Response to:

U.S. Department of Energy (DOE)
Advanced Research Projects Agency – Energy (ARPA-E)
DE-FOA-0001199
Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation

Submitted By:

University of California – Berkeley, Institute of Transportation Studies

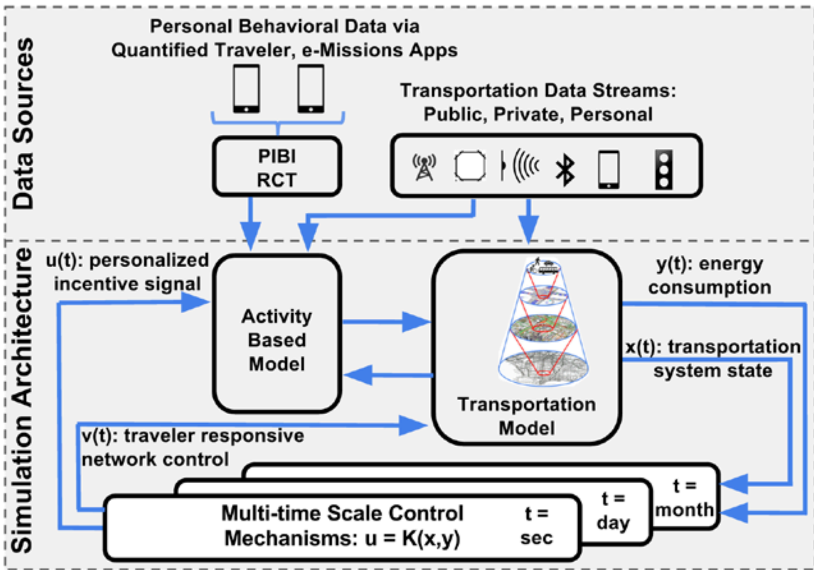
Title: Traveler Routing, Assessment, and Control for Energy Savings (TRACES)

Primary Investigator: Alexandre Bayen

EXECUTIVE SUMMARY

Urban transportation in the United States is changing. While use of public transportation, non-motorized options, and the shared transportation economy are growing, travelers increasingly rely on convenient personalized information. Many millennials are unlikely to even acquire a driver's license. Despite these trends, energy-intensive transportation choices prevail in metropolitan areas and represent 25% of total US energy consumption. New strategies are needed achieve long-term behavioral shifts toward energy-efficient modes with large-scale network optimization in order to achieve deep cuts in transportation-related energy consumption and greenhouse gas emissions.

To meet this need, The University of California – Berkeley (UCB) proposes a $5,548,370 (with 11% TPC cost share), 30 month program: Traveler Routing, Assessment, and Control for Energy Savings (TRACES) platform, as depicted in Figure 1. This pioneering system model and control architecture is designed to realize large-scale behavioral shifts to energy-efficient modes in addition to real-time network controls that maximize long-term sustainable energy savings. It will demonstrate, in simulation, potential energy savings of 0.05 Quads in just the Los Angeles metropolitan area. If TRACES is scaled and implemented to all the major metropolitan areas in the US, we estimate potential energy savings of 1.03 Quads.



Schematics of the TRACES architecture

The successful implementation of the novel TRACES architecture will radically transform US transportation. TRACES can determine and deliver optimal personalized signals that consider both human behavior and the real-time network state (e.g. congestion events, accidents, transit occupancy). For the first time, transportation agencies and private companies alike will benefit through shared data and control. The collaboration will decrease both system congestion-induced energy consumption and individual energy consumption, without compromising quality of service. Upon successful demonstration in a simulation informed by real-world data, the highly replicable TRACES platform can be implemented in commercial applications to drive significant emissions reductions and energy savings throughout the US.

1.1 Overall Description

TRACES Platform – Targeting Deep Energy Savings in the Transportation System

Transportation in the United States is changing. There is an increasing reliance on public transportation and non-motorized transport options in urban areas; many millennials often do not even own a driver's license. At the same time, travelers have access to an unprecedented amount of individualized travel information through Google, INRIX, and other services. Individuals may soon have the ability to use real-time information to inform travel choices based on cost, time, environmental impact, and more. In addition, new systems like UberPool and LyftLine are making it easier to connect travelers and increase vehicle occupancy and utilization. Vehicle occupancy, however, is still only 40% of nominal capacity. While individual access to information and travel options has vastly expanded, optimization of the transportation system remains elusive. Today's traffic management systems do not integrate and leverage the disparate sources of transportation network data to optimize and improve the efficiency of the overall system. A persistent, large-scale behavioral shift toward mode efficiency and trip volume reduction needs to be coupled with a fully integrated transportation network in order to achieve long-term, deep cuts in transportation energy consumption, which currently accounts for 25% of all energy used in the US and an estimated 28% of greenhouse gas emissions.

We propose the Traveler Routing, Assessment, and Control for Energy Savings (TRACES) platform as the solution to overcome these inefficiencies. TRACES will be the first simulation architecture to simultaneously optimize both long-term, large-scale transportation behavioral change and short-term network and vehicle in-use change to maximize energy savings. The University of California – Berkeley (UCB) Institute of Transportation Studies (ITS), in conjunction with Lawrence Berkeley National Lab (LBNL), Cambridge Systematics (CS) and Systems Metrics Group (SMG), proposes to develop this innovative project to demonstrate that impactful energy efficiency gains are possible through an implementable control architecture.

This proposal has the following objectives:

1. Accurately understand and predict individual traveler behavior from real-world data, in order to simulate the impact of information, incentives, and operations on energy consumption.
2. Accurately understand and predict metropolitan mobility options with energy consumption.
3. Develop an incentivization and communication structure that will effectively induce users to make long-term, persistent, and testable shifts to energy-efficient transportation choices.
4. Produce recommendations to optimize transportation network efficiency based on human behavior models of travel choices.
5. Validate recommendations through displayed reductions in energy use, emissions and congestion in simulation.
6. Apply these finding, using a multi-scale simulation, to the Los Angeles metropolitan area, the second largest city in the US.
7. Transition TRACES technology to market to enable real-world implementation.

Given these objectives, the proposed system will operate through the following (as shown in Fig. 1):

Within the Activity Based Model (ABM) (a), the traveler behavioral models will be developed, run, and calibrated through real-world observations and behavioral testing of individual travelers. Behavioral models will inform simulated traveler mobility within all levels of a Telescopic Traveler Mobility model (b) and will thus propagate impacts of user decisions throughout the network, across the four scales of this integrated model. Models (a) and (b) will be combined with associated energy consumption models to account for energy savings generated by behavioral change and the resulting impacts on traffic. The output from these models will feed into multi-timescale control mechanisms (c), which output personalized signals to users in the system.

Upon successful demonstration of the integrated simulation architecture, the development team will engage with end users to determine a pathway for commercialization and implementation in the LA area, with replication capacity throughout the US. This project is based on over a decade of transportation, modeling and network architecture development work completed by UCB, LBNL, CS and SMG. The team will be complemented by a robust advisory team of industry leaders in the field: INRIX, HERE (NAVTEQ/HERE/Nokia), Google, AT&T, TSS, TomTom, IBM, Siemens, Toyota, Ford), each of which has a past history of collaboration with our group. Five of these companies (INRIX, HERE, AT&T, ITERIS, Automatic.com) have committed to share data with this project at no cost.

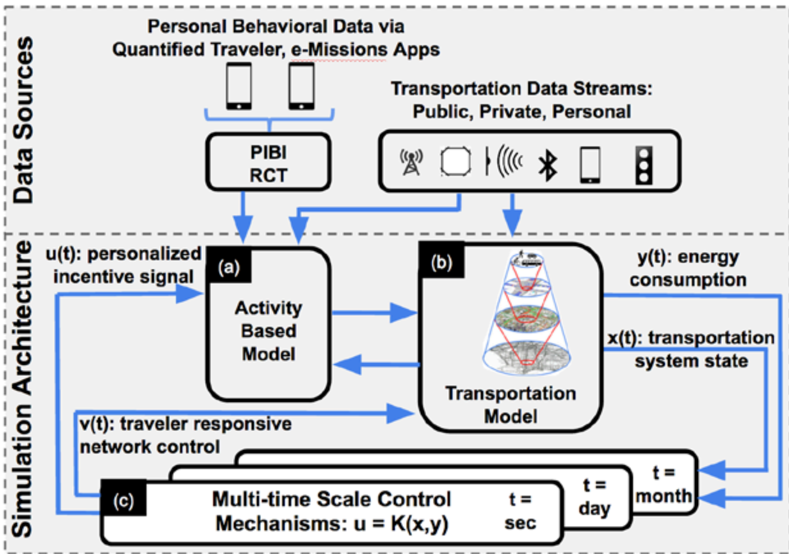


Figure 1: Schematics of the TRACES architecture.

1.2 Potential Impact

Problem Addressed The successful implementation of the TRACES architecture has the capacity to radically transform transportation in the US. Currently, the everyday travel choices made by people in the US are very energy intensive and mostly rely on suboptimal travel advisory systems. Private sector services (Google/Waze, TomTom, INRIX, HERE, Apple) aim only to improve short term travel conditions for the individual, but do not consider how individual-scale signals affect the overall network efficiency, nor do they have access to system level data. As a result, the best the private sector can do is to "learn" the traffic by gathering data, which has been shown many times [55] to lead to sub-optimal less efficient solutions at the system level.[1] On the other hand, transportation agencies operate the travel infrastructure, but do not possess the proper decision support systems to influence travelers, nor can they leverage the data or communication streams maintained by the private sector and are therefore unable to conduct individual demand management or traffic control in a personalized manner. Large-scale mobility data analytics tools to support such needs are not currently implemented in the US.

The novel TRACES architecture has the capacity to address these issues by (1) introducing personalized control signals for maximum system energy efficiency and (2) integrating individual responses with multimodal mobility management at the network scale. For the first time in history, we will demonstrate, in simulation, the ability to bring public transportation agencies and private sector companies together to collaboratively decrease both individual energy consumption and congestion-induced energy consumption.

Disruptive nature of the solution. TRACES creates a technology platform to enable an energy-efficient transportation system without sacrificing individual level of service. This new platform can be used to the benefit of both public transportation agencies and private sector companies. This relies on three disruptive breakthroughs in a combination of research fields:

- Data-enabled behavioral science, applied to large scale mobility management
- Coordination of control on the demand side and the supply side
- Large scale urban data analytics

Upon full commercialization of the project, private sector companies that make use of the recommendations provided by the TRACES platform would immediately experience a competitive advantage. TRACES data will radically improve user guidance, so non-adopters would not benefit from the information owned (and not shared) by the transportation agencies, such as timing plans for traffic lights, planned coordination, and playbooks. Successful implementation of the concepts and techniques developed through TRACES will enable transportation agencies to improve traffic and influence private sector traffic management. The private sector is incentivized to optimize operations of the network as a whole and will benefit from access to information that has traditionally been unavailable to them.

The control strategies developed for this work will show statistically relevant reduction in energy use, in simulation, based on the behavioral models implemented in the system. The scenarios rely on a small subset of participants (Nash-Stackelberg (NS) framework), based on personalized incentivization achieved through connected devices. The simulations will occur at four levels simultaneously (micro-, meso-, macro- and agent based), with energy savings accounted for at all levels (vehicular at micro- level, and mode, trip, and modal orientation behavior at the individual traveler level). Agents' specification in activity-based layer will be extended to represent decision-making functionality (activity planning, mode choice, destination location choice, social coordination logic, shared vehicles and rides, route choice, re-route aversion) according to the model of behavioral response developed in this work. Individual-level behavioral response models will be developed that reflect the influence of the innovative incentive mechanisms, grounded in behavioral science and targeted on long-term changes.

Commercial deployment of TRACES will offer an interface to inform a range of private sector travel advisory systems in a coordinated fashion. A new generation of advanced travel

[1] "LA Neighborhood blames Waze App for Morning Traffic Jams," Dina Abou Salem, ABC News, Dec. 2014.

advisory information systems (Google, Apple, TomTom, INRIX, HERE, 511) will include personalized behavioral interventions (social norming, environmental and public health messaging, injunctive instruction, monetary incentives, etc.). Moreover, this interface will inform private sector implementations of connected cars, automated vehicles, and vehicle-to-infrastructure coordination/communication (see letters of support from AT&T, Google, Toyota and Siemens). The successful real-world implementation of TRACES will have the capacity to radically impact both energy use and emissions reductions, while also generating massive monetary and time savings. As outlined in Fig. 2, if TRACES is scaled to areas that total 100 million single occupancy vehicle trips each day, it will result in energy savings of 1.03 Quads per year. This will avoid 102 million tons of CO_2 emissions and fuel cost savings of nearly $25 Billion. One of the benefits of the TRACES approach is that it relies on data that is ubiquitous, hence the platform can be replicated and applied to any other region in the US. Data provided by project partners AT&T, INRIX, HERE, etc. are accessible at the national level, not only for LA. This will allow TRACES, upon validation, to be implemented in multimodal population centers throughout the US, exponentially increasing project impact.

1.3 Innovativeness

The TRACES project represents a breakthrough for the transportation network as it will enable, upon commercialization, a process for real-time communication of highly accurate, energy-efficient travel data to individuals, while simultaneously optimizing the efficiency of the transportation system. Through the commercialized version of TRACES, individuals will benefit from a simple, optimized product that will enable informed travel decisions and incentivize behavior that increases energy efficiency and reduces GHG emissions. The TRACES model will provide the first integrated system that integrates behavioral incentives with individual and metropolitan scale data to generate an optimized transportation planning system. The metrics by which the success of the control architecture will be measured are (1) final energy saved, (2) greenhouse gas emissions avoided, and (3) the mean (i.e. quality of service) and variance (i.e. reliability) of travel time are not statistically increased. The ability to achieve this transformational product relies on innovation in six key areas:

Shift from single occupancy vehicle to	Energy savings from shift (%)	% Of travelers shifted	Energy saved (Quads) by shifting 100M travelers
Trip Elimination	100	1.00%	0.034
Non-Motorized mode	100	3.00%	0.102
Commuter Rail	90	5%	0.152
Transit Bus	75	4.00%	0.102
3 person carpool	67	25%	0.567
Eco-Driving	5	25%	0.042
Congestion relief	2	50%	0.034
Total Energy Savings (Quads)			**1.03**

*Assumed single occupancy traveler fuel efficiency 25 miles/gallon
*Assumed single occupancy distance traveled per day 20 miles

Figure 2: Energy saving potential of TRACES

Energy Reduction. We seek to quantify, for the first time, transportation network energy reduction given the following three elements: 1) personalized incentive mechanisms (social norming, environmental and public health messaging, injunctive instruction, monetary incentives, etc.); 2) probabilistic individual response rate; 3) economic value of time, energy, emissions and quality of service.

Accuracy at scale. No prior effort has tackled simulation of metropolitan areas to this degree of accuracy with the proper model calibration and validation process. To our knowledge, mesosimulation models have not been calibrated and validated at this scale and accuracy to represent true traffic conditions and travel demand.

Coordinated demand and supply control mechanisms. The proposed project integrates models of network control mechanisms, which have never been used in coordination before, such as personalized behavioral intervention coordinated with infrastructure control.

Integrated Mobility-Energy Consumption Models. Energy consumption models will be integrated with mobility models to predict energy consumption at the individual trip level, including modalities such as personal vehicles, busses, light-rail, and freight trucks.

Behavioral Economics Integrated with System Simulation. To date, no system transportation model has been interfaced with behavioral economics models to directly quantify the effects of behavioral changes on regional-scale energy consumption. Using a randomized controlled trial, we will: 1) test behavioral interventions deeply rooted in existing behavioral theories and evidence; 2) measure outcomes based on objectively observed behavior; 3) combine interventions to maximize the likelihood of a successful response rate; 4) introduce an element of personalized information, which will lead to future intervention design that can be highly targeted based on individual behavior; and 5) integrate results from the behavioral models into the large scale transportation simulation, incorporating the impact of human behavior on energy consumption.

Data. Our team has access to an unprecedented variety of data. These data include 1) all the Call Data Records (CDR) from AT&T for the entire state of California (including nearly half of the population of all of Los Angeles), 2) hundreds of millions of GPS data points from two major providers -- INRIX and HERE -- amounting to millions of trips, 3) infrastructure data from dozen of dedicated feeds (thousands of traffic sensors, cameras, Bluetooth readers, license plate readers, signal timing plans, metering lights, changeable message signs), 4) data feeds from energy consumption apps and devices from connected cars, as well as 5) traffic information providers (INRIX, HERE, 511, PeMS, Automatic.com, myGreenCar, e-Mission). These sets of data, which can be bundled to characterize the entire trips of a user, significantly improve our capacity to understand consumer behavior. Energy consumption and cell phone details have enabled comprehensive knowledge of specific trip details on a per mile basis outside of GPS data. TRACES represents the first confluence of data streams incorporated in a single transportation project.

2. PROPOSED WORK

TRACES Platform – Targeting Deep Energy Savings in the Transportation System

Deep reductions in transportation energy consumption and greenhouse gas emission are possible via large-scale, sustained behavioral shifts to more efficient modes, reduced trip volumes, and optimized routing. The TRACES platform will be the first of its kind to simultaneously optimize long-term, large-scale transportation behavioral change to maximize energy savings and short-term network and vehicle in-use energy savings in simulation. Estimated energy savings resulting from a traveler shifting from a single occupancy car/light truck with no eco-driving or awareness of congestion are as follows:

1. Trip elimination due to provision of desired service in place = 100%
2. Non-motorized mode = 100%
3. Commuter Rail (at 80% occupancy) = 90%
4. Transit Bus (at 80% occupancy) = 75%
5. 2 or 3-person carpool rideshare = 50 - 67%
6. Eco-driving of personal car/light truck = 5 – 15%
7. Congestion relief through rerouting of single occupancy vehicles = 2 – 15%

Largest savings derive from long-term shifts of types 1-5. Shifts of type 6 and 7 yield smaller savings on a per traveler basis, but can yield large savings due to the prevalence of single occupancy car travel. The near zero, low-end savings estimates for eco-driving result from reversion of driver behavior in the long-run, if implemented manually. Similarly, according to the NS framework, congestion is likely to be re-induced in the long-run, resulting in low energy savings. The *Personalized Incentivization and Behavioral Interventions* (PIBI) of the TRACES platform focuses effort on long-term, sustained shifts in options 1-5 above, while operating on shorter time scales to yield efficiency improvements in 6 and 7. Our focus is not only on short-term trip decisions, but we also aim to steer behavior away from traditional reliance on personal use vehicles and towards lifestyles that utilize alternative, less energy intensive options.

TRACES consists of a lifestyle based activity and travel demand model, a telescopic four-tiered mobility model and control architecture to support simulations that impact behavioral change on transportation energy consumption (Fig.1). The model will shift through various scales of population density and user behaviors to predict influences of incentivization signals on traveler action and corresponding reductions for energy consumption and emissions. In addition, the system will enable the integration of a wide variety of individual traveler data to produce recommendations to improve system efficiency faster than real time. The system will be demonstrated at the scale of the LA Basin, a US urban region with nearly 18 million inhabitants. The proposed project site contains over 7 million inhabitants, accounting for a minimum of 3.041 million inhabitants considered in the modeled region, with associated travelers (see Figure 3).

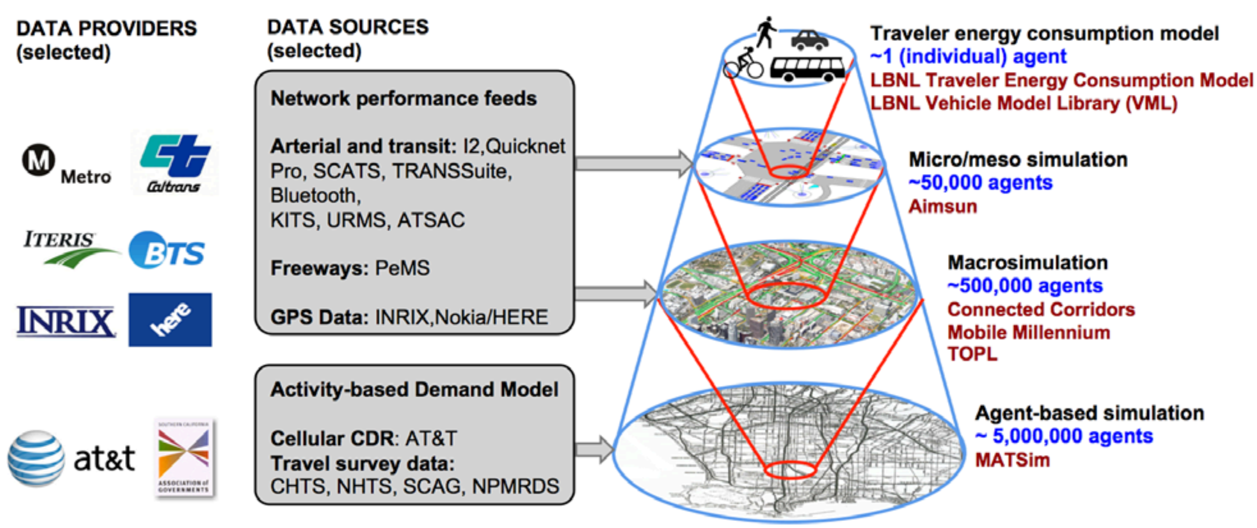


Figure 3: Telescopic TRACES model, with four model layers, and corresponding (selected) data sources currently used by the team.

This system will quantify, for the first time, transportation network energy reduction given the following three elements: 1) personalized intervention and incentive mechanisms; 2) probabilistic individual response rate; and 3) economic value of time, environmental impact and quality of service.

2.1 Approach: TRACES Model Development, Calibration, Validation, and Deployment

The proposed work builds on significant assets developed at UCB/LBNL, each supporting one layer of the telescopic model. In order to achieve the effective simulations, the Agent-Based Microsimulation (ABM) will provide the 3M+ scale simulations required. Through layers of the telescopic model, energy consumption will be computed at the individual vehicle level. This architecture will enable integration of the four proposed layers (Fig. 3: component (b) of Fig. 1).

Agent-Based Microsimulation (individuals). ABM is a computational approach that handles complex interactions within and between coupled social, environmental and infrastructure systems. The agent-based layer of TRACES builds upon MATSim [10, 47], the well-established open source multi-modal transportation micro-simulation engine. In MATSim, agents adapt travel behaviors in order to accomplish a set of prescribed mandatory (home, work, school) and discretionary (shopping, leisure, social, etc.) activities. Each activity brings an associated utility, accounting for lateness/earliness in accomplishing it in time [24]. Travel between activity locations carries a mode-specific time and cost disutility. Co-evolutionary programming is applied to maximize utilities over person-specific feasible activity subsets, departure times, modes and routes on the network at metropolitan scales. To shift the computational load towards optimization over agent behavioral choices and achieve scalability, MATSim traffic flows are based on the simplified [70] kinematic wave model [62,85] with computationally efficient link [78] and node [36] representations. The Berkeley AMPLab Spark cluster processing software stack will be used to further scale the optimization step. While the outcomes of this layer will include details such as mode choice, distribution of vehicle type by population, and routing under congestion, it cannot assess vehicle energy consumption based on traffic dynamics, nor is it aligned with supply-side control methods; more detailed traffic modeling levels are required.

Macrosimulation. The project will leverage a rich suite of macrosimulation models developed at UCB in the last decade. These models have produced a computational engine called *Connected Corridors,* which integrates earlier engines developed at UCB, in particular *Mobile Millennium* [12] and *TOPL* [26]. *Connected Corridors* also includes various macroscopic models including *Lighthill Whitham Richards* (LWR) [62,85] and perturbed and second order models [8,21] in their discretized form, in particular using discretizations such as the Godunov scheme [41,61,101] or the Cell Transmission Model (CTM). The system is capable of implementing all features of the US arterial system, i.e. how vehicles behave at intersections (traffic lights, permissive turns, protected turns etc.) [81,3,4]. This will enable simulation of "what if" scenarios [99], forecasting [88, 46], estimation [109], data assimilation [19], aggregate emission and energy consumption estimation [89] and control and optimization [83]. The system has been used since 2009 to simulate and perform real-time estimation of traffic in the entire San Francisco Bay Area, for all roads of category 1 to 4 in the NAVTEQ / OSM map classification, i.e., any major arterial to freeway. This system will be replicated for LA. TRACES will create and implement disaggregation techniques to translate aggregate states of the macroscopic models (density and flows) to individual vehicles in the higher precision models (micro- and meso) to account for the energy consumption. This requires modeling and algorithmic work, leveraging significant past achievements [27,69,7,77] on car-following models, extensions, and disaggregation techniques.

Mesosimulation. Our team developed the largest calibrated mesoscopic simulation model in the US in 2014 for LA. UCB will extend existing mesosimulation model data using Aimsun (see letter) to seamlessly integrate the meso and microscopic simulation layers. This dynamic assignment platform combines transportation network and individual traveler tracking every second. The proposed solution will process in near real time all types of traveler responses to changing conditions including route diversion, mode shift, and time of day. Extensive micro-models of the LA region will be integrated with the so-called *gateway cities* meso-model (developed by our team member Cambridge Systematics), which includes the regions in Fig. 4, as well as all light rail and express bus lines to model transit mobility problems.

Microsimulation. To produce trajectories with accelerations for consumption models, the team has extensive experience with advanced transportation modeling systems and will use the commercial Aimsun traffic platform produced by our partner Transport Simulation Systems (TSS) [103], which is currently integrated into the *Connected Corridors* platform. Our computational resources can enable faster than real-time implementations of these models on *high performance computers* (HPC), such as the NERSC cluster (see letter) used for this work and Amazon EC2 clusters available to us through the AMPLab (see letter). Both UCB and CS have a long standing working relation with TSS (see letter); for years TSS has embedded its staff at UCB to jointly work on common projects (*Connected Corridors* in particular).

Integration of the models. The project spans an area covering 3.041 million inhabitants; it is likely that we will expand it through the project. Figure 4 shows the geographic reach of simulation capabilities of the team, based on calibrated models (in red and green); with the potential additional area (yellow). The area covered by MATSim expands beyond the boundary of the figure. Our work will involve running existing algorithms on new sources of data, and ultimately developing new algorithms if new data types are used. This will be implemented on the NERSC cluster for computational efficiency, and will produce individualized velocity and acceleration profiles capable of feeding the energy models described below, at the scale of individual vehicles. We will work together with TSS on integration of energy models inside Aimsun to provide direct accounting of the energy saved by the incentivization schemes proposed below. This feature will be an open source extension of Aimsun relying on existing multi-class vehicle models already implemented inside Aimsun. Finally, the micro-model also includes lightrail lines to integrate multi-modalism as well.

Traveler mobility and demand model calibration. The TRACES platform is unique in its calibration for an agent population and activity-based travel demand that augments the state-of-practice regional model (available from SCAG) with cellular Call Detail Records (CDRs). CDRs available to TRACES are routinely collected by AT&T [14]. This anonymized data feed contain mobility records of millions of individual travelers at the spatial resolution of deployed cell tower antennas, and available with a time latency of several minutes. We will generate a set of daily activity plans for the study population using CDR-inferred locations of primary (home, work, school) and discretionary activities (shopping, leisure, social) for each user [66,80]. A recalibration procedure [54] will be used to allocate the population into the areal units of traffic analysis zones (TAZs) and correct sampling biases. Locational differential privacy methods [64] adopted by US Census bureau will be applied to the raw data stored and processed internally on secure AT&T servers

Activity-based tour/trip composition and modality choice will be based on the concept of modality lifestyles [105,106] implemented with latent variable discrete choice models in which an individual belongs to a particular (latent) modal orientation that drives all of their travel decisions. It is a principled framework for modeling operational interventions that also carry long-term sustainable behavioral shifts shown to be indispensable for achieving energy savings [87]. The MATSim engine will be used to produce initial dynamic traffic assignment from the set of activity plans of the population [10,47,66,80]. Model calibration will be operated from data available for the model by minimizing an error functional quantifying the discrepancy between measurements and model predictions. The data to be used for this will include loop detector data, in particular PeMS (see ITERIS letter), advanced detector data for the arterials (see letters from LA Metro, Caltrans and SCAG), GPS data from INRIX and HERE/NAVTEQ (see corresponding letters). The calibration of the non-vehicular parts of the model (lightrail and express bus lanes) has been completed by our partner Cambridge Systematics (see corresponding letter). For this we will inherit an already calibrated model of Los Angeles.

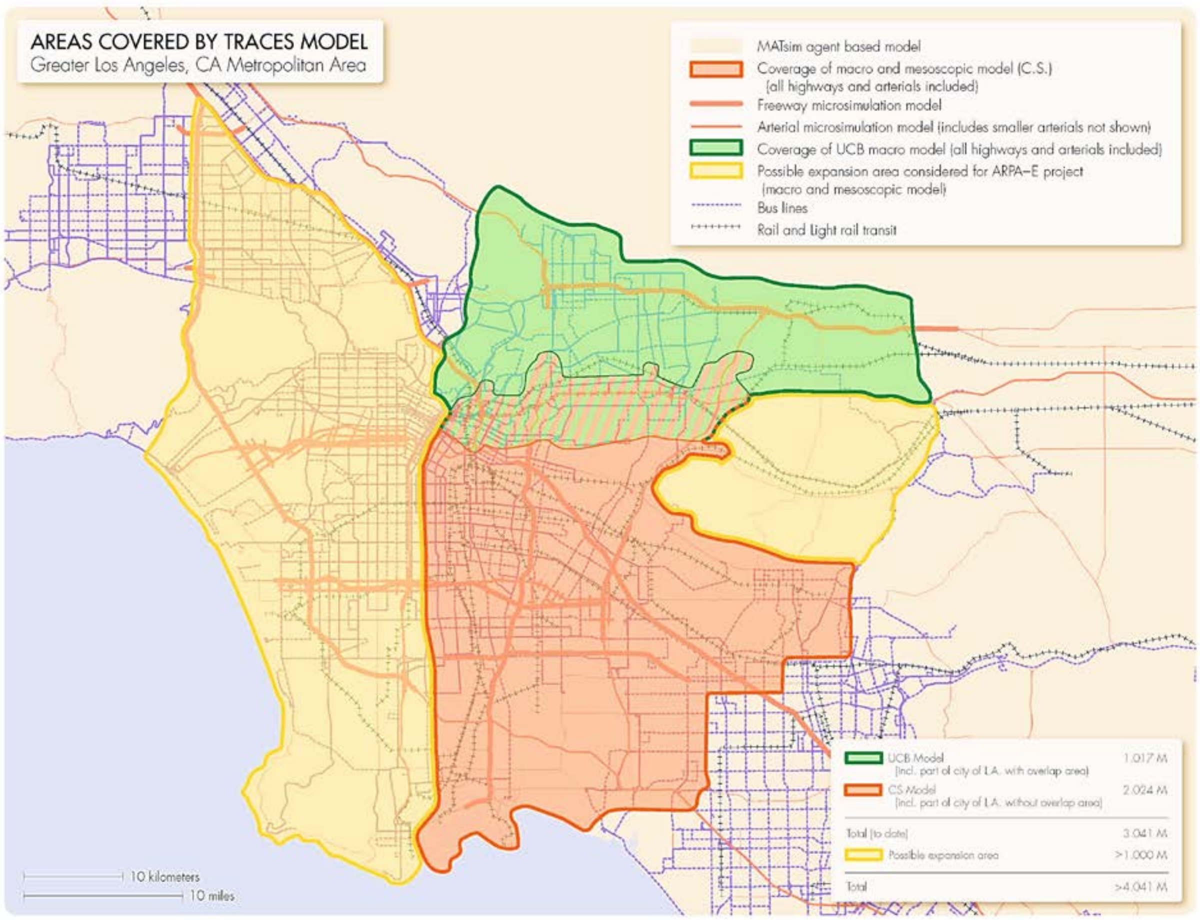


Figure 4: Areas covered by the TRACES model in the greater Los Angeles metropolitan area, with selected details on population count, modes and modules.

Integration of energy models with mobility models. Energy consumption models will be integrated with mobility models to describe powertrain systems and predict energy consumption at the individual vehicle-level, given velocity-elevation-time profiles from the microsimulation models. Figure 5 provides a schematic of the energy consumption model. The individual powertrain models are generated from a library of components [42], including: internal combustion engines, transmissions, electric motor/batteries and longitudinal vehicle dynamics.

These components can be mixed in a plug-and-play fashion to generate energy consumption models for personal vehicles, busses, light-rail, and freight trucks. PHEV, HEV and EV models have already been built in our Vehicle-to-Grid Simulator (V2G-Sim) software [60], which will be augmented by internal combustion-powered vehicles (gas and diesel), for personal vehicles, busses, trains, and truck freight. Model parameters and equations are available through Autonomie, an individual vehicle-level modeling and simulation toolkit developed at Argonne National Laboratory [43]. TRACES, in contrast, seeks to predict energy consumption transportation network (up to millions of vehicles). Consequently, model-reduction [33] and aggregation techniques [67] must be applied to generate computationally efficient energy consumption models with sufficient fidelity. The research team has extensive experience developing custom-tailored powertrain models, using Autonomie as a resource, for infrastructure-level analysis and optimization [11, 92-94]. Vehicle fleets will be modeled by considering EPA Size Class and CA DMV data. These powertrain models will be calibrated and validate with the support of project partners, e.g. LA Metro, Ford, Toyota (see support letters). Representative vehicle powertrains are generated from the aforementioned models, using appropriate component parameter values. In aggregate, this clustering approach is expected to produce accurate energy consumption predictions.

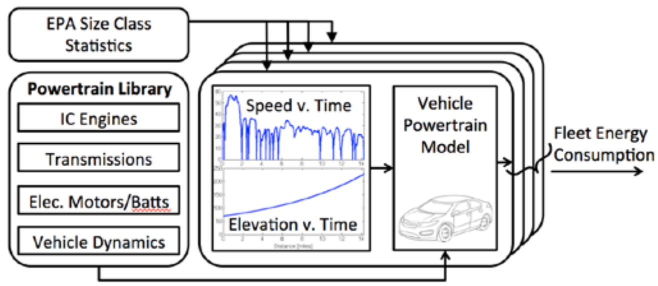


Figure 5: Schematic of energy consumption models.

Integration of personalized traveler response models into mobility models. As described above, models will have the ability to map demand to mobility flows at the metropolitan scale. However, the system must also integrate feedback to simulate user reaction to specific control mechanisms and to an interface with the *Personalized Incentivization and Behavioral Interventions (PIBI).* We will design individual-level information channels simulating personalized travel advisory systems combined with the incentives and interventions tested in then PIBI randomized controlled trial: environmental and public health messaging, injunctive instruction, pre-commitment and construction of a travel plan, monetary incentives, social norms and peer pressure signals (a development in consultation with Google and Facebook, see letters of support). The developed response models will be implemented to reflect the influence of the intervention mechanisms on heterogeneous travelers' trip choices and longer term modal orientations [37,38,52,105,106]. Agents' specification in the agent-based layer will be extended to represent decision-making functionality (activity planning, mode choice, destination location choice, social coordination logic, route choice, re-route aversion) according to developed model of behavioral response.

Validation of LA-scale energy savings simulation capabilities. Upon completion of model development, the model will be validated at scale to assess calibration. INRIX and HERE GPS data, along with processed traffic feeds data, will provide an independent source of data to assess traffic model validation at macroscale. Energy consumption models will be verified by Automatic.com (see letter of support) and our own app, myGreenCar, which can be used directly on selected users of Los Angeles. The energy consumption validation can happen on specific users as a subset of the entire driving population.

The traveler energy models follow a top-down to bottom-up approach. For top-down, inputs from higher level models (e.g. macro to meso to micro) are provided to the individual vehicle and traveler energy models. For bottom-up, vehicle and traveler data are aggregated across varying scales of increasing numbers of vehicles and travelers. At the individual vehicle level, energy models will be validated against chassis dynamometer measurement data. At the regional level, overall energy consumption results will be verified by comparing our regional-scale energy model results against expectations for 3.041M vehicles within the LA region for a typical travel day. Uncertainty propagation between the traveler data information flows will be quantified along with overall energy consumption results. For a finite number of representative TRACES simulation scenarios, three sets of simulation cases will be executed to quantify the effects of uncertainty propagation.

Adaptation of personalized data collection apps for use with TRACES platform. Integration of the four layer telescopic model will provide an applied research grade system. This will follow efforts currently underway to integrate the *Connected Corridors* platform with TSS's Aimsun Micro modeling platform (see letter of support from TSS). This provides research support, expertise and assistance in collecting, persisting, and managing high data volumes to ensure the performance and scalability of TRACES. In addition, UCB has developed three apps that can be used to collect data for model calibration and validation: 1) e-mission: smartphone based automated multimodal trip tracker, 2) myGreenCar: energy consumption monitoring app, and 3) Quantified Traveler: mode detection and energy consumption assessment tool.

In order to integrate these data streams, the apps will push data to the TRACES platform. This platform will be a framework to support the data from multiple apps designed to capture individual travel activity across a variety of modes and then integrate with the simulation environment. Rather than define an overly-simplified, singular overarching way to describe trips and travel intent, we take a many-to-one translation based approach. This enables easy integration of existing and new applications in the future, simply by developing translation software that maps particular trip data formats into the necessary input format for TRACES.

Field data collection for randomized controlled trial (RCT) of the Personalized Incentivization and Behavioral Interventions (PIBI) for long-run sustained energy efficient transportation choices. The RCT will test the effectiveness of PIBI to change individual transportation choices and patterns in a real world setting. In this RCT, which is a scientifically rigorous method to measure the effect of behavioral interventions, we will focus on persistent, long-run behavior change, not real-time or short-term trade-offs which are unlikely to be sustained. Participants will be randomized into one of several experimental cells, including a control group. Objective individual-level travel data will be collected via e-Mission and Quantified Traveler apps prior to any implementation of an intervention as well as during the experiment; outcomes (i.e., actually choices people make) will be objectively observed through GPS data, rather than relying on self-reported survey responses. Using this method, we can generate a valid and unbiased estimate of the effect of the behavioral interventions, controlling for any pre-treatment differences in experiment participants. The results will be used to calibrate the large-scale simulation through the activity-based model.

The intended effect of the interventions in the RCT is to cause experimental participants to switch to one of the following less energy-intensive travel options: no trip taken, walk or bike, public transit (bus, rail, etc.), ride-share or drive-time shifting. More importantly, we target long-term, sustained shifts in modal orientation, away from private vehicle use. Many factors affect travel choices; the experiment is designed to allow for personalization of options and flexibility in how the individual can respond. The personalized signals will be tailored to the habitual driving patterns of each participant in order to make the choice set relevant and salient.

Behavioral interventions have been shown to be highly influential in a variety of settings including energy consumption, voting, and green behaviors. However, similar efforts in transportation have proven less successful [5]. Addressing limitations of past experimental behavioral work in transportation, our study will (i) test interventions deeply rooted in existing behavioral theories and evidence; (ii) measure outcomes based on observed behavior; (iii) combine interventions to maximize the likelihood of a successful response rate; and (iv) and introduce an element of personalized information to the messaging framework. The incentives and behavioral interventions we will test include peer pressure, social norms, environmental and public health messaging, injunctive instruction, pre-commitment and construction of a travel plan, monetary incentives. The motivation for these interventions and further description follows.

Treatment A will combine three types of behavioral signals found to be effective in inducing behavior change in the energy consumption space: 1) public social comparisons with injunctive messaging, which motivates behavior through injunctive norms, peer pressure, guilt, and competition [1,2,31,102]; 2) information provision using environmental and public health message framing, which have been found most effective in changing energy consumption [6]; and 3) injunctive instruction, through ranked choice sets of transportation options [1,2,102].

Treatment B will combine Treatment A with a written commitment statement and travel plan, where the participant commits to using a less energy-intensive travel option on a future date. Most individuals behave in congruence with a powerful behavioral economic concept: present-biased preferences, where any choice requiring upfront hassle cost is likely to be avoided or delayed, sometimes indefinitely [30]. The commitment and travel plan enables the participants to figure the alternative travel option out ahead of time, effectively making it a less costly choice. This increases the likelihood that the individual will incorporate this new choice into their long-term, habitual behavior. Additionally, commitment itself can increase the likelihood of follow-through, as individuals seek to avoid cognitive dissonance. Pre-commitment has been effective in the case of voter turnout [76] and increasing “green” behaviors in hotels [9].

Treatment C will combine Treatment A and Treatment B with a monetary incentive. Individuals will be asked to write their commitment statement and travel plan several days prior to the action taking place and are credited a sum of money. If they do not follow through with their travel plan, the money will be taken back. The monetary incentive is strengthened by taking advantage of another powerful behavioral theory: loss aversion, where people tend to overweight losses relative to gains, such that taking away credited money is more influential than providing money after the positive action is taken [e.g., 15,40]).

Demand side control: system-wide optimization strategies of personalized interventions. This effortsynthesizes automated and personalized incentive/control signals that reduce transportation demand and therefore energy consumption. The control algorithm incorporates a reduced form of the mobility and behavioral models. Namely, this control-oriented model maps the current transportation network state, behavioral mechanisms, and individual response rate statistics to transportation demand/energy. The control design task is to synthesize personalized incentive signals that achieve desirable reductions in energy consumption without statistically increasing mean and variance of travel time, representing quality of service and reliability, respectively. Model predictive control (MPC) is ideally suited to solve this problem, since it is model-based, explicitly enforces constraints, and optimizes a performance criterion - energy reduction in this case. This project brings forth three novel control aspects. First, the actuators - individual travelers - respond stochastically. Second, the incentives (PIBI) operate at various time-scales (shown in Fig. 1). Namely, eco-driving, re-routing, and mode-shifting operate roughly at 1-sec, 1-day, and 1-month time-scales. Third, the individuals compete for mobility resources, inducing Nash-Stackelberg games. The optimization of the Nash Stackelberg problem will either result in closed form solutions already available through our previous work [58,59] of adjoint based optimization on the marcoscopic flow models, following our earlier work [83], performed numerically at scale (NERSC cluster and AMPLab Spark on EC2 clusters).

Infrastructure based supply-side control: development of network control mechanisms responsive to personalized guidance and incentivization. The previous section described the use of personalized control to change demand. This means that based on the optimization algorithms we devised we will be able to provide the proper incentivization to nudge behavior to save energy, and compute the corresponding energy savings. However the infrastructure is not responsive to this novel type of guidance at the present time (i.e. problems due to congestion causing-apps such as Waze happen). We will devise control mechanisms that are able to accommodate the unplanned flows and can be done by agent based optimization [82,83,84,91]. We will provide improved network control schemes to accommodate the induced and shifted demand. The algorithms proposed will be of two categories:

1. Traffic-app responsive metering: adjusting the metering rates at the entrance of freeways based on the prediction of incoming flows, available through apps.
2. Traffic-app responsive signal coordination: adjusting signal timing based on shifted demand, to accommodate changes in flows generated by apps.

The private sector is very eager to engage in this research with government agencies and ITS is mandated to do so as part of its public service mission. TomTom and INRIX will specifically work with us on these issues (see support letters). The proposed work will thus result in optimized network control strategies capable of maintaining operational performance in the presence of modified demand generated by apps. Thus, we will be able to simulate the following type of scenarios (and induced energy savings): “If 2% of flow is diverted by the apps from freeways to arterials using personalized guidance, a change in timing plans to accommodate the extra flow on arterials will save 200 hours in cumulated travel time over a period of 4 hours during rush hour". The incentive for app providers to participate and share data with government agencies is obvious: by sharing in advance the number of rerouted motorists they can see using their apps, they improve the travel time of these motorists. The incentive for the government agencies that operate the infrastructure to participate is that they will be able to operate their local network more efficiently in light of the shift in demand caused by the private sector, which is progressively taking over the guidance of travelers through the transportation network. The TRACES platform will enable the computation of the energy savings by simulating the corresponding "what-if" scenarios, using our traffic responsive algorithms [25,26,81,97].

In the TRACES platform block diagram in Fig. 1, supply-side control is represented by signal v(t), traveler responsive network control signals. The signal is generated via a model predictive control framework (MPC). That is, we iteratively simulate the transportation network and activity-based models forward in time (over several hours) to optimize the infrastructure control signals that minimize energy. This iterative process is performed in a receding horizon fashion over 15 minute intervals, using the TRACES telescopic model whose states are initialized by real-time data feeds (i.e., AT&T, INRIX, HERE, PeMS, etc.). This MPC framework builds upon previous work on distributed optimal control of freeway networks [82, 83], yet applied at a much larger multi-modal scale while incorporating individual traveler behaviors.

System design and integration of control mechanisms at scale. System control architecture will be designed and implemented using cluster computing techniques to allow horizontal scaling and ensure compatibility with cluster operation. This control architecture will be aligned with agent-based model in demand-side interventions mechanisms and traffic simulation layers for supply-side coordinated network controls. Modeling steps will be structured as easily parallelizable pipeline steps, with no shared system state. The cluster computer toolset that we plan to use is Apache Spark, developed in the AMPLab at UC Berkeley, and provides Resilient, Distributed Dataset (RDD), which represents an immutable, partitioned collection of elements that can be operated on in parallel [48,49].

Demonstration of integration of optimization models with behavioral and network control models; demonstration of the energy benefits. The main achievement of this component will be the ability to demonstrate, in a simulation environment, reduction of energy in the transportation network by application of the various control mechanisms described earlier. For this, the TRACES platform will follow the standard control scheme presented in Fig. 1, in which the control module developed earlier is used to close the loop on the plant (which is the simulator of TRACES). The forward loop in the diagram shown in Fig. 1 represents the TRACES model, i.e. the simulation of the real-world in a virtual environment. It also includes a measurement model, to simulate in the virtual environment that the knowledge of the traffic is always imperfect and that any control algorithm needs to take this fact into account (as we have done in our work). The corresponding measurements are used either for rewards to participating "nudged" users, and to feed the control module described earlier.

The closed loop system of Figure 1 will be implemented at scale, i.e. run for 3.041M travelers, and will be demonstrated for the LA Basin region shown in Figure 3, which includes 10,000 miles of arterials, hundreds of miles of freeways, thousands of arterial intersections, numerous bus transit lines and light rail. The resulting savings will be accounted for at the full scale of the deployment area with 3.041M inhabitants, and results into a cumulated energy savings curve which can plot the energy savings as a function of the adoption rate, based on the behavioral economics models provided through this work.

Technology Transfer and Outreach (TTO). Some of the personalized incentives designed in TRACES can be monetized and hence require a source of financing or a self-sustaining business plan. While a full-fledged financing or business plan is not necessary for this phase, it will be necessary in the event of a field operational test and subsequent full implementation. The TRACES team will explore two pathways that can finance the PIBI part. First, we will explore opportunities within an existing policy framework (like California's Climate Action Plan) that can monetize the energy or greenhouse gas savings achieved by implementation of TRACES. The Sustainable Communities and Climate Protection Act of 2008 (California State Assembly 2008) supports the State of California's climate action goals to reduce greenhouse gas (GHG) emissions through coordinated transportation and land use planning with the goal of more sustainable communities. To achieve these targets, the plan of SCAG includes the option for "innovative finance mechanisms that incentivize reduced VMT". However, there is no precedent or established methodology to design a financing mechanism for the approach outlined in TRACES. Hence, the TRACES team will develop and propose possible mechanisms by working closely with our local partners, SCAG, Caltrans District 7, and LA Metro.

Second, we will consider and evaluate incentive designs that are self-financing. We will design and evaluate personalized incentives that could be feasibly self-financed. Various competitive game frameworks can be designed to be amenable for self-financing. For example, a neighborhood competition to verifiably reduce personal transportation energy consumption that requires a contribution of funds to participate that are then distributed to the winners. Another example is a lottery framework with a larger pool of participants and a very small cost of entry.

Initial TT&O will be undertaken with support through our industry and government agency advisory board. These groups represent the end users of the TRACES product and are invaluable to the commercialization process of the program. Members include Google, Siemens, TomTom, IBM, INRIX, Caltrans, LA Metro, and SCAG. They will provide advisory services throughout the project, including input for product development to assure an efficient pathway to market.

2.2 Technical Risk

Validity of Numerical Parameters in Behavioral Models. The largest risk is the accuracy of the assumptions developed for the behavioral model, as the capacity to drive individual consumer behavior through incentivization. To ensure behavioral model accuracy, the project will utilize novel techniques and empirical studies to evaluate incentivization response rates. Two sources of empirical data will be used for calibration of representative human behavior.
E-Missions, myGreenCar, Quantified Traveler. Developed by our group and already available on Android or iPhone, these apps collect traveler data on modes of transportation, personalized

energy consumption, and energy patterns. TRACES will access all current and future data streams.

Automatic.com. This fast-growing startup, which originated at UC Berkeley's ITS, is a leader in measurement of precise energy consumption and driving habits in the US. It has over 20,000 users already and is quickly growing. We can access their entire data set (see letter), and thus incorporate data from motorists who are not part of our controlled research environment.

Our mitigation strategy is to use field data to calibrate our models, so we know that the parameters we are producing are meaningful. In the past, we have been able to follow this exact methodology specific to the "value of information" (message influence), "value of green" (incentive for efficiency). The project will use these experimental findings for user behavior shift obtained with real users to design our experimental strategies to measure such values for LA.

Successful Implementation of the RCT Experiment. We believe that the value of our work is much higher if our behavioral models rely on actual field data (collected through our three apps and Automatic.com) rather than academic assumptions, hence the experimental data collection. There are several risks inherent in running a field experiment. First, obtaining a large enough sample of participants in order to have enough statistical power to identify the size of the effect we will obtain with these types of behavioral interventions. Second, ensuring that the sample of participants we do recruit is as representative as possible of the full area being simulated. Third, is the operationalization of the experimental mechanisms themselves (correct operation of the app messaging, communications with the participants, and accurate tracking of participant behavior). Our mitigation strategy for these risks is to target study participants from a large pool of people (employees of large companies with offices in key transit areas, public city employees, etc.). In order to make this pool of participants as representative as possible, we will compare demographic information from our participants to census data from the full region included in the simulation, and weight the estimates we obtain accordingly. Finally, to limit the potentiality of technical difficulties in implementing the experiment, we will conduct a small pre-pilot run of the experimental mechanism (listed in task 2.1), including the communications flow, data flow, and participant tracking, which will allow us to ensure accuracy when implemented in the full experiment.

Accuracy and Meaningfulness of Results. The initial phase of the project is focused on the extension and development of simulation models at the agent, micro, meso and macro scale, and integration with our energy consumption models. The inherent risk associated with running these models to meet project scale is not about the scale itself, but the meaning of the results produced at that scale. Running a model for an area with 3.041M agents is not computationally challenging for us, given the participation of AMPLab members, and NERSC support. The challenge to run these models meaningfully, means: with proper calibration and proper validation against data.

Particularly, there is difficulty the models in settings where not all parameters of urban infrastructure are known. To our knowledge, no research group in the US has ever integrated all traffic light timing plans into a single, synchronized model due to fragmentation of urban infrastructure and lack of available support data. Most urban areas (Chicago, New York, LA, etc.) have dozens of systems running concurrently that integrate a variety of traffic controllers

(170 and 2070 models for example) but installed by different jurisdictions over 40+ years, poorly documented and often without single standards like the synchro standard. The notion that one could run "an entire" city simulation in a single-model often relies on very rough assumptions (for example that all traffic lights in the city will have nearly the same features – when they do not). In addition, large scale agent based models (such as the ones we are running, MATSim) by definition need to run at much higher scale than the macro models below it, and the micro models, which are local and cannot run at global scale. Hence the necessity to integrate models which work at different scale.

To remediate this difficulty, (see section 2.1) each tier of the proposed simulation model will build upon fully operational and validated models including MATSim, Connected Corridors (incl. Mobile Millennium and TOPL), and Aimsun. The underlying algorithms and performance have been validated and calibrated, and the team can access to all operational data to date; the risk lays with the capacity to integrate extensive accurate simulations and predictions. This risk will be addressed by properly interfacing the models at various scales, and with the proper validation, using the unique data sets we have been accessing for years (INRIX and Here probes, PeMS, AT&T). Wherever the data allow it, micro-simulation models can be used meaningfully (i.e. relying on the precise knowledge of the urban infrastructure and traffic light timing plans). Wherever these data are not available precisely or not required (i.e. places not concerned by control strategies directly, or where congestion is not a factor), the use of aggregate models provide the right level of abstraction without precise knowledge of local traffic features.

Adoption. An additional risk posed to implementation of the proposed approach is adoption by the private sector end user. It is necessary for the end users to understand how to appropriately monetize the product and make it commercially viable. As a first of its kind, transformative product, it is possible that the marketplace may not fully understand the potential impact that TRACES presents and would desire to maintain existing business practices. To remediate this risk, the project team has implemented an industry Advisory Board, represented by the largest potential users in the US market, including Google, Facebook, TomTom, INRIX, Siemens, IBM, HERE, Toyota and Ford. We have included signed letters from each company, stating interest in the opportunity to participate to the development of the platform early in the process. This will enable them to influence some of the features to align with their interests and will ensure smoother transition once the platform is launched.

2.3 Schedule

TRACES Schedule		Year 1				Year 2				Year 3	
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Task 1: Traces Model Development, Calibration, Validation and Deployment											
1.1	Traveler mobility model development										
1.2	Traveler mobility and demand model calibration										
1.3	Model Calibration is sufficiently accurate Milestone:										
1.4	Integration of personalized traveler response models into mobility models										
1.5	Validation of LA-scale energy savings simulation capabilities										
1.6	Adaptation of personalized data collection apps for use with TRACES platform										
Milestone	Integration of 4 layered traveler model with energy model				M						
Milestone	Integration of combined traveler model and energy model with behavioral model				M						
Go/No-Go	Integration with behavioral model fails (end of 1.4)					G/NG					
Go/No-Go	Verification of the functionalities of the integrated models fails (1.5)					G/NG					
Task 2: Field Data Collection for Personalized Incentivization and Behavioral Interventions (PIBI)											
2.1	Refine experimental design of PIBI										
2.2	Deploy full scale data collection experiment of PIBI										
2.3	Data analytics and behavioral analysis										
Milestone	Finalization of the models (modes, incentivization mechanisms)							M			
Milestone	Completion of the RCT							M			
Go/No-Go	RCT do not return acceptable value --> this task is eliminated, but the rest continues to operate (i.e. we do not use field data for the models)							G/NG			
Task 3: Optimize personalized interventions and network control mechanisms											
3.1	Demand side control: system-wide optimization strategies of personalized interventions										
3.2	Infrastructure based supply-side control: development of network control and energy saving paradigms										
Milestone	Successful demo (simulation) of both demand control side and supply control side interventions							M			
Go/No-Go	Demand control side control cannot be implemented across the 4 layers.							G/NG			
Go/No-Go	Supply side control cannot be implemented across the 4 layers								G/NG		
Task 4 Demonstration and Network Control Architecture											
4.1	System design and calibration for integration of control mechanism at scale										
4.2	Demonstration of energy benefits at scale										
4.3	Technology transfer and outreach										
Milestone	Scaling up at >3M scale.								M		
Milestone	Demonstration of the energy savings at scale									M	
Go/No-Go	System does not scale up									G/NG	
Go/No-Go	Energy savings are not satisfying (then come with a negative report outcome: "cannot be done this way")									G/NG	

2.4 Task Descriptions

Task 1: TRACES **model development, calibration, validation and deployment**

Overview: Within this task, all mobility models will be successfully integrated, calibrated and validated against the data we have, at scale for LA. The models will be integrated with the energy models, so energy can be accounted for. The models will be integrated with behavioral models, including reaction of travelers to incentivization. Apps will be adapted so they can collect data needed to calibrate the behavioral models. Upon completion of task, all models will be useable for simulations, but require the behavioral models of Task 2, to function.

1.1: Traveler mobility model development Integration of 4 layers of models: Agent based, macro, meso- and micro- models, user feedback and transit model into platform. Build interface to pass variables across layers (controls, state, and energy consumption).

1.2: Traveler mobility and demand model calibration LA-scale calibration of activity based demand model from AT&T/SCAG data. Macro models calibration of from static sensor data and INRIX/HERE. Selected deployment and calibration of meso/micro-models in critical TRACES deployment site areas (see map). Transit modeling: mesoscopic model includes all light rail lines and bus lines, micromodels also include light rail.

1.3: Integration of energy models with mobility models Define representative vehicle fleet characteristics. Collect and archive powertrain component model equations. Parameterize and validate powertrain models, aggregate energy consumption models. Interface Vehicle Consumption Model w/micro models and Energy Consumption Models w/macro-models.

1.4: Integration of personalized traveler response models into mobility models Implement Personalized Incentivization Models (PIM) and (PIBI) to simulation platform. Extend agent specification in activity-based layer and upgrade behavioral response decision-making functionality. Implement feedback interface between simulation platform and app-based dissemination of personalized incentives and interventions.

1.5: Validation of LA-scale energy savings simulation capabilities Verification of functionalities on baseline scenarios for 3.041M inhabitants scale and personalized intervention functionality. Cross-checking models with alternate source date at all scales (Automatic.com, myGreenCar). Demonstrate real-time system simulation of TRACES at scale.

1.6: Adaptation of personalized data collection apps for use with TRACES platform Adaptation of apps currently available for behavioral models calibration: e-Mission, myGreenCar and Quantified Traveler. Integration with Automatic.com data (OBD2 data). Integration of app feeds into the TRACES platform.

Task 2: Field data collection for Personalized Incentivization and Behavioral Interventions

Overview: This task first identifies the various travel modes that will be targeted during incentivization. Furthermore, the different mechanisms to be used for the incentivization to nudge the participants will be identified, and the process used to collect data from the field to calibrate the models will be outlined through the various tests proposed. Once data are collected and the analysis is performed, the behavioral economics models can be run with real world parameters, proposed in Task 3.

2.1: Refine experimental design of PIBI Enumerate and order transportation behavioral shifts for individual travelers. Refine intervention strategy: environmental/public health messaging, social norm and peer pressure, commitment mechanism and monetary incentives. Refine messaging

through focus groups. Design recruitment materials and enroll participants. Small-scale experimental mechanism and app pre-pilot testing: test data acquisition flow, data storage, and feedback mechanisms.
2.2: Deploy full scale data collection experiment of PIBI Implement randomized control trial (RCT) of experimental behavioral interventions: recruit field pilot participants; collect pre-treatment data to personalize treatment interventions and implement. Manage data flow and storage. Gather data in response to various incentivizations.
2.3: Data analytics and behavioral analysis Clean intervention data and conduct econometric analysis of experimental outcomes to estimate behavioral parameters and treatment effects; estimate parameters of behavioral and incentive interventions for incorporation into ABM.

Task 3: Optimize personalized interventions and network control mechanisms
Overview: This task proposes two main actuation schemes. The first one is based on the application of the incentivization to travelers, and the quantification of the corresponding energy savings, either directly through the energy they save, or indirectly through the positive effect they have on the network. The second one is based on the better interfacing between the urban infrastructure and the personalized guidance apps, which using the TRACES outcomes, can be shown in simulation to improve the energy efficiency of the system.
3.1: Demand side control: system-wide optimization strategies of personalized interventions Find optimal operations control given response rate (Task 2), budget, geography and network. Employ NS game theoretic framework to find proper subgroup incentivization to achieve optimal solution given response rate.
3.2: Infrastructure based supply-side control: development of network control and energy saving paradigms Traffic and infrastructure signals for responsive personalized guidance (with network control algorithms for apps). App responsive infrastructure control (infrastructure to account for personalized guidance). Demonstrate corresponding energy savings: reduction of vehicle energy consumption and induced savings from congestion reduction (system responses to INRIX, Google, TomTom etc. and to PIBI).
Task 4: Demonstration of network control architecture
Overview: This task first scales the system to enable it to run at scale, using the technology developed at the AMP lab. It subsequently runs a series of scenarios at scale to achieve the Program operational goals for LA. Finally, outreach provides strategy development for real world implementation, with the proper financing plan to support incentivization mechanisms.
4.1: System design and calibration for integration of control mechanisms at scale Integrate behavioral model as control module for system model. Design of single Spark-powered High Performance Computing (HPC) platform to run the 4 layer model at scale on the NERSC cluster, ingesting all the data sources and interfacing with the multiple apps deployed through project.
4.2: Demonstration of energy benefits at scale Demonstration of the ability to run behavioral signals to travelers inside mobility models. Demonstration of the ability to optimize over these models (mobility models, energy consumption model, user feedback models). Optimization over random actuation in networks. Demonstrate ability to reduce energy consumption for a 3.041M population simulation.
4.3: Technology transfer and outreach**.** Develop a financing and business plan for personalized incentivization in the event of a full implementation.

3. TEAM ORGANIZATION AND CAPABILITIES

3.1 Organization

The TRACES project team allies three essential complementary components: academia, one national lab, and two private sector companies with practical experience in the field of infrastructure controls, both with physical presence in Los Angeles. We will have project two advisory boards. Our industry advisory board includes most of the leading players in the field of personalized signals for transportation: Google, INRIX, HERE, TomTom, as well as Facebook, essential for the personalized guidance work we plan to do, and AT&T, which has the best possible data set for demand modeling in the US. Several of these companies are providing us with project-related data at no cost. Most of the members of the government board have previously funded development of components leveraged by this work and have significant interest in the success of this proposal (letters appended).

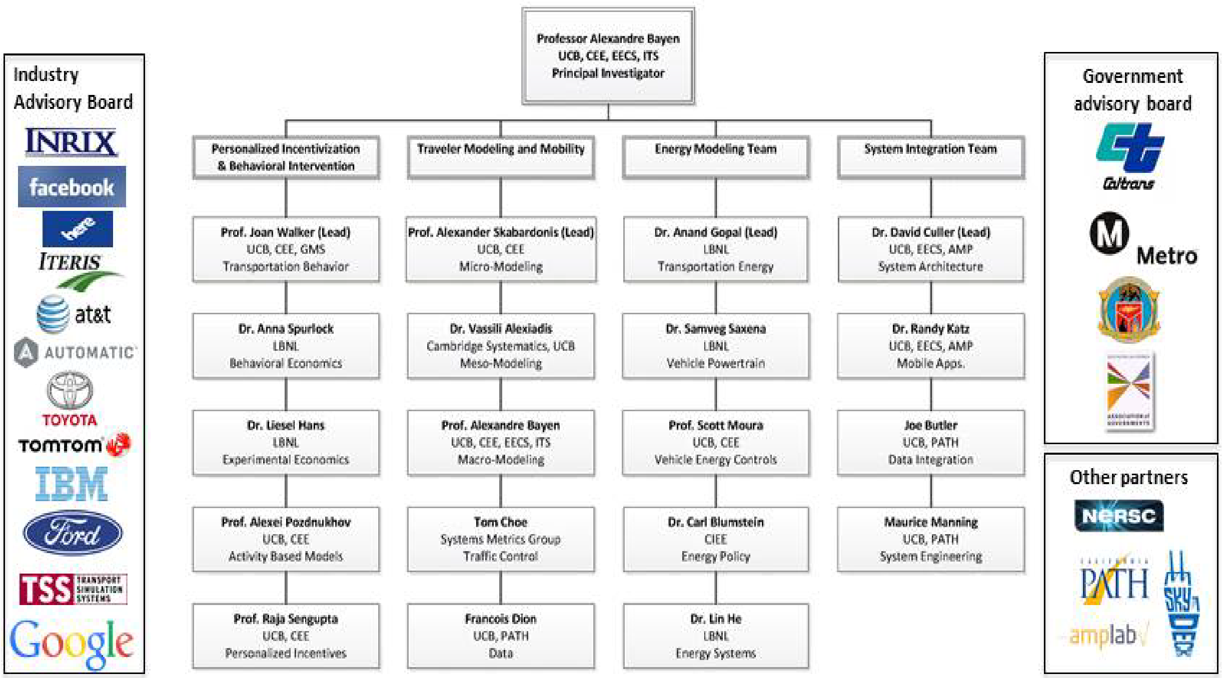


Figure 6: Team organization, industry advisory board (includes several of our data providers), and government advisory board. See letters of support for all. All have committed to participating to the project.

The **Institute of Transportation Studies** (ITS) at UCB has more than 60 years of track record leading the field of intelligent transportation systems, totaling more than $750 million of research funding devoted to transportation. It encompasses seven research centers, with notable successes such as the implementation of metering lights on Bay Bridge (30 years), the first US demonstration of automated driving in 1997, and the first ever deployed smartphone app to collection of traffic information from GPS data in the US, *Mobile Millennium*, running on Rim and Symbian phones (prior to the existence of GPS enabled iPhone and Android). The proposed research will be hosted at PATH, *Partners for Advanced Transportation tecHnology*, one of the seven research centers of ITS. PATH has led intelligent Transportation Systems since 1986.

The **Energy Technologies Area** *(ETA)* at LBNL is a leader in transportation economics, policy, behavior and technology. ETA's economics and policy research has laid the foundation to inform governments around the world as the move towards a cleaner transportation future. By drawing upon its behavioral science methods in appliances and grid systems, ETA brings considerable expertise to explore how people can be incentivized towards adopting more efficient means of transportation. ETA includes many of the U.S. Department of Energy's premiere research facilities and expertise in vehicle energy technologies, spanning from batteries, to fuel cells, to combustion. For this proposal, systems-level research in ETA will bridge fundamental understanding and innovation in vehicle energy technologies through to full vehicle powertrain and vehicle-infrastructure systems (e.g. transportation networks and V2G).

Cambridge Systematics (CS) is the premier transportation analysis firm in the U.S. with a deep understanding of the inner workings of development and implementing analysis tools. CS has served on several innovative project teams, including Integrated Corridor Management Analysis Modeling and Simulation (ICM AMD) and Next Generation SIMulation (NGSIM), which bridged federal research with real-world applications. In particular, CS has a thorough understanding of existing simulation models in the LA region, has AMS experienced staff in LA and good working relationships with local agencies. Credentials include ICM AMS, NGSIM, SHRP2 C10, and experience in the interfaces between models, simulation algorithms, and pre- and post-processors. The CS team has expertise in, and licenses for, all major transportation analysis tools. CS' role in the team will be mainly in the development of the micro-, meso- and macro-models, and transit model work, as well as the corresponding data analytics.

System Metrics Group (SMG) is a transportation consulting firm founded by senior professionals with backgrounds in economics, civil engineering, and electrical engineering and advanced degrees in business, transportation engineering, and transportation planning. With offices in San Francisco and Los Angeles, SMG specializes in managing large and complex transportation strategy projects in California, but its professionals have national experience. SMG bridges the gap between transportation economics/planning/engineering and policy-level decision making. SMG's work covers strategic planning, economic analysis, planning analysis, development of analysis tools, and the integration of performance measurement into decision making. The company has proven expertise to manage projects requiring flexible leadership and the ability to synthesize and explain complicated issues clearly. The role of SMG in the project will be to provide expertise in practical control of infrastructure local to Los Angeles.

Key Personnel

The project will employ an industry leading-team of senior personnel with very high credentials, including two NAE members, two White House PECASE awardees, and two NSF CAREER winners, in addition to dozens of other awards from the ASCE, IEEE, and other professional societies. This team has collaborated on 40 state and federal awards, including 20 from DOE (two of which are from ARPA-E).