cruise Operation:** This application includes normal vehicle operation at a range of vehicle speeds and accelerations that closely mimics city driving and highway cruise operation. These modes of operation may be conducted in isolation or in a cohort of collaborating vehicles.

The effectiveness of each proposed NEXTCAR VD&PT control Technology will be evaluated in each CAV application with a range of simulation or testing deployment factors. These factors are listed in column B of Table 3 and are as follows:

- **CAV Technology Penetration Rate:** The percentage of vehicles that are equipped with the proposed CAV technology in the traffic stream. For example, three rates could be considered: 10% (low penetration), 50% (medium penetration), and 100% (high level of penetration).
- **Level of Congestion:** The overall number of vehicles in the proposed vehicle test roadway compared to the number of vehicles encountered on an average given day. Three levels could be considered, namely uncongested traffic or low traffic density, average traffic conditions, and a congested traffic condition.
- **Lane Utilization Scheme:** Many CAV applications (such as platooning) can be used in a specific traffic lane, dedicated for that purpose, or can be applied on an ad hoc, temporary basis in any travel lane. Two schemes are to be considered: dedicated lane usage and free lane selection usage for the technology developed.
- **Facility Type:** The type of roadway or corridor used for the technology validation and testing. Three broad types are considered applicable in the context of this Program, namely freeways, arterial roads and city streets.
- **Number of vehicles in the cooperating cohort:** The total number of vehicles in a cooperating unit, such as a platoon. A range of collaborative vehicles could be considered, namely a single isolated vehicle operating alone, a small cohort of cooperating vehicles (say 5 CAVs), and a larger group of cooperating vehicles (10 CAVs, for example).

The Technology to be developed under this Program must be designed, simulated, physically implemented, and ultimately tested and validated (either in a vehicle on the road or on a chassis dynamometer), in such a manner that will allow its future deployment over the full extent of applications in Column A of Table 3, and for the specified range of corresponding testing scenarios in Column B.
For the purposes of simulation, the performance and efficiency of the Technology must be simulated across as wide a range of CAV applications and simulation and testing factors in Table 3 as is possible.
Actual field testing and validation must include at least two CAV applications, and at least two testing factors. For example, Applicants could first simulate and then ultimately test their proposed Technology on a CACC application for a technology penetration level of 100%, in a highly-congested corridor, using a dedicated lane setup for CAVs in a platoon with a maximum number of 5 vehicles on a freeway section. Depending upon the test factor used (for example, use in a highly-congested corridor with no platooning vs. non-congested corridor with 3 vehicles in a platoon) and the type of the powertrain architecture selected (ICVs, HEVs, BEVs etc.), the Technology to be developed should minimize the total vehicle energy consumption by at least 20% relative to the 2016 baseline vehicle for a range of appropriate vehicle speed, wheel torque and acceleration requirements. Table 3 is not intended to be a fully prescriptive list of simulation, validation and testing applications and factors, and it is up to each Applicant to expand on the information listed in the Table, or to state where deviations from those recommended test and validation scenarios are justified.

ARPA-E also encourages applications stemming from ideas that still require proof-of-concept R&D efforts. Submissions requiring proof-of-concept development and demonstration may propose a project with the final deliverable being an extremely creative, but partial solution. However, Applicants are required to provide a convincing vision as to how these partial solutions would enable the realization of the full Program metrics with further development.

All Submissions should contain an appropriate cost estimate, project duration and a project plan that is described in sufficient technical detail to allow reviewers to meaningfully evaluate the proposed project. Proof-of-concept (or partial) solutions must at the very least demonstrate a 10% reduction in energy consumption over a comparable 2016 baseline vehicle (with a defined vehicle class, powertrain configuration and fuel), using connectivity and automation. ARPA-E may make one, multiple or no awards that will qualify as partial solutions, and only a small portion of the total amount to be awarded under the NEXTCAR Program is likely to be allocated to partial solutions.

E. TECHNICAL PERFORMANCE TARGETS

Only transformational Technologies with the potential to meet or exceed all NEXTCAR Program targets will be considered for funding. Applicant teams must propose to meet the following targets, or state where their Technology will not meet or deviate from these targets. Funded Applicants will be required to demonstrate via real-world testing that these targets have been met by their Technologies, by the end of the award period.

ID	Description	Target
1.1	Target Vehicle Applications/Operating Scenarios	All reasonable scenarios of vehicle operation. See Table 3 for representative descriptions of CAV applications and testing factors. Applicants must develop a Simulation, Testing and Validation Plan using the CAV applications and testing factors described in Table 3, or describe how their proposed Plan deviates from this.
1.2	Target Vehicle Emissions	Must demonstrate no degradation in tail-pipe out exhaust emission levels over the 2016 Federal regulations and a pathway for significant future reductions.
1.3	Target Vehicle Utility	Must meet current applicable Federal vehicle regulatory drive cycle and customer performance requirements, including acceleration, top speed, gradeability, startability, operating temperature range, NVH, driveability and ease of use.
1.4	Customer Acceptability	The operation of the Technology must be transparent to the user or driver.
1.5	Energy Consumption Reduction Target over a 2016 Baseline Vehicle*	≥20%**
1.6	System Cost Target	**$1,000** for a LD vehicle, **$2,000** for a MD vehicle, and **$3,000** for a HD vehicle, upon full commercialization of the Technology. Vehicle classes are as defined in Appendix 1 of the FOA.

***Baseline Vehicle**: Applicants must select a baseline 2016 vehicle and specify and describe the following: Vehicle class (LD, MD or HD), powertrain type (e.g. engine-only, hybrid electric, battery-only, etc.) and fuel/energy type. The above mentioned characteristics of the baseline vehicle cannot be modified to achieve the metrics of this Program. However, for the purposes of cost assessments, Applicants may assume that the baseline vehicle will be equipped for and capable of operation up to the L3 level of operation through the use of enabling technologies such as DSRC, stereoscopic cameras for machine vision, radar, LIDAR, and acoustic/ultrasonic sensors, etc. In other words, it is to be assumed that all of the required hardware that is needed to enable the required connectivity and automation is available at no incremental cost. For example, the baseline 2016 vehicle may be equipped only with a L0 level of automation but the CAV Technology implementation can assume a L1-L3 level of capability provided the Applicant provides justification that the technologies for enabling the connectivity and automation are either (i) currently available, or (ii) likely to be available on all vehicles before 2025, or (iii) are or will be available at no incremental cost. Any additional hardware beyond that described above should be justified from a technology and cost point of view.

****Due to the technical advances that are likely to be implemented in vehicles as a consequence of the implementation of pending future fuel efficiency standards, it is recognized that a 20% reduction in the energy usage of a 2025 vehicle will necessarily result in a lower total absolute amount of energy saved than the corresponding 20% reduction for a 2016 baseline vehicle. The energy reduction potential of the Technologies to be developed under this Program is anticipated to be additive to, and independent of, those energy reductions already expected to be implemented in future vehicles (due to future fuel efficiency regulations, for example).

Supplementary Explanations of Targets

1.1 The Technology proposed to be developed in the NEXTCAR Program must be designed, simulated, physically implemented, and ultimately tested and validated (either in a vehicle on the road or on a chassis dynamometer), in such a manner that will allow its future deployment over the full extent of applications in Column A of Table 3, and for the specified range of corresponding testing factors in Column B. For the purposes of simulation, the performance and efficiency of the Technology must be simulated across as wide a range of CAV applications and testing factors in Table 3 as is possible. Actual field testing must include at least two CAV applications, and at least two testing factors as described in Table 3, or an alternative CAV approach with justification should be proposed.

1.2 The Technology proposed must not degrade the Target Vehicle's certified emissions below those of the 2016 baseline vehicle. Additionally, the Technology must allow for the relevant class-appropriate future emissions regulations (including those for NOx, CO, HC, PM and CO_2) to be met in the 2025 timeframe, without significant further development or cost.

1.3 The Technology proposed must deliver full vehicle utility comparable to that of the 2016 baseline vehicle. This utility includes, but is not limited to, regulatory drive cycle performance, acceleration time, top speed, gradeability, startability, operating temperature range, NVH, driveability and ease of use.

1.4 To ensure full customer acceptance and the successful eventual commercialization of the Technology, the Technology must be easy for the driver to operate and understand, if required.

1.5 The Technology must deliver a ≥20% reduction in energy consumption without changing the defining features of the 2016 baseline vehicle, including vehicle class, powertrain type and fuel type. (For instance, if the 2016 baseline vehicle is a light duty PHEV with a nominal all-electric range of 40 miles that operates on gasoline, the improved vehicle should at a minimum retain those characteristics).
Method of Verification: A ≥20% reduction in energy consumption relative to the baseline 2016 vehicle must, by the end of the Program, be demonstrated to ARPA-E over each of the real-world scenarios selected by the Applicant from Table 3 and validated first through simulation, and ultimately through real-world testing (on a chassis dynamometer or on-road, as applicable).

1.6 Applicants must demonstrate the achievement of the applicable system cost target through techno-economic analysis for 100,000 units of production for LD vehicles, 20,000 units for MD vehicles and 10,000 units for HD vehicles, depending upon the vehicle class selected by the Applicant. Applicants may assume that the baseline vehicle will be equipped for and capable of operation up to the L3 level of operation provided the Applicant provides justification that the technologies for enabling the connectivity and automation are either (i) currently available, or (ii) likely to be available on all vehicles before 2025, or (iii) are or will be available at no incremental cost. Any additional hardware beyond that described above should be justified from a technology and cost point of view.