U.S. Department of Energy
Advanced Research Projects Agency – Energy
Request for Information (RFI)
DE-FOA-0001473
On
Energy Efficiency Optimization for Connected and Automated Vehicles

Description:

ARPA-E seeks input from researchers and developers in a broad range of disciplines including automotive vehicle control, powertrain control and transportation analytics regarding the development of advanced energy efficiency optimization technologies for future connected and automated vehicles (CAVs). ARPA-E is requesting information on new and emerging full vehicle and powertrain control technologies that can reduce the energy use associated with automotive transportation, beyond those technologies currently expected to be deployed in future vehicles. These additional energy efficiency optimization technologies may include, but are not limited to, advanced technologies and concepts relating to future full vehicle and powertrain control, individual vehicle and powertrain operation, control and optimization facilitated by connectivity, and the reduction of the fuel and/or energy consumed by future individual vehicles undergoing either human operation or automated operation.

Any potential technical solutions that might be of interest to ARPA-E would ultimately require a demonstrable pathway through commercialization and widespread deployment to reduce the fuel and energy consumed in the current and/or future vehicle transportation fleet. 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, waste energy recovery and parasitic load reduction, are specifically not of interest in this Request for Information (RFI).

The emphasis of this RFI is on reducing the energy consumption of *individual vehicles*, and not on transportation system technologies such as transportation network optimization, ridesharing, or transportation mode shifting. (ARPA-E has previously solicited technology solutions to minimize energy consumption in America's surface transportation network through the use of network control mechanisms that operate through personalized signals directed at individual travelers through the TRANSNET FOA[1]). While it is clear that transportation system optimization is an invaluable energy efficiency tool, the focus of this current RFI is on maximizing the energy efficiency of each *individual* vehicle (while acknowledging that each such individual vehicle will potentially be an element of a broader transportation system).

A range of improved powertrain control techniques will be made possible in the near future by the increase in information available to on-board vehicles through connectivity such as V2X (e.g. look ahead data), and it is clear that certain further improvements in powertrain controls will occur even without this additional technology. In this RFI, it is envisioned that the future total reduction in energy consumption of an individual vehicle will be due

[1] http://arpa-e.energy.gov/sites/default/files/documents/files/TRANSNET_ProgramOverview.pdf

to some combination of improved on-board powertrain controls (with improved real or virtual sensing and/or the use of V2X connectivity and real-time optimization), improved vehicle controls (using real or virtual sensing and/or the use of V2X), new inputs from external or fleet-level optimization, and ultimately the ability to operate in a driverless fashion in the case of automated vehicles (thereby removing the effect of the human driver from the vehicle and powertrain control systems).

Technologies contemplated in this RFI 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 acceptable) vehicle performance, utility, cost of ownership and operation, functionality, drivability, power and energy storage density, reliability and maintainability, without compromise.

From a control point of view, currently vehicles 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 cooperative fashion with other surrounding vehicles. The effects of individual vehicle or powertrain control on the cumulative energy efficiency of a cohort of vehicles undertaking cooperative vehicle behavior[2] have not yet been fully explored.

The focus of this RFI is on the potential improvement in the energy efficiency of each *individual* vehicle in the automotive fleet, through the improvement of powertrain control and vehicle dynamic control, by utilizing emerging technologies and strategies in sensing, communications, information, control and automation.

The purpose of this RFI is to solicit input for ARPA-E consideration to inform the possible formulation of future programs intended to help reduce the total energy used in the transportation sector. This RFI provides the broad research community with an opportunity to contribute views and opinions regarding current and future powertrain and vehicle control technologies, and their use in energy efficiency optimization.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below, and note in particular: the information you provide may be used by ARPA-E in support of program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Background:

Over the next few decades the automotive **vehicle fleet** (light-, medium- and heavy-duty vehicles) will continue to be predominantly powered by internal combustion engines (ICEs), or be hybrid electric vehicles (HEVs), fuel cell electric vehicles (FCVs) or battery electric vehicles (BEVs). (The fuels used will presumably continue to include gasoline, diesel fuel, electricity (for BEVs and plug-in HEVs), hydrogen, natural gas and biofuels. For the purposes of this RFI, no preference is expressed for any particular fuel or energy source for propulsion).

Powertrain in the context of this RFI refers to a vehicle's engine, transmission, and any propulsive electric machine(s) and associated energy storage and conversion systems, where applicable.

[2] Cooperative vehicle behavior is assumed to require connectivity and at least partial automated capability.

Powertrain control refers to the control of powertrain systems to produce the required output power, performance, efficiency and emissions over a range of timescales and environmental and operating conditions.

Optimization refers in this context to the minimization of energy usage or emissions subject to a number of constraints in operation.

Full vehicle control (or vehicle dynamic control) refers to the control of vehicle longitudinal and lateral dynamics through the operation of safety critical inputs such as accelerator (throttle), brake, transmission control and steering.

Future vehicle **fuel economy standards** (such as the 2025 light-duty vehicle Corporate Average Fuel Economy, or CAFE standards) and medium- and heavy-duty greenhouse gas (GHG) emissions standards (EPA/NHTSA Phase 2 standards) will by necessity result in the reduction of energy consumption by individual vehicles. This RFI is aimed at investigating technologies that may provide additional opportunities for energy efficiency improvements beyond the base case expected across the next decades, noting that transportation currently accounts for 28% of the US primary energy usage.

Fuel and energy efficiency refers to the reduction in the total amount of energy utilized by a vehicle to perform a certain operation or duty cycle.

Connectivity in the context of this RFI includes high bandwidth, localized information such as that obtained through vehicle to vehicle (V2V) communication protocols such as DSRC (Dedicated Short Range Communications), and/or higher latency information obtained through vehicle to infrastructure communications (V2I). V2V is considered to include high bandwidth, low latency for secure, safety critical short- to medium-range communications, such as DSRC. V2X is considered to include vehicle-to-cloud communications, at higher bandwidths but with greater latency, and is assumed to include cellular, Wi-Fi and satellite communications. Vehicle connectivity is at present being developed primarily for safety and crash avoidance (in the case of V2V) and infotainment (for V2X). Connectivity, along with enhanced on-board sensors (primarily to allow for machine vision and proximity sensing of fixed or moving objects), will allow for advanced levels of vehicle control automation.

Automated[3] vehicles will rely on an array of on-board sensors (such as stereoscopic cameras for machine vision, radar, LIDAR, and acoustic/ultrasonic sensors) and additional off-board-derived information to enable fully automated operation and navigation.

The Current State of the Art of Automotive Vehicle Operation and Control:

The most common light-, medium- and heavy-duty vehicles today (at Level 0 – with no automated vehicle control features) are predominantly either powered by internal combustion engines (ICEs), hybrid electric vehicles (HEVs), or battery electric vehicles (BEVs). These vehicles mostly rely on a human driver to provide high-level control of the vehicle through the actuation of accelerator pedal, brake pedal, and steering input (and sometimes

[3] Refer to standard DOT/NHTSA Levels of Automation. See for example (http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development)

gear selection). In turn the actual instantaneous powertrain operation is controlled by an electronic engine or powertrain controller that ultimately dictates the real-time powertrain power output, output speed, and by default 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 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) in an almost entirely reactive fashion to dictate any required modifications to the vehicle control inputs.

Powertrain control at this level is almost exclusively reactive and backward-looking, with limited sensor feedback except for crude or indirect measures of combustion efficiency and/or emissions (where relevant), along with somewhat more sophisticated measures of vehicle dynamic behavior (speed, acceleration, and instantaneous power produced). As a result, powertrain operation is frequently non-optimal with regard to energy consumption minimization, and considerable opportunity arises for energy efficiency optimization.

Automated vehicle operation is viewed today almost exclusively as a safety enhancement, allowing for higher vehicle driving speeds (and hence traffic throughput on roads) with vastly reduced crash rates, and thereby freeing up the driver’s or occupant’s time for other pursuits. Automated vehicles will rely on an array of on-board sensors (such as stereoscopic cameras for vision, radar, LIDAR, and acoustic/ultrasonic sensors) and additional off-board-derived information to enable fully automated operation and navigation. 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 rapidly becoming the norm. 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, connectivity, 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.

L4 vehicles (fully automated and driverless) have the capability of leading 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 automated vehicle operation becomes the norm, total Vehicle Miles Traveled (VMT) by the automotive fleet have 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. Due to well established patterns of vehicle ownership, reliability and replacement, the incumbent vehicle fleet largely turns over in a 15 to 20-year time frame, thus requiring that for the next few decades, L4 vehicles will have to co-exist on the road with L0 vehicles of higher vehicle weights and reduced levels of safe operation capability. This 20-year timeframe is also consistent with the expected longevity of the internal combustion (IC) engine, thus ensuring that at least part of the future L4 fleet will continue to have fuel-consuming engines. The improvement of the fuel efficiency of this part of the future vehicle fleet is clearly of national interest, for reasons of energy security, economic security and climate change mitigation.

Current Trends in Powertrain Control:

The advent of vehicle connectivity allows for the use of additional, exogenous inputs for both vehicle and powertrain control. In the near future, in addition to offering advanced levels of crash avoidance and crash prevention, V2V communication (such as DSRC) will facilitate extensive automated collaborative operation between neighboring vehicles – for platooning, cooperative ACC and congestion mitigation, for example. **This connectivity, and the resultant exchange of information, is anticipated by the industry to be between *vehicle* controllers, as opposed to between *powertrain* controllers.** Untapped opportunities exist however for the efficiency enhancement of the future vehicle through optimization of powertrain operation including real-time powertrain calibration and optimization via connectivity. V2V communication, for example, effectively equips each vehicle with foreknowledge or a preview of its own future actions as DSRC gives warning of the actions and intentions of the vehicles immediately ahead in traffic. This knowledge can potentially be used to create a specific trajectory of optimized powertrain control inputs to minimize the fuel or energy consumption of each individual vehicle across some finite future time horizon, for example.

The utilization of additional information obtained through V2X in powertrain control systems can also enable significantly higher individual vehicle efficiency through combustion optimization (in the case of ICEs or HEVs), energy storage optimization (in the case of HEVs and BEVs), route optimization, and optimized operation for all vehicles. For ICEs or HEVs, the addition of "perfect information" on fuel chemistry, engine and after-treatment condition, weather and environmental conditions, and perhaps driver behavior (for example), could lead to meaningful enhancements in the energy efficiency of each and every vehicle.

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 any additional information available through connectivity. Model-based control with real-time optimization of operation through the use of additional inputs facilitated through connectivity has the potential for useful efficiency gains for individual vehicles, and hence by extension, the full vehicle fleet.

For example, connectivity might allow for a vehicle to "know" with some certainty about its future operation with respect to acceleration, deceleration, braking and grade climbing. This look ahead or preview information can be used to optimize the vehicle energy efficiency over a portion of a trip, or indeed in the case of 'perfect information', over a full, extended trip. Technologies such as these, implemented on either a single vehicle basis, or across a cohort of cooperative vehicles, or even the entire fleet, could lead to significant energy efficiencies.

A Convergence of Technologies:

Opportunities for individual powertrain optimization with advanced sensing and control algorithms are being enabled by additional information. From a control point of view, currently vehicles operate as a single entity even in traffic. Developments in connectivity and automation will in addition allow vehicles in the future to operate in a cooperative fashion with other surrounding vehicles. The effects of individual vehicle powertrain control on the energy efficiency of cooperative vehicle behavior have not fully been explored.

Table 1. Current and Future Capabilities for Powertrain and Vehicle Functionality.

Functionality	Existing Capability	Future Potential Capability
Powertrain Control	Backward looking, reactive (table-based)	Forward looking, predictive (model-based)
Powertrain Control Feedback	Limited	Wide range
On-board Computational Capability	1x	100-1000x
Calibration Optimization	Once, at production	Continuous, in real-time
Vehicle Control Decision Making	Human-based, 'selfish'	Machine-based, cooperative
Communication and Connectivity	Receive only, low bandwidth, high latency	Transmit and receive, high bandwidth, low latency
Time Scale of Operating Decisions	Seconds to minutes ahead	Milliseconds to hours ahead
Advanced Knowledge of Traffic Patterns and Behavior	Limited by human vision capability	Limited by machine vision capability and connectivity
Route Management Decision Criteria	Time, speed, distance	Time, speed, distance and energy usage

ARPA-E seeks information on the convergence of new powertrain control technologies and vehicle control technologies enhanced by improved sensing, information, computation and vehicle automation for future L3 or L4 levels of vehicle automation.

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future programs intended to help reduce the total energy used in the transportation sector. Information obtained may be used by ARPA-E on a non-attribution basis. This RFI provides the broad research community with an opportunity to contribute views and opinions regarding approaches to energy efficiency optimization in current and future powertrain and vehicle control technologies. Based on the input provided to this RFI and other considerations, ARPA-E may decide to issue a formal FOA for this area. If a formal FOA is issued, it will be issued under a new FOA number. No FOA exists at this time. ARPA-E reserves the right to never issue a FOA in this area.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E will not pay for any information provided under this RFI, and there is no guarantee that any project will be supported as a result of this RFI. This RFI is not a FOA, and ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Response to this RFI will not be viewed as any commitment for the respondent to develop or pursue the 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. **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 email address ARPA-E-RFI@hq.doe.gov by 5:00 PM Eastern Time on February 1, 2016. ARPA-E will accept responses to this RFI immediately.

Please insert "Response to RFI for DE-FOA-0001473" in the subject line of your email, and include your name, organization, type of organization (e.g. academic, industry, government, individual, non-profit etc.), email address, and contact telephone number in the body of your email. Responses to this RFI are limited to no more than 3000 words in length, and an additional 2 pages of schematics if required.

ARPA-E will not provide any debriefings or prepare or publish any synopsis of materials received in response to the RFI. Thank you very much for your time and effort in helping inform ARPA-E in the area of reducing transportation energy consumption and energy efficiency optimization.

Information Being Sought in this RFI:

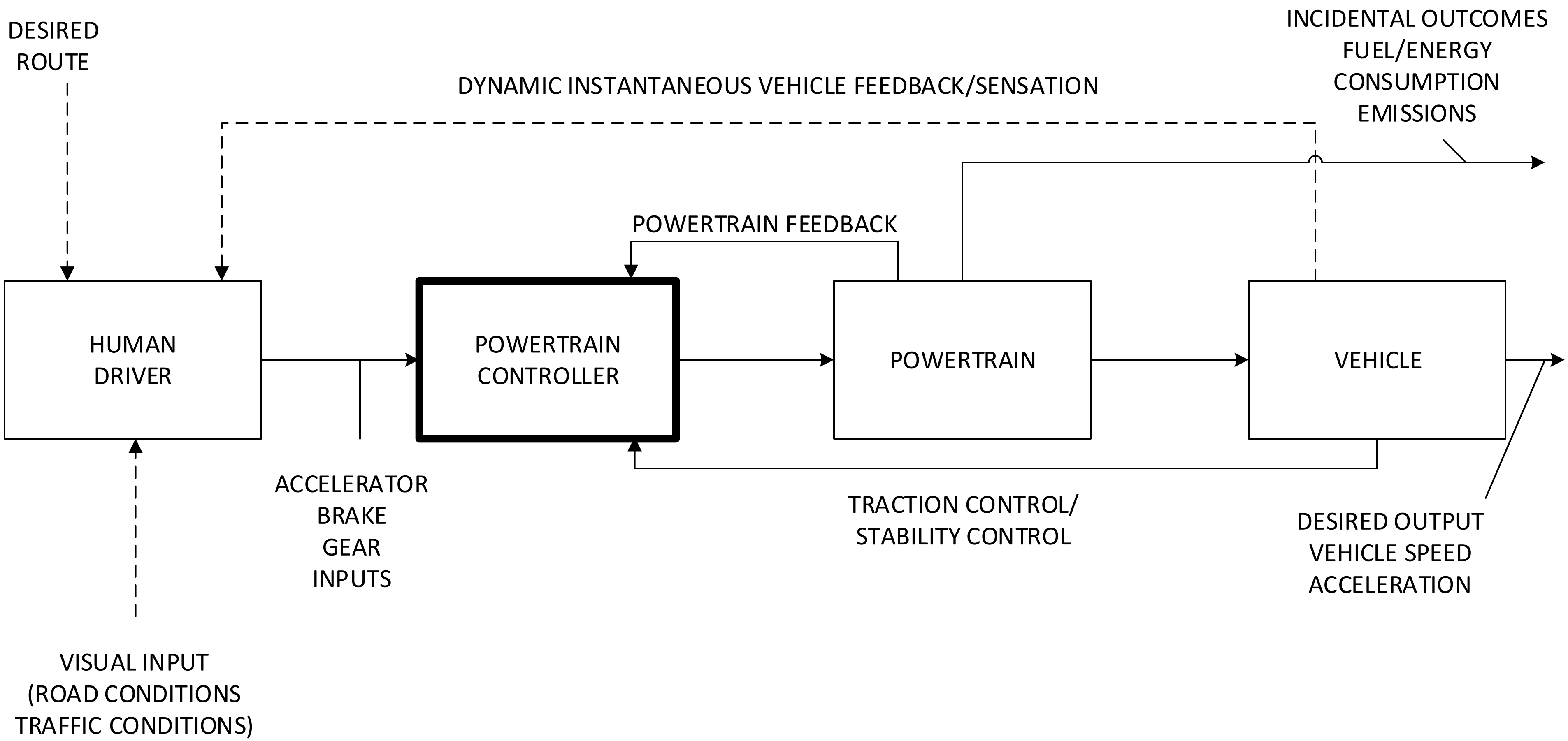
In your response, please provide answers to the **following questions**. Please indicate clearly whether the solutions you envision represent primarily software improvements, or require additional sensors, actuators, or modifications to current or future powertrain or vehicle hardware. Please feel free to provide additional technical perspective outside of the areas delimited by these questions as required.

1. What information not currently available on-board vehicles would be beneficial for improving the fuel or energy efficiency of an individual vehicle? How could this information be accessed or made available to each vehicle? Which of this additional information can be provided through either additional on-board sensing or through connectivity?
2. What is the time-horizon(s) of the additional on-board and off-board look-ahead information that is (are) necessary and useful for powertrain and/or vehicle efficiency optimization?
3. What individual vehicle or powertrain control technologies should be developed to improve the fuel or energy efficiency of future L0-L3 vehicles (i.e. vehicles that retain human drivers) that can leverage information accessed through either additional on-board sensing or connectivity?
4. What would be the cost for the technologies detailed in Q3? Please estimate any potential efficiency improvement and provide the estimated incremental cost per unit energy usage reduction for these new technologies ($/% energy usage reduction).
5. What individual vehicle or powertrain control technologies should be developed to improve the fuel or energy efficiency of future driver-less, fully automated L4 vehicles that can leverage information accessed through either additional on-board sensing or connectivity?
6. What would be the cost for the technologies detailed in Q5? Please estimate any potential efficiency improvement and provide the estimated incremental cost per unit energy usage reduction for these new technologies ($/% energy usage reduction).

7. Considering future vehicle and/or powertrain technologies that will be implemented on vehicles of all levels of automation, what modifications should be made to Figures 1 and 2 to accurately represent the system logic for each type of vehicle?
8. What technologies in real-time vehicle and powertrain control and optimization should be developed to reduce the fuel and energy consumption of future vehicle operation?
9. Using connectivity and automation technologies, how can collaborative vehicle applications (beyond those already established or emerging, such as platooning, eco-routing, traffic signal management, speed harmonization and congestion mitigation) improve the fuel or energy efficiency of future vehicles, either individually or collectively?
10. What gaps currently exist in our understanding of these concepts that should be filled to allow for the energy efficient operation of future individual vehicles and hence the entire vehicle fleet? What additional useful future technologies for individual vehicle energy efficiency optimization have not been contemplated or described in this RFI?
11. The topics investigated in this RFI span multiple disciplines and might require new collaborations to fully address the topic areas. What types of expertise and what specific entities would be best suited to develop either partial or comprehensive solutions to the topics contemplated in this RFI?

Concepts specifically not of interest for this RFI include:

- technologies already well understood or commercially implemented,
- technologies that rely solely on modification of vehicular propulsion systems, or the development or improvement of engines, transmissions, energy conversion devices, energy storage technologies, or advanced computational capability alone,
- technologies that offer fuel or energy efficiency through (human) driving behavior modification alone,
- technologies that rely solely upon collaborative vehicle behavior, such as platooning, without the modification of individual vehicle and powertrain energy efficiency,
- technologies that rely solely upon enhanced navigation, such as eco-routing or congestion avoidance, without the modification of individual vehicle and powertrain energy efficiency,
- technologies that employ mobility sharing services, ridesharing, shared ownership or ‘mobility on demand’ services,
- technologies such as transportation mode shifting, transportation network optimization, air travel, rail, transit services or marine transportation,
- technologies such as hybridization, electrification, light-weighting, aerodynamic drag reduction, parasitic load reduction, friction reduction, rolling resistance reduction or alternative fuel substitution or fuel or energy shifting,
- technologies that use vehicle connectivity exclusively for safety, accident avoidance, navigation, driver notification, congestion mitigation, traffic management system operation or interaction, or infotainment, without any energy efficiency implications, or
- technologies pertaining to cybersecurity, policy issues, human factors or the human machine interface (HMI).



CURRENT L0 VEHICLE OPERATION

POWERTRAIN CONTROL

- LIMITED INPUTS
- REACTIVE
- TAKES ONLY HUMAN INPUT, WITH POWERTRAIN FEEDBACK AND DYNAMIC VEHICLE FEEDBACK

FIGURE 1

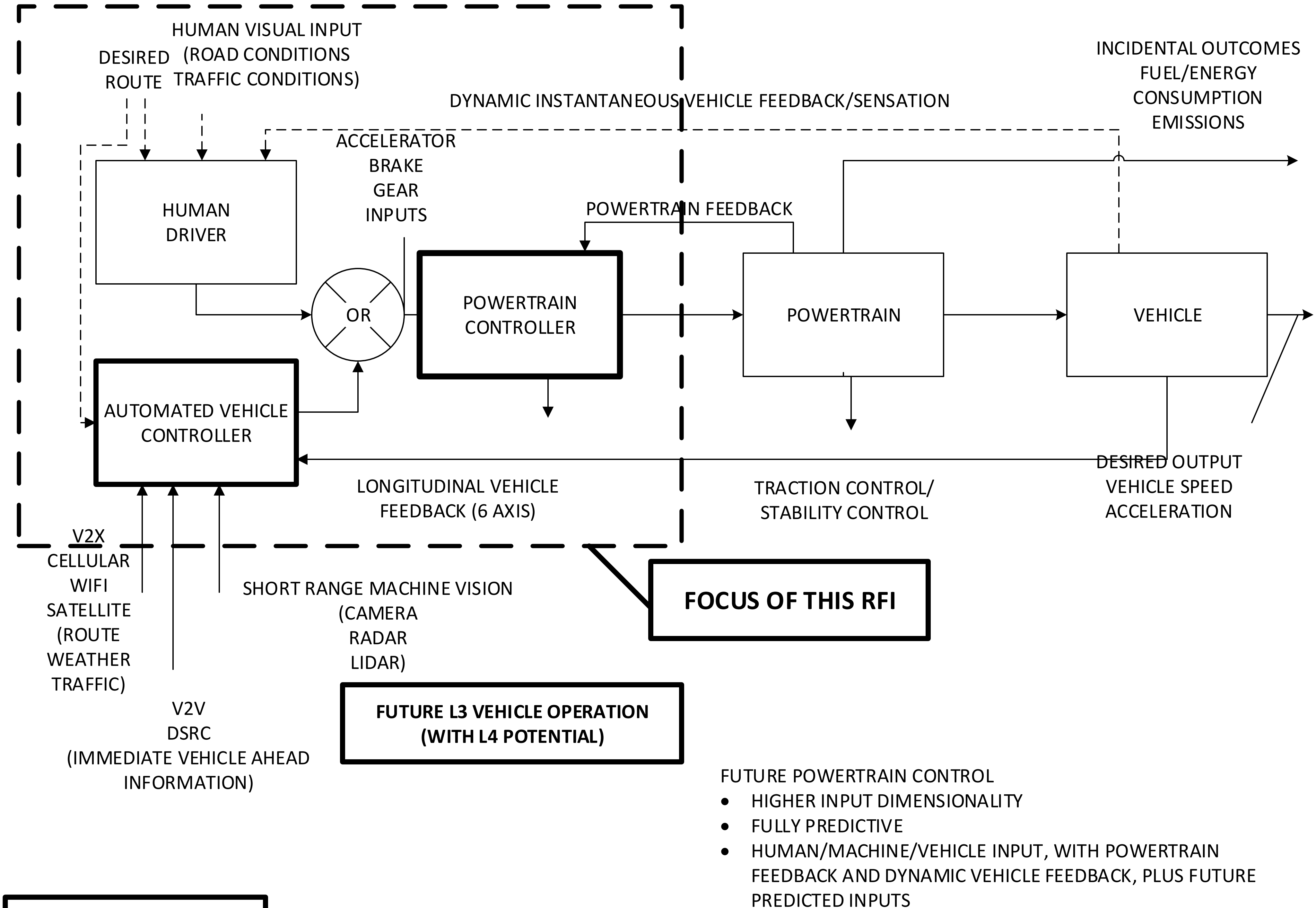

HUMAN VISUAL INPUT (ROAD CONDITIONS TRAFFIC CONDITIONS)
DESIRED ROUTE
DYNAMIC INSTANTANEOUS VEHICLE FEEDBACK/SENSATION
INCIDENTAL OUTCOMES FUEL/ENERGY CONSUMPTION EMISSIONS
ACCELERATOR BRAKE GEAR INPUTS
HUMAN DRIVER
POWERTRAIN FEEDBACK
OR
POWERTRAIN CONTROLLER
POWERTRAIN
VEHICLE
AUTOMATED VEHICLE CONTROLLER
LONGITUDINAL VEHICLE FEEDBACK (6 AXIS)
TRACTION CONTROL/ STABILITY CONTROL
DESIRED OUTPUT VEHICLE SPEED ACCELERATION
V2X CELLULAR WIFI SATELLITE (ROUTE WEATHER TRAFFIC)
SHORT RANGE MACHINE VISION (CAMERA RADAR LIDAR)
FOCUS OF THIS RFI
V2V DSRC (IMMEDIATE VEHICLE AHEAD INFORMATION)
FUTURE L3 VEHICLE OPERATION (WITH L4 POTENTIAL)
FUTURE POWERTRAIN CONTROL
• HIGHER INPUT DIMENSIONALITY
• FULLY PREDICTIVE
• HUMAN/MACHINE/VEHICLE INPUT, WITH POWERTRAIN FEEDBACK AND DYNAMIC VEHICLE FEEDBACK, PLUS FUTURE PREDICTED INPUTS

FIGURE 2