TRANSNET Program Overview

B. PROGRAM OVERVIEW

The Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET) program seeks solutions that 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.

In 2013, the United States used more than 25% of its energy supply for the purpose of moving people and goods from one place to another, i.e., in the transportation sector.[1] Even modest improvements that reduce transportation energy consumption can reduce energy imports and greenhouse gas emissions, two of ARPA-E's primary goals. To date, technologies directed at transportation have focused primarily on the diversification of energy supplies (e.g., the production of alternative liquid fuels and electrification) or on improvements in vehicle fuel efficiency (e.g., combustion efficiency, weight reduction, and aerodynamic design).[2] The TRANSNET program takes an alternative, complementary approach through the development of technologies that target both the factors that drive energy consumption and the overall energy efficiency of personal transportation, without changing the mechanical efficiency of each mode (car, bus, train, etc.) within the network.

The time is ripe for this new approach. Today, personal transportation is entering a period of rapid change, enabled by the introduction of new technologies. Such technologies apply not only to the vehicles themselves (e.g., autonomous/semiautonomous vehicles, vehicle-to-vehicle (V2V)/vehicle-to-infrastructure (V2I) communications, and electric/natural gas fueled vehicles), but also to a number of approaches that enable transportation information to be collected and disseminated by wireless communication and the Internet (e.g., Waze, Uber, Zipcar, and Lyft, as well as social networks such as Facebook, Twitter, etc.). How can these innovative technologies be used to reduce energy use in transportation networks? The answer is not completely clear. But ARPA-E envisions significant opportunities for new and emerging technologies, with deliberate and thoughtful development, to create a framework for a practical system with real-time response to make energy efficiency an integral part of the optimized transportation network of the future.

In the context of this opportunity, several descriptive and common terms require accurate definitions, which may be found in the Technical Glossary in Section I.D of the FOA. Please review these definitions so that the intent of this funding opportunity is clear.

Summary of the Opportunity

ARPA-E believes that the transportation network can be made more efficient, without substantial investment in new infrastructure, improvements in modal efficiency, or perceptible reduction in either the quality-of-service or the reliability of the system. While the size of the impact is difficult to quantify precisely, given the human element, significant energy is wasted in personal transportation: Occupancy is only 40% of nominal capacity for passenger vehicles,[3] driving styles contribute to a 45% reduction in the on-road fuel economy (per driver),[4] and congestion (which is related to non-optimal

[1] In 2013, the US consumed 97.534 quadrillion BTUs (Quads) of energy, 26.990 Quads of this were associated with transportation. Source: DOE/EIA-0035 (2014/07), U. S. Energy Information Agency, Monthly Energy Review, July 2014. 17 August 2014. http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

[2] For example, see the ARPA E programs Electrofuels, BEEST, PETRO, REMOTE, RANGE, MOVE, and METALS. http://arpa-e.energy.gov/?q=arpa-e-site-page/view-programs

[3] The National Highway Transportation Survey reports average occupancy of 1.67 persons over all types of trips. The average number of seats is assumed to be 4.

[4] Sivak, M. & Schoettle, B."Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy", Transport Policy 22 (2012) 96–99. See also LeBlanc, D., Sivak, M., and Bogard, S. "Using Naturalistic Driving Data to Assess Variations in Fuel Efficiency among Individual Drivers" University of Michigan Transportation Institute Report UMTRI-2010-34, December 2010.

route choice) increases the energy used in transportation up to 33%,[5] even before soft factors such as lost productivity and lower quality of life are accounted for.

Applicants are challenged to develop mechanisms for individual travelers that both signal and guide them toward improvement of the energy efficiency of the transportation network in multimodal urban areas. Because a purely experimental, complete analysis of the transportation network would be prohibitively expensive and time consuming, ARPA-E seeks the development of simulated network control models of energy use in personal transportation, based on real-world data, that incorporate personalized signaling and guiding mechanisms. A suitable model will need not only to describe the current state of the personal transportation network but also to predict the impact of changes to the network, both from travelers' choices, such as mode and departure time, and from network changes, such as those that result from incidents and lane closures. The model must also be robust with respect to inaccuracies that stem from incomplete and noisy sensor data. Optimization will require development of a high fidelity system model that allows guidance and control hypotheses to be tested, refined, or discarded in full view of this uncertainty. These hypotheses will be embodied through simulation to achieve ARPA-E's core objective, a control architecture that enables the practical network control through personalized guidance. The design of this control architecture defines the central challenge of the TRANSNET program.

Challenges in Signaling and Control Mechanisms

In today's transportation network, guidance and control mechanisms are, for the most part, impersonal. For example, in private vehicles, every traveler experiences speed limits, traffic signals, and tolls identically.[6] However, over the past ten years, digital technology has altered the landscape dramatically. Personal, wireless technologies combined with low-cost sensors are ubiquitous and these technologies possess an intrinsic transformational potential[7] to change how to move people from one place to another efficiently. Software advances complement these hardware and communications network technologies, fueling computational approaches that help process the data to both predict and influence the choices made by individuals.[8]

Here, we seek the development of a control architecture that acts to reduce energy use in transportation through personalized signaling, guidance, and control mechanisms. This architecture is subject to the physical constraints imposed by existing infrastructure (e.g., highways, arterials, rail lines, etc.). Because such a structure also needs to be practical for, and implemented by, travelers themselves, it must not reduce either the individual's quality-of-service or the network's system reliability.

Figure 2 shows energy use at the level of the individual traveler (expressed both as total energy consumed, in quadrillion BTUs or quads, and in consumer-friendly, miles-per-gallon-equivalent per traveler, MPGe). Personal transportation is dissected by mode, and plotted in order of increasing efficiency. We see that the least efficient choices, cars and trucks, consume most of the energy in personal transportation. Further, we see that, on a per person basis, all forms of road transportation are less efficient than air or rail; this is largely the consequence of occupancy, which is about 33% for cars and trucks, and 30-40% for city buses,[9] but exceeds 80% for commercial airlines. The relatively low occupancy of Amtrak

[5] This is an approximation of the maximum effect. See Roughgarden, T., "The Price of Anarchy in Games of Incomplete Information", http://theory.stanford.edu/~tim/papers/inc.pdf.

[6] Note that even rudimentary differentiation by vehicle class can be a remarkably effective control mechanism. For example, the use of single-occupancy HOV lane stickers in California for alternative vehicles is considered to have been successful in reducing both emissions and congestion, with sticker-bearing Priuses valued thousands of dollars more than their sticker-free siblings.

[7] In 2014, the International Telecommunications Union reported that the cellular telephone market is approaching saturation, that is, one phone per person over the entire planet! [See http://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx.] In this same report, mobile broadband adoption appears to trail cellular adoption by about 10 years. Assuming these trends persist, nearly every person on the planet will be connected to the Internet via wireless devices within the next decade.

[8] Lohr, "Sizing Up Big Data, Broadening Beyond the Internet", New York Times Blog. August 23, 2014. http://bits.blogs.nytimes.com/2013/06/19/sizing-up-big-data-broadening-beyond-the-internet/ See also Thaler, R. H. & Sunstein, C. R. "Nudge: Improving Decisions About Health, Wealth, and Happiness", Penguin, 2009, and Ariely, D. "Predictably Irrational: The Hidden Forces That Shape Our Decisions", HarperCollins, 2008.

[9] The average occupancy of a city bus is about 9 (Table 2.12, Transportation Energy Data Book, Edition 33, 2014, http://cta.ornl.gov/data/index.shtml), the average capacity of a city bus is about 30 (seated).

(about 25%) is more than offset by the extraordinary energy efficiency of rail,[10] a factor that is also captured in Light Rail efficiency.[11]

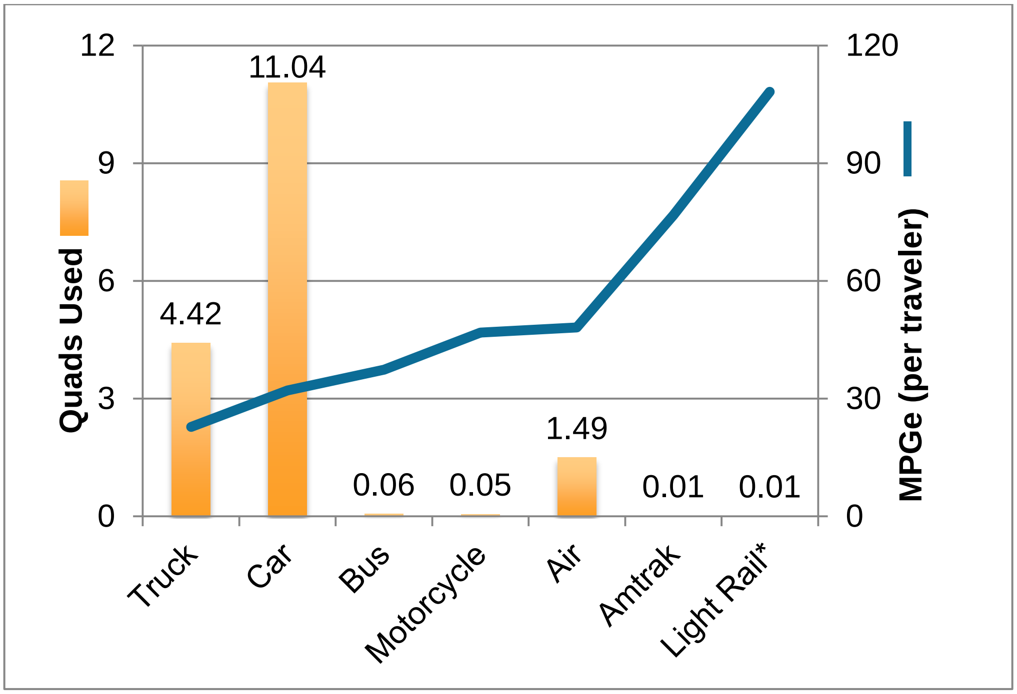

Figure 2: Energy used in personal transportation by mode and efficiency. For each mode, values are based on CY2011. Except for Light Rail, data is derived from USDOT RITA BTS "National Transportation Statistics", 2014 Tables 4-20, 4-21, 4-22, 4-24, and 4-26. MPGe is calculated based on the energy used and the energy content of gasoline, rather than the customary fuels used by each mode of transportation. *For Light Rail, value is derived from the National Transit Database (http://www.ntdprogram.gov/) as a ratio of total passenger miles to energy consumed, from Tables 17 and 19 respectively.

Of course, different modes are not ideal substitutes for one another, and mode choice is only one factor that influences transportation energy efficiency. For a large number of travelers, while shifting to mass transit would lead to energy savings, it also provides lower quality-of-service. Figure 2 also illustrates the importance, in energy terms, of targeting individual travelers. Today, travelers operate more or less independently under a control architecture comprised of uniformly displayed signals and controls and highly variable drivers. Cars and trucks are wasteful, but they are flexible modes that operate at low occupancy, addressing unique personal needs for transportation. In the TRANSNET program, we seek a way to leverage this feature of today's transportation network to provide both better control and improved network energy efficiency.
Technologies based on significantly improved computational capabilities, personalized signals, and control mechanisms will be needed in order to realize this opportunity. The strategic advantage of network control architecture lies in its ability to adjust both the schedule and routing of individual elements, such that optimization becomes both possible and predictable. In transportation networks, the components of such a control architecture are already in place:

- Microscopic simulation models at different scales have been[12], or are being, developed[13] but dynamic, personalized signaling, guidance and control mechanisms have not been considered.

[10] This is derived from the limited access character of railroad, which results in fewer stops, and the low rolling friction of steel-on-steel. For more information, see the Association of American Railroads at https://www.aar.org/keyissues/Pages/Energy-And-Environment.aspx. The rolling resistance of automobile tires is approximately 15-fold higher than rail.

[11] For light rail, which is exclusively electric-powered, energy units were converted as 1 kWh = 3,412 Btu. This does not consider system losses in electrical generation; if those losses are considered, Light Rail efficiency drops to a less dramatic 34.9 MPGe.

[12] Treiber, M. & Kesting, A. "Traffic Flow Dynamics", Springer, 2013.

[13] There are a number of academic and private modeling efforts. See for example "POLARIS", https://www.tracc.anl.gov/index.php/polaris, a project under development at Argonne National Laboratories with funding from FHWA, and Zhang et al "Integrating an Agent-Based Travel Behavior Model with Large-Scale Microscopic Traffic Simulation for Corridor-Level and Subarea Transportation Operations and Planning Applications", J. Urban Plann. Dev. 2013.139:94-103.

- The behavior of controlled dynamical systems can be predicted in advance of experiment using modern computational methods (Computational Fluid Dynamics, for example), so modeling and flow control in transportation networks needn't be a purely descriptive exercise.

- Model based network optimization is widely accepted practice, for example, in power systems and in air traffic control.

Consequently, ARPA-E believes that there are components in related fields of investigation that provide an opportunity for innovation, if these fields can be successfully integrated and the combined technology reduced to practice.

The first step is to develop a high fidelity system-level model of an urban multimodal network. This is expected to be a new effort that may build upon existing transportation models, which in many cases treat individual travelers as agents whose choices are independent, made largely before travel commences. The result of these uncorrelated choices is not optimal for the whole network, as first noted by economist A. C. Pigou in 1920.[14] The model must answer the central question: "What fraction of travelers must communicate directly, and in real time, both with each other and with a control network, to provide significant overall energy savings?" Such a model must not only take into account what happens when travelers communicate and the system is optimized based on personalized signaling and network control mechanisms, but also must be able to be grounded in (and tested by) real world data.

As a second, more important step, personalized signaling and guidance strategies need to be embodied in a control architecture that reflects the incomplete and inaccurate sampling environment of the physical world. This architecture is intended to provide the basis for implementing personalized signaling and guidance in actual urban environments.

Challenges in Measurement

Particularly with the widespread deployment of low cost sensors, the energy used in transportation can certainly be measured with a high degree of accuracy—there is little technological challenge implicit in the development of new energy meters at the level of the mode (car, bus, train, etc.). In practice, however, energy use data is not collected effectively or at the level of the individual traveler, and conceptualizing the problem from the traveler's viewpoint exposes several technological shortfalls. The problem can be reduced to one of mapping the energy used by the mode to the energy used by the traveler.

To illustrate this problem, consider an individual commuter in the Washington (DC) metropolitan area, an area with many different transportation options. Suppose, for the purpose of illustration, that our traveler is a commuter who lives in the suburbs, but works downtown, and uses public transit to get to work. On a particular day, our traveler drives from home to the transit station, parks, rides the DC Metro rail system into work, attends a business lunch across town, and returns home by reversing the steps of the morning commute. During the first leg of the journey, our traveler drives (alone) from home to the train station. Modern automobiles have computer-controlled fuel injectors, such that the precise amount of fuel (and hence energy) used by the vehicle is readily measured, from data available on the On-Board Diagnostics (OBD-II) port that has been mandated in all new vehicles since 1996. During the second leg of the journey, our traveler boards the DC Metro. While the total amount of energy used by the train is certainly known, this data and the *occupancy* of the train is difficult to obtain by any individual traveler, especially in real time. The energy used by the traveler is, of course, the *pro rata* portion of the total energy used by the train, in other words, the total energy use for the mode divided by the occupancy. Next, our traveler arrives at work, ending the first part of the transportation day. Then, at lunch, our traveler has a cross-town business lunch and decides to take a taxi both ways. The OBD-II sensor in the cab can certainly provide precise energy use data to our traveler, with suitable connectivity, but there are additional unknowns. For example, how far away did the cab need to travel (without a passenger) to pick up our traveler?[15] Finally, the energy used in reversing each of these steps is not equivalent to that used in the forward steps, even though the distances traveled may be identical, due to factors such as modal occupancy, local traffic, and parking.

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[14] Pigou, A. C., *The Economics of Welfare*, Macmillan, 1920. A pithy, transportation-relevant treatment is given in Roughgarden, T. "Selfish Routing and the Price of Anarchy", MIT Press, 2005, Chapter 1.

[15] Personalized controls may eventually seek to reward specific choices made by travelers who are also drivers, so, another question is, can the technology differentiate passenger and driver? Note that the traveler occupancy of the cab is 0 when it is not engaged. The traveler and the driver are separate in this case, unlike the first car trip. This example exposes data collection problems associated with vehicle to passenger/driver communication.

Collecting data at the level of the individual traveler is another part of this conceptually simple yet technically challenging problem, even though the overall answers are known: Average daily traffic speeds, fuel sales, vehicle miles traveled, transit ridership, and taxi trips are all tabulated (in principle). But, these data are not without issue: In the real world, sensor reliability and manual reporting reduces the quality of the data.[16] Personal data collection is, of course, treacherous due to privacy concerns,[17] such that it is unrealistic to expect the availability of a comprehensive data set to support any real world system model or control architecture. Fortunately, we believe that the proliferation of sensors in recent years will oversample the transportation network, and redundant data sources (from different sensors) will serve to mitigate at least some of the noise and inconsistency.[18] Regardless, the knowledge of aggregate numbers allows various models to be calibrated using real world data.

B. PROGRAM OBJECTIVES AND STRUCTURE

This funding opportunity solicits the development and testing of new network optimization approaches entirely in a simulation environment. The primary objectives are twofold: (1) To demonstrate that energy efficiency gains are possible through implementable control architectures, and (2) To identify key technology gaps that limit such implementation. A second phase program (if pursued) would involve real-world validation of the system model and trial implementation of the network control architecture developed in the initial phase of TRANSNET. **However, a second phase will only be considered if significant positive impact is demonstrated during the course of the awards made through this FOA.**

Each applicant must develop two interdependent modules: (1) a system model and (2) a control architecture. A system model is a fully parameterized model of a multimodal urban personal transportation network, and must functionally represent the real world. A control architecture is a detailed, comprehensive approach to network control and will be implemented within the system model in the same way it could be implemented in the real world, with the objective to reduce system level energy use by providing signals to individual travelers.

Each applicant should clearly define the incentive structure and the nature of the individual choices to be influenced by the incentives. The applicant must clearly describe how the control architecture will identify the preferred choices and how the response to incentivizing those choices will be introduced as changes in the model system.

The System Model

The system model must have two broad capabilities, (1) the ability to simulate a complete set of data that could be measured/obtained from the real world and (2) the ability to describe traveler behaviors and responses to guidance and control signals in a realistic way. The characteristics of system models that deliver these capabilities are provided in

Table 1 Applications should propose a model that addresses each of these characteristics; however, ARPA-E recognizes that flexibility in the model is required and that model development and refinement will continue during the course of the award.

[16] See for example El Faouzi, NE et al. "Data fusion in intelligent transportation systems: Progress and challenges – A survey", Information Fusion 12 (2011) 4–10

[17] For a transportation-related example, see de Montjoye, Y.-A., Hidalgo, C.A., Verleysen, M. & Blondel, V.D. "Unique in the Crowd: The privacy bounds of human mobility". Sci. Rep. **3**, 1376.

[18] See for example, Bachmann, C. et al., "A comparative assessment of multi-sensor data fusion techniques for freeway traffic speed estimation using microsimulation modeling", Transportation Research Part C 26 (2013) 33–48

Table 1.

Characteristics of the System Model	
DATA & DATA QUALITY	To be defined by applicant. Data must be based on the requirements of the control architecture. Applicants should estimate data accuracy and quality for each source to help with sensitivity evaluation of the model. Sources fall into three classes, public, private, and personal. DATA STREAMS MUST BE CURRENTLY ACCESSIBLE. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) data and communications, while likely to be widely deployed in the future, are *not* widely available in today's fleet. However, Traveler-to-Traveler (T2T) and Traveler-to-Infrastructure (T2I) are omnipresent through wireless devices, and may provide an opportunity to simulate these data.
Public:	These data will serve as the ground truth for the system model and must be comprehensive. Data outside the training set must also be available.
Private:	If used, data providers must be involved, ideally with the data provider as a member of the project team. Privacy features must be incorporated up front, and should be highlighted, where necessary to protect both private and personal data.
Personal:	It is assumed that individual wireless devices associated with each participating traveler will provide this data. Consequently, the applicant should clearly define what data is needed from each traveler and incorporate it into the system model. Real-world parameterization of this specification is expected. Personal data should be collected as needed, rather than as a continual stream, to minimize privacy and bandwidth concerns, but may include a zone around each traveler that is collected using peer-to-peer wireless technologies. See the Control Architecture section for further guidance.
REPORTING	In addition to energy use, other aggregate data, e.g., average vehicle speed and density on key highways and arterials, must be reported for model validation. These data are expected to closely approximate actual measurements, particularly during peak conditions. For transit, similar aggregate measures might include, for example, hourly ridership on public transit. Reporting should also include metrics of quality of service and system reliability (See Definitions).

Characteristics of the System Model (continued)	
MODEL PERFORMANCE	▪ Fast enough to support the testing of a real time control architecture, but need not be "real time" itself ▪ Modular, developed and available under an open software standard.[19] If commercial software is used, the commercial software must be widely and readily available, and the source code for the module(s) developed under this award must be made publicly available. ▪ Written in a widely-available computer language To promote wide dissemination of the model, the standard intellectual property provisions of an award may be modified.
REGION OF INTEREST	US urban region of greater than 3 million inhabitants, based on the 2010 Census and metropolitan statistical areas defined the Office of Management and Budget[20] using a region that has robust multimodal options
DESCRIPTORS FOR PARTICIPANTS	Descriptors for both travelers and drivers should approximate the natural population. Models that employ individualized unique driver or probe data as descriptors will be strongly preferred. See Control Architecture section for suggested implementation of driver behavior in the absence of control.
VALIDATION AND SENSITIVITY ANALYSIS	Performance should be validated using historic data from anonymous sources (e.g., loop detectors) both during normal conditions and after actual incidents. Error rates and missing data parameters should be explicit.
CALCULATION OF ENERGY USED PER TRAVELER	Ability to calculate energy used by each traveler at any given time, and to re-calculate it dynamically as changes occur in traveler's choices and in the network.
CALCULATION OF AGGREGATE ENERGY USED	Aggregate energy use for travelers in the selected region should be calculated to within ±10% of overall estimates published by, or derived from, public sources such as the region's Metropolitan Planning Organization, as well as ±10% within each subcategory as defined by these sources.
DEMONSTRATION OF IMPACT	Determination of how energy reduction depends upon the fraction of participating travelers.
EXPANDABILITY	The model should be constructed to anticipate future technologies. These should be able to be incorporated in a modular fashion.

Supplementary Information:

Teams that expect to employ private data must explicitly involve data providers, with letters of support (at a minimum). Personal data should be assumed to be transmitted by individual wireless devices, but may include data that could be collected locally, including external sources (such as the automobile's OBD-II port) outside the devices themselves. Applicants may propose the use of additional data collection hardware in addition to smart phones and other personal wireless devices, but the applicant must discuss in detail the estimated cost and proposed deployment strategy for this data collection technology.

The system model must have the capability for sensitivity analysis, a process that is intended to simulate imperfections and uncertainties found in real world data, including erroneous, noisy, or missing data (for example, imperfect communications systems), as well as emergent situations such as road closures and traffic incidents.

The model must also report metrics associated with the traveler's quality-of-service and overall system reliability (see Definitions), such that no individual traveler or group of travelers is forced to bear a disproportionate burden. The system

[19] See for example http://opensource.org/osd

[20] See http://www.whitehouse.gov/sites/default/files/omb/bulletins/2013/b13-01.pdf

model must identify and account for the measurement of difficult-to-measure aspects associated with individual participants, such as modal occupancy, openness to mode switching, and personal driving style.

The system model must also be a virtual test bed, capable of an authentic response to realistic personalized signals (see below). These signals will target participants to adjust behavior of travelers and drivers according to modern behavioral theories.[21] The description of both travelers and drivers in this model should thus explicitly factor in their human characteristics.

Model validation protocols are currently envisioned as a set of realistic scenarios (and extreme scenarios) that are intended to determine under what circumstances the system model "breaks". Tests will be designed in coordination with each awardee, to confirm that the model represents a fair and accurate test bed for the control architecture. Further, we anticipate that the system models may become useful tools either for transportation planners or for future transportation control simulations. Consequently, models that are modular and developed under public, open software standards, in commonly used computer languages are preferred. To facilitate this extension, once the program is underway, awardees that have similar approaches will be encouraged to collaborate on their system models, to provide added resources, perspectives, and robustness.

The system model and control architecture described below are strongly coupled. Because it may be easier for applicants to envision a control architecture that relies on a complete parameterized model of the transportation system, one approach is to construct a reduced complexity model based on sampling specific information from the system model. In this case, the development and validation of the reduced complexity model against the system model will be an important deliverable. Further, if this approach is taken, the control architecture and the reduced complexity model must be able to run concurrently with the system model itself, such that decisions and control outputs can be fed back into the high fidelity system model to evaluate the impact of the control architecture in a real-world, real-time setting.

The Control Architecture

The control architecture is a key deliverable. Developing a control architecture that interacts with the system model will allow ARPA-E to assess the usefulness of personalized control for energy savings in transportation. The control architecture should be scalable, thus capable of quantifying micro-, meso-, and macro-scale impacts of control on real-time reduction of energy use.

The characteristics of the control architecture are provided in Table 2. Applications should devise an architecture that addresses each of these characteristics; however, ARPA-E recognizes that the specifics of the architecture will evolve during the course of an award as tested via simulation using the model system.

Table 2.

Characteristics of the Control Architecture	
EVENT HORIZON	Successful controls will show statistically significant reduction in energy use based on predicted state, mode, and energy use of the system at least 15 minutes into the future.
PERSONALIZED DATA AND PARTICIPATION IN CONTROL STRUCTURE	Control scenarios should assume that only a small portion of those eligible participate, but may include a zone around each participant that utilizes peer-to-peer wireless technologies as presently embodied. The impact of the approach needs to be evaluated at varying degrees of technological penetration, so this is essentially a sensitivity analysis based on the number of control nodes in the network.

[21] There are many examples of this type of approach, too numerous for this document. For a concise guide to possible approaches, see http://peec.stanford.edu/docs/energybehavior/Data Jam - 5 Behavioral Techniques Guide.pdf

RESPONSE TO NETWORK CHANGES	Capable of rapid response to traffic incidents, providing relevant, wireless signals to travelers within 30 seconds of the time of the incident (and updated thereafter as the extent of the disruption caused by the incident becomes clearer). This constraint will affect data collection frequency and density.
DIMENSIONAL SCALES OF ENERGY EFFECTS	Micro-:[22] At this scale, individual travelers are observable as individuals, and naturalistic variations are evident. Meso-:[23] At this scale, traveler demand is aggregated across a region. Mesoscale zones should be no larger than 0.5 mile in radius. Microsimulated zones interact with one another in an open fashion, but interaction is limited to exchange of individual travelers between zones. Macro-:[24] This is the entire scale of the transportation simulation. Mesoscale zones interact with one another in a closed fashion to describe the entire region.
	Characteristics of the Control Architecture (continued)
QUALITY OF SERVICE	Based on travel time (with expected statistical uncertainty) for each traveler in the uncontrolled model, an increase in travel time upon control is never statistically significant (p<0.05)
SYSTEM RELIABILITY	Based on travel time (with expected statistical uncertainty) for all travelers in the uncontrolled model, the distribution of travel time upon control is never statistically broader (p<0.05)
WIRELESS DELIVERY OF SIGNALS	Required. Signals should be provided after an incident to affected travelers within 30 seconds.
INTENT	Patterns and historical data should be incorporated, but, for sensitivity analysis, applicants should assume that a variable fraction of the participants are willing to enter detailed trip information (e.g., destination).
CONTROL STRATEGIES	Applicants should employ individualized control strategies that are grounded in modern behavioral science, rather than those based on broad economic principles. Active control should influence energy use at the system level, and impact of control must be quantifiable in energy terms.
TRAVELER DECISION CRITERIA	In the absence of a control signal, model should assume that traveler decisions are essentially independent of all other travelers (i.e., a Nash equilibrium), based on anticipated total travel time. In the presence of a control signal, participants are expected to respond in a probabilistic way, providing an alternative response when a personalized control signal is presented.
CAPABILITY FOR EXPERIMENTAL OPTIMIZATION	Personalized controls should incorporate intrinsic variables that can be adjusted to optimize participant responses when presented with a control signal. It is understood that each participant will not be individually predictable, but will instead show reproducible statistical tendencies are a population.
IDENTIFICATION OF KEY TECHNOLOGY GAPS	Applicants should identify key gaps in hardware of software that would be required to implement the proposed control architecture in the real world. Anticipated gaps in hardware and software might include: occupancy meters, driving style meters,[25] intent sensors (e.g., two-way turn signals), hands-free delivery of diverse personalized signals, traveler-to-traveler or traveler-to-infrastructure communication, and intent prediction algorithms.

[22] Hollander, Y. & Liu, R., “The principles of calibrating traffic microsimulation models”, Transportation 35: 347-362 (2008)

[23] In mesoscale transportation systems, the statistical nature of local traffic can be used to develop a fluid-like conservation model of traveler flow, with average characteristics such as traffic velocity and vehicle density taking the place of individual travelers. See Horowitz, Roberto. (2003). Development of Integrated Meso/Microscale Traffic Simulation Software for Testing Fault Detection and Handling Algorithms in AHS: Final Report. California Partners for Advanced Transit and Highways (PATH). UC Berkeley: California Partners for Advanced Transit and Highways (PATH). Retrieved from: http://www.escholarship.org/uc/item/61z020hf

[24] The macroscale simulation is essentially the entire simulation described by the virtual test bed.

[25] See Progressive Insurance SnapShot, http://www.progressive.com/auto/snapshot-common-questions/

Supplementary Information:

The control architecture should facilitate interactions with other micro- and mesoscale zones and routing infrastructure (e.g., traffic lights) and should query modes of transportation using a common protocol, where feasible. A personalized control architecture with partial adoption is important because, in contrast to today's dominant traveler control mechanisms (i.e., road signs, signals, etc.), new individualized controls are unlikely to be adopted immediately and universally. Therefore, applicants must objectively assess the participation level for personalized guidance and control where they begin to have a measurable impact on energy use. This architecture must therefore use <u>incomplete</u> data sampled in a realistic way.[26] The control architecture should be designed to overcome bandwidth, privacy, and analysis issues generated by the now dominant "collect first, interpret later" strategy.[27] Further, the control architecture must assume that individual (personal) information will be available from a wireless app primarily from opt-in participants and thus will provide data only on an as needed basis, rather than as a continuous stream. This is not a rigid requirement: Simulations that rely on large amounts of largely anonymous (or anonymized) cell phone tower data are entirely appropriate and will be considered.[28] The intent is to provide for system-wide information acquisition from anonymous (or anonymized) data sources (which must be available today), supplemented and enhanced by personal data collected from a subset of participants, who will have opted both to provide more granular data and to be network control points. One approach to this is a query-response architecture that has direct or indirect access to data commonly collected by commercial transportation apps on a mobile device such as Google Maps and Inrix. Applicants should assume that data from all travelers would be fed into the control architecture through wireless communications.

Optimization algorithms should assume that the data, particularly from travelers, is of variable quality. The practical capacity to sample in the real world depends on the (limited) bandwidth of the network. Thus, while sampling of wireless sensors (as embodied in the wireless devices that individual travelers carry) will be limited both by penetration and bandwidth, the use of aggregate data streams based in the cloud (such as those available from the Google Maps "traffic" feature) is encouraged. Disproportional leverage by small groups of participating travelers is not unprecedented, since computational studies of congestion behavior show that the re-routing of only a few percent of the vehicles can lead to substantial reduction in congestion for all travelers.[29] For example, during periods of congestion, numerous analyses indicate that an improvement in efficiency is possible in theory through a more informed route selection:[30] The control architecture should attempt to quantify this expected improvement using practical personalized controls and real world data.

Unforeseen events such as traffic incidents, as well as foreseeable events such as road closures or anomalous traffic due to specific occasions, occur frequently, so the control architecture must lead to accurate and timely predictions of resulting <u>changes</u> in traffic patterns. The control strategy should predict changes in patterns as needed for control computation, but the system model should be able to represent/capture any non-nominal behaviors. Because the responsiveness to unforeseen events is crucial during periods of high volume, in particular, the model must be capable of rapid control and readjustment to enable rerouting of responsive travelers in a timely fashion.

Because the control architecture will be benchmarked against the system model also specified by the applicant, the two must be closely aligned. Key data needed for the control architecture must be gathered and processed in a timely fashion, both from the system model and in the real world. The control architecture will be evaluated as a predictable response of the system to differential, personalized controls.

ARPA-E seeks control strategies that are grounded in modern behavioral science.[30] The use of broad, non-personalized economic incentives as controls will <u>not</u> be considered adequate for this solicitation. Examples of these discouraged incentives include variable tolls tied to a group of travelers (rather than the individual traveler) and collective incentives such as preferential lanes.

[26] For many examples, see Roughgarden, T. "Selfish Routing and the Price of Anarchy", MIT Press, 2005.

[27] See Bertolucci, J. "Big Data Fans: Don't Boil The Ocean", Information Week, May 12, 2014. http://www.informationweek.com/big-data/big-data-analytics/big-data-fans-dont-boil-the-ocean/

[28] See for example Wang, P., Hunter, T., Bayen, A.M., Schechtner, K. & Gonzalez, M.C. Understanding Road Usage Patterns in Urban Areas. Sci. Rep. **2**, 1001

[29] See for example Robert A. Johnston, Jay R. Lund, and Paul P. Craig (1995). "Capacity-Allocation Methods for Reducing Urban Traffic Congestion." *J. Transp. Eng.*, 121(1), 27–39.

[30] Wardrop, J. G.; Whitehead, J. I. *op cit*. For a more recent treatment that suggests even more improvement is possible, see Kerner, BS, *J. Phys. A: Math. Theor.* 44 (9) [2011].

Personalized signals should be targeted at selected participants, including both travelers and drivers, but these signals must intentionally influence energy-related transportation choices (e.g., mode, departure time, etc.) by travelers. Selection of these participants must be justified, where possible, through market adoption analysis based on the diversity and variation of Americans, rather than simply assuming statistically random participation. Thus, potential participants should be grouped based on their likelihood of adoption of the technology (e.g., a smartphone app combined with a particular personalized signal approach) and the probability of their affirmative response to a positive guidance and control signal—this can be approached essentially as a market segmentation exercise. Signals should not presume that the traveler is, or wishes to be, particularly energy aware or influenced by potential savings, either in energy or in cost. It will be more important to anticipate systemic energy reduction through personalized control signals than to make more participants aware of their energy choices.

Applicants will be asked to numerically estimate the impact of deployment of the proposed technology at various levels of participation and responsiveness and thereby determine, among other things, what fraction of participation is needed for impact. If implemented in the real world, signal strategies are expected to be refined experimentally (based on responsiveness and predictability), such that a direct feedback of the effectiveness of the signal must be implicit in the signaling architecture. Consequently, this control architecture must be designed to allow for trials and evaluation of different signal approaches to measure the effectiveness of different incentives strategies.

The response to a signal must be relevant to energy use by the traveler, e.g., changes in route, departure time, and mode, etc. While specific, punitive financial controls such as congestion pricing are excluded (as being known strategies), specific non-punitive financial controls such as coupons, tax relief, etc., will all be considered, provided they are personalized.

ARPA-E is interested in identifying key technology gaps allow that enable the control architecture to interact with the real world more effectively without extensive human input or interaction. In some instances, like the OBD-II connector mentioned previously, the essential technology is already deployed and Bluetooth® connectivity to wireless devices is already commercially available.[31] In other instances, however, technologies for measuring crucial parameters (such as modal occupancies) in a seamless, automatic fashion are more challenging. An applicant’s concept may show significantly better performance when data that is currently unavailable from already-deployed sensors, either from modes or from personalized devices, becomes available. Applicants should identify both the new technologies (hardware or software) required and the data these will provide.

[31] See for example the OBDLink LX Bluetooth Scan Tool, http://www.scantool.net/obdlink-lx.html

D. TECHNICAL GLOSSARY

Participant	Either a traveler or a driver who opts-in voluntarily to participate in the control architecture
Traveler	The individual who has a need to move from one place to another
Driver	The individual who controls the mode. For the predominant mode, single-occupancy vehicles, the driver and the traveler are identical.
Mode	The specific transportation vehicle (car, bus, train, etc.) by which a traveler is moved
Route	The path by which the traveler moves. This is the traveler's personal choice.
Personal transportation network	The segment of the transportation sector that is involved in moving travelers in and around an urban center.
Personalized Signals	Information and incentives provided to individual travelers and drivers intended to affect their decisions while participating in the personal transportation network. *[Note: Only a limited number of* participants *will be available for personalized signaling.]*
Network Control	A predictable response of the personal transportation network to personalized signaling
New infrastructure	Deployment of additional resources, in the form of new roadways, new signals, or new sensor networks independent of personal mobile devices, as a prerequisite for real-world implementation.
Quality-of-service	Referenced to today's travel experience, primarily in terms of departure and arrival times. It is the overall measured or perceived performance of transit service from the traveler's point of view.[32] It has long been known that the efficiency of the transportation network during times of congestion is suboptimal (see Wardrop's Principles).[33] This can be framed as a shift from a selfish, Nash equilibrium (where individuals make independent choices that lead to a suboptimal solution) toward a more efficient system optimal equilibrium (where collaboration among individuals leads to a better situation for all).
System Reliability	The consistency of on-time arrival,[34] based on the expectation of the traveler. These are primarily related to travel time reliability: the consistency or dependability in travel times, as measured from day-to-day and/or across different times of the day.

E. APPLICATIONS SPECIFICALLY NOT OF INTEREST

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.C of the FOA
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed solely at discovery and/or fundamental knowledge generation.

[32] See: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp100/part 3.pdf
[33] Wardrop, J. G.; Whitehead, J. I. (1952). "Correspondence. Some Theoretical Aspects of Road Traffic Research". *ICE Proceedings: Engineering Divisions* **1** (5): 767.
[34] See: http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/Pages/Reliability_159.aspx

- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).
- Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.
- Applications that propose the following:
  - Applications that propose examining only a single transportation corridor or sub-region with limited population (< 3 million inhabitants).
  - Applications that focus primarily on freight demand and goods movements.