UCR | College of Engineering- Center for Environmental Research & Technology

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Evaluating Energy Efficiency Opportunities from Connected and Automated Vehicle (CAV) Deployments Coupled with Shared Mobility in California

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DOE Vehicle Technologies Office
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Project ID # DE-EE0008212

Overview

Timeline

- Project start date: 10/01/2017
- Project end date: 09/30/2019
- Percent complete: 75%

Budget

- Total project funding
  - DOE share: $1,094,578
  - Contractor share: $122,882
- Funding for FY 2018: $513,889
- Funding for FY 2019: $580,689

Barriers

- Measuring the transportation system-wide energy impacts of CAVs
- Determining the value and productivity derived from new mobility technologies
- Sourcing empirical real-world data applicable to new mobility technologies

Partners

- National Renewable Energy Laboratory
  - Jeff Gonder

Objectives

- **Project Objectives:**
  - Evaluate energy efficiency opportunities from large-scale (e.g., regional or statewide) deployments of Connected and Automated Vehicles (CAVs) coupled with Shared Mobility
  - Propose an integrated model to quantify the impact of new mobility technologies on travel behavior and traffic performance
  - Investigate under a variety of roadway infrastructure, traffic congestion levels and market penetration rate
  - Major focus on California
- **Objectives over the past year (Apr 2018–Mar 2019):**
  - Completed CAV data collection and model implementation tasks
  - Developed an energy intensity model (RouteE) with capability to model the impacts of CAVs
  - Develop an agent-based model for Riverside, California in BEAM to characterize the change of operational performance and travel behavior due to new technologies with a focus on shared mobility

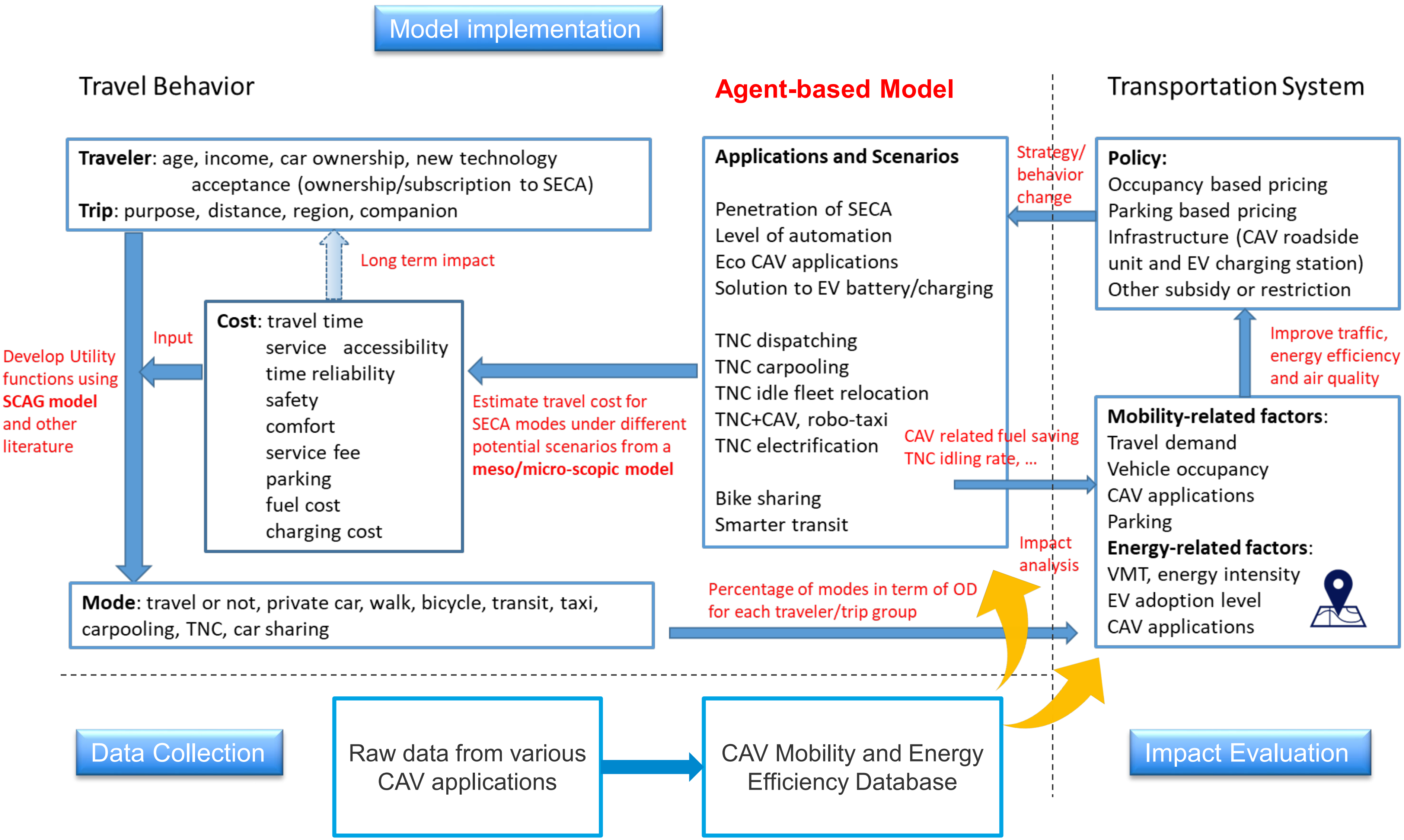
Relevance

- **This project addresses multiple VT Office/EEMS barriers by:**
  - Quantifying the energy impact of disruptive transportation changes
  - Identifying real-world data sources for CAV and shared mobility applications
  - Investigating travel cost and travel behavior changes due to emerging transportation technologies and services
- **Impact of the project:**
  - Close the knowledge gap on understanding potential system impacts of large-scale CAV technology deployments in the shared mobility era
  - Reduce uncertainty in estimating energy saving opportunities from new mobility technologies and services
  - Support policymakers in steering CAV and shared mobility development in an energy-favorable direction

Milestones

Milestone	Description	(Planned) Completion Date	Status
FY 2018			
Data source identification and experiment setup complete	Data source identification and experiment setup complete	12/31/2017	Complete
Collection and processing of LDV data complete	Complete collection and processing of LDV-No Automation real world data	3/31/2018	Complete
Collection and processing of HDV data complete	Complete collection and processing of HDV-No Automation data and LDV simulation data	6/30/2018	Complete
Assessment of Data Collection Complete	Determine if a sufficient amount of data have been collected to support model implementation	9/30/2018	Complete
FY 2019			
Energy intensity (EI) model implementation	Complete implementation of models for estimating impacts on energy intensity by CAV technologies	12/31/2018	Complete
Completion of Model Implementation/Validation	Determine if all models have received sufficient validation for supporting statewide energy inventory efforts	3/31/2019	Complete
Framework Development	Complete the development of statewide energy inventory framework	5/30/2019	Ongoing
Impacts Evaluation	Complete the evaluation of CAV-induced energy impacts in California	7/30/2019	Ongoing

Approach – Conceptual Framework



Approach – Data Collection

- Define five scenarios that cover almost all CAV deployments and experiments
- New experiments focus on less-explored areas: mixed traffic, multiple CAV (various market penetration), impact on other vehicles, heavy-duty vehicles

Single CAV with no other vehicles

Impact on equipped CAV:

EAD with fixed signals (Richmond, CA; Riverside, CA; McLean, VA)

EAD with actuated signals (Riverside)

GlidePath (McLean, VA)

CARMA Multi-Intersection EAD (McLean, VA)

Single CAV in mixed connected traffic

Impact on equipped CAV:

EAD with actuated signals (Palo Alto, Riverside, CA)

ACC impacts on driving and fuel use (NREL/Volvo Cars under SMART)

Truck Eco-Drive (LA County, VISSIM)

Connected Eco -Bus (Dyno -In-The-Loop)

Impact on other vehicles:

EAD with fixed signals (Paramics)

Truck Eco-Drive (VISSIM)

Connected Eco -Bus (Dyno -In-The-Loop)

Multiple CAVs in fully connected traffic

Impact on equipped CAV:

EAD with platoons (Paramics)

Saxton Lab CACC (Philadelphia)

CACC-VISSIM 2.0 on OSADP (VISSIM)

Eco-Speed Harmonization (Paramics)

TOSCO: CACC -enabled EAD (VISSIM)

CARMA2 Vehicle Testing (Virginia)

Multiple CAVs in mixed connected traffic

Impact on equipped CAVs:

EAD with platoons (Paramics)

Eco-Freight Signal Priority (Paramics)

TOSCO: CACC -enabled EAD (VISSIM)

Controlled truck platooning testing (NREL/LBNL under SMART)

CACC in freeway stream (Path)

Impact on other vehicles:

EAD with platoons (Paramics)

Eco-Freight Signal Priority (Paramics)

TOSCO: CACC -enabled EAD (VISSIM)

Controlled truck platooning testing (NREL/LBNL under SMART)

CACC in freeway stream (Path)

Other CAV applications

For safety and mobility: Lane Speed Monitoring, Electronic Emergency Brake Light, High Speed Differential Warning, Cooperative Smart Lane Selection, Automatic/Anticipatory Lane Change, and Lane Hazard Prediction (VISSIM); **Safety Pilot Model Deployment (SPMD) program (Ann Arbor, M I)**

For transit time reliability: **Transit Signal Priority (Utah)**

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Existing Simulation

Existing Field Test

New Simulation

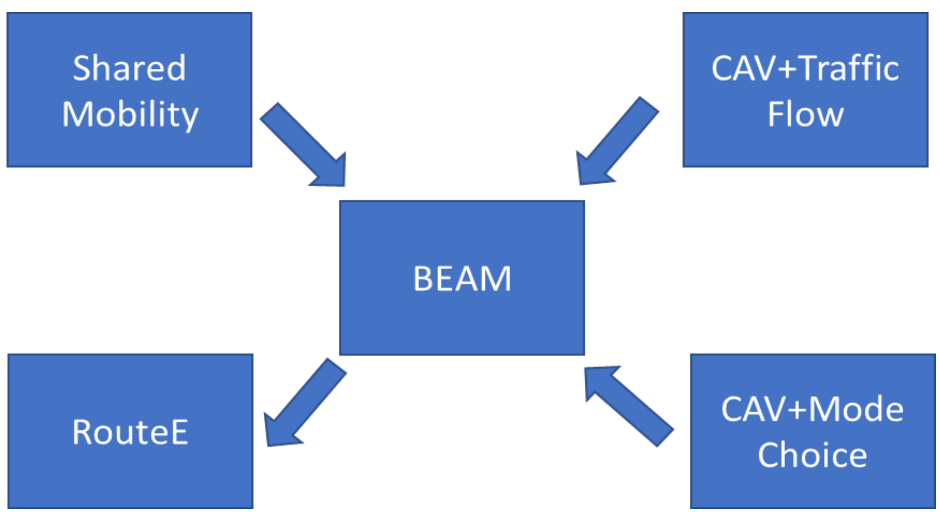
New Field Test

Approach – Model Implementation

- Select BEAM model as the main agent-based simulation platform: support to ride-hailing and ridesharing model, effectiveness on large-scale network, existing Bay Area network, etc.
- Create road network (OpenStreetMap), traffic demand and agent-based activity (SCAG) model for the City of Riverside as the input of BEAM
- Develop three key components based on the BEAM platform in addition to the existing shared mobility module

Centralized controlled ride-hailing fleet with ridesharing features (developed by LBNL)

Address the impact of CAVs on traffic using CAV Mobility and Energy Efficiency Database

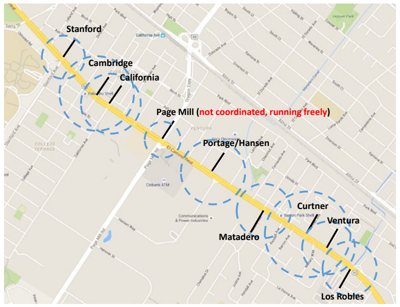


A data-informed model integrated in BEAM on energy estimation for both human-driving and CAV scenarios

Quantify the travel behavior impact (e.g. induced demand, mode shift) due to CAVs and shared mobility

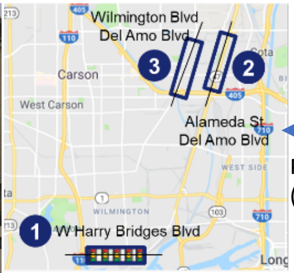
Accomplishments – Data Collection

Example new field experiments and demonstrations



El Camino Real Testbed
(11 intersections)

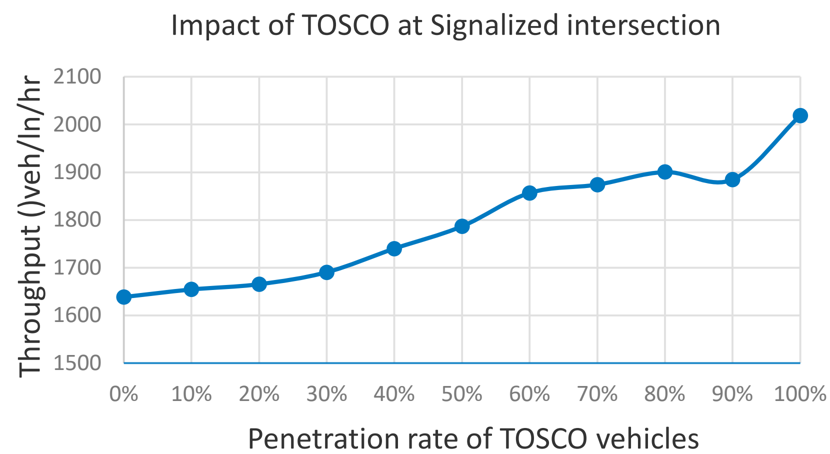
City of Riverside Innovation Corridor

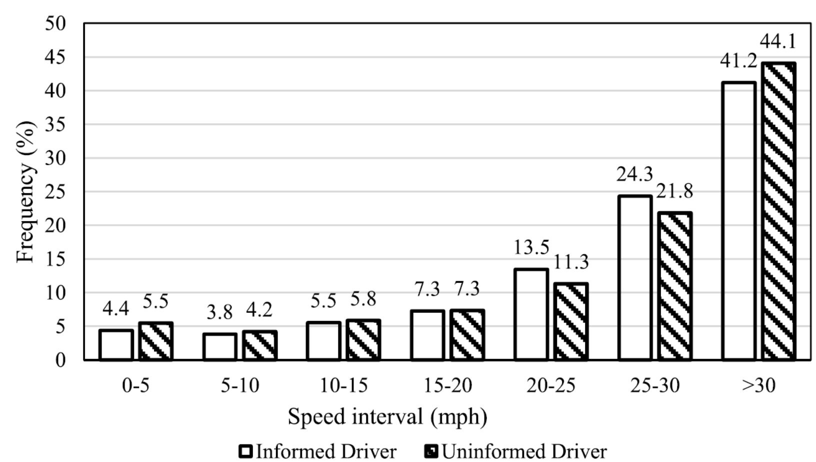


Port of LA Freight Eco-driving
(15 Intersections)

Accomplishments – CAV Efficiency Database

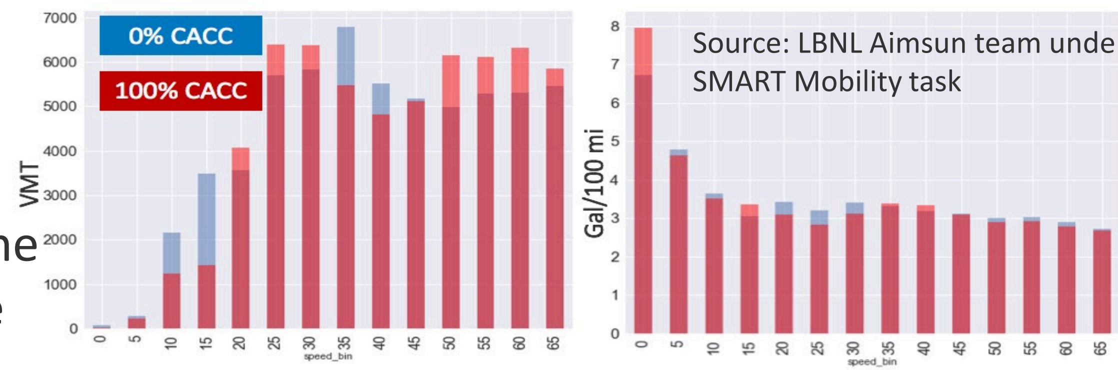
- The CAV Mobility and Energy Efficiency Database focuses on two CAV-related phenomenon:
- Throughput improvement
  - Simulation under various penetration
  - Arterials: Results from TOSCO (CACC+ EAD) at Riverside Innovative Corridor
  - 22% improvement at 100% penetration
  - Freeways: Use CACC model (Liu et al, 2018) or platoon model (Bujanovic, 2018)
  - Higher Improvement on freeways: 67%
- Trajectory smoothing effect
  - Using field data for low penetration case, and simulation data for high penetration
  - Based on EAD test in real traffic, the idling/near-idling cases are reduced by 22%



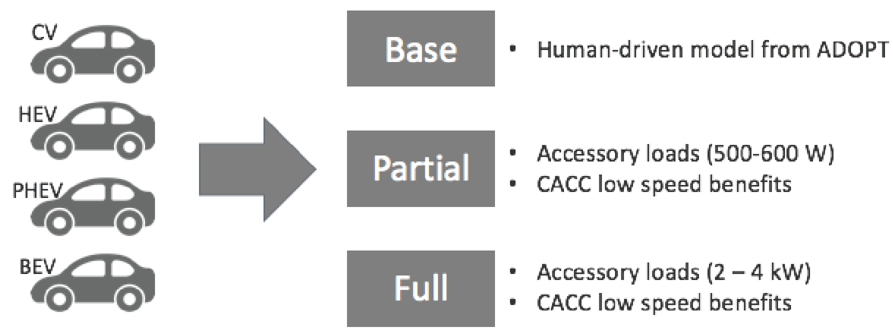


Accomplishments – Energy Intensity

- RouteE model: trained on FASTSim energy consumption results over real-world drive cycles from the Transportation Secure Data Center (TSDC)
- A library of 175 pre-trained RouteE vehicle models have been provided to the BEAM team for integration
- Drive cycle effects of CAVs
  - Shift on link average speed distribution
  - Less energy use at same average speed bin due to smoothing effect

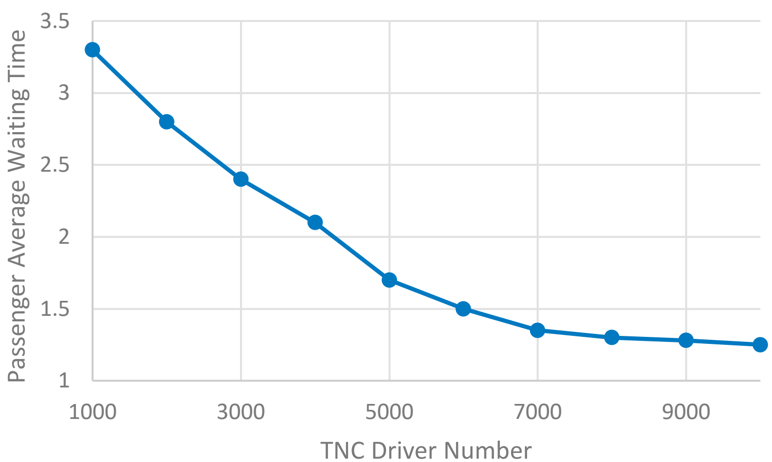


- Significantly higher vehicle accessory load to power the additional required sensor hardware and computational resources

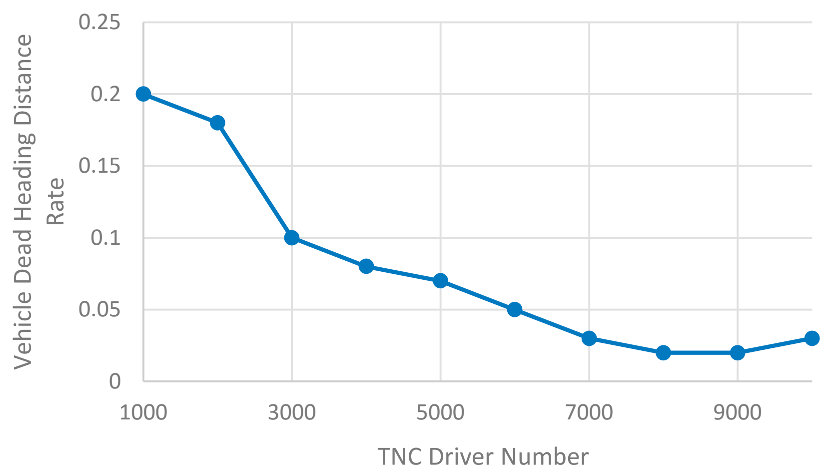


Accomplishments –BEAM Riverside Model

- Developed BEAM model for the City of Riverside with over 24,000 agents.
- Southern California Association of Government (SCAG) data are applied to generate travel demand and estimate travel activities.
- Sensitive analysis on CAV's impact: about 40% travel time reduction at 100% CAV penetration rate in the peak hour.
- Sensitive analysis on ride-hailing penetration: reduced waiting time and vacant trip number if the number of TNC driver increases



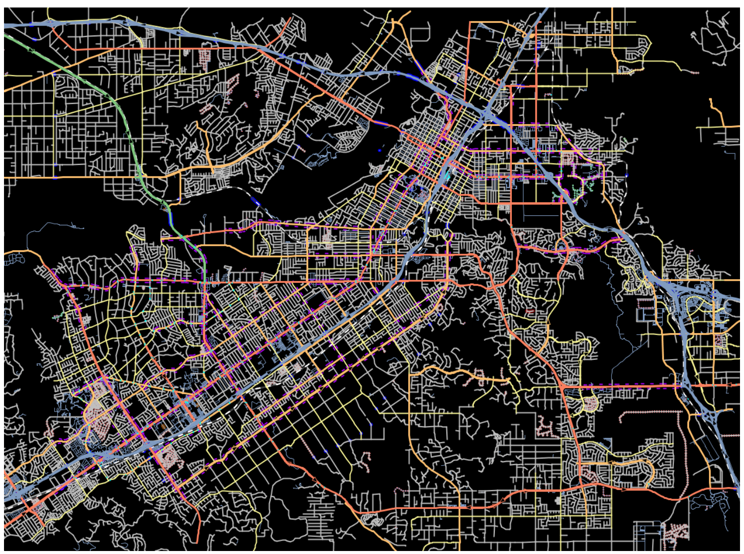
The impact of TNC penetration rate on passenger average waiting time



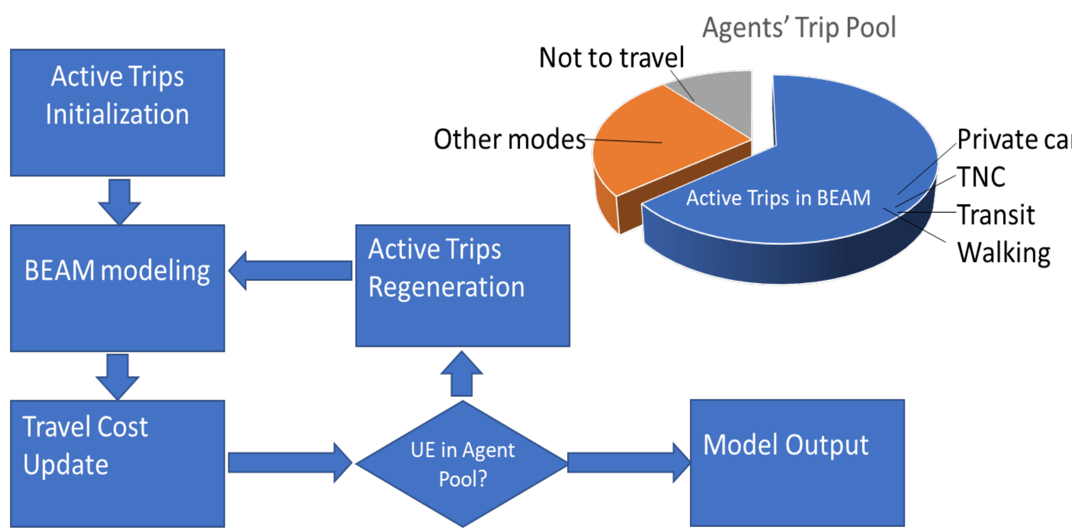
The impact of TNC penetration rate on TNC vacant travel distance.

Accomplishments – Trip Generation Model

- Modeling induced demand from CAV and shared mobility is critical
- Developed a hybrid model that consists of:
  - Default modal choice module of BEAM
  - External discrete choice model for the modes that is not represented in BEAM, including the choice of not to travel
- Designed a "BEAM-in-the-Loop" logic to solve trip generation and mode choice problems simultaneously



Riverside City Network



Trip generation and mode choice using BEAM platform

Accomplishments – Mode Choice Model

- Conducted comprehensive literature review on mode choice modeling for CAVs and TNCs
- Developed a mode choice model considering new transportation services: A mode choice model based upon a set of fundamental factors that influence mode choice decisions

$$V = \beta_1 Acc\_T\_O + \beta_2 Acc\_T\_D + \beta_3 T_{task} + \beta_4 T_{physical} + \beta_5 T_{productive}$$

  - V: utility of taking a travel mode
  - β_i: parameters of utility function
  - Acc_T_O: access time at origins
  - Acc_T_D: access time at destinations
  - T_{task}: travel time required for performing task
  - $T_{physical}$: travel time requiring physical activities
  - $T_{productive}$: travel time that can be productive

  – The parameters estimated from the observed data from existing transportation modes can be applied to new transportation services

- Estimated model with sample data from the California state add-on dataset from the 2017 National Household Travel Survey
- The preliminary results proved the proposed model can reasonably represent travelers’ mode choice preferences and has the potential to estimate the likely uptake rate for new/novel travel modes

Responses to Previous Year Reviewers' Comments

- **"There is no clear plan to fill the data gaps needed for this work to produce significant new results."**
  - We defined five types of CAV experiment scenarios and made a plan to fill the gaps on four less-explored areas: 1) mixed traffic, 2) heavy-duty vehicles, 3) high market penetration, 4) impact evaluation on other vehicles. New field experiments focused on 1 and 2, while new simulations focused on 3 and 4.
- **"The model framework makes sense but still needs significant work to add detail. The project especially needs more work on behavioral elements such as value of travel time and other hedonics."**
  - Based on the conceptual model framework last year, we made specific models on travel behavior, system operation and energy evaluation using BEAM as the main platform. A novel mode choice model was developed to characterize the behavior elements.
- **"How the team will incorporate empty (TNC) vehicle movements into the analysis, when most travel demand and traffic assignment modeling tools do not include these vehicles."**
  - In BEAM, TNCs are modeled as a fleet of taxis controlled by a centralized manager that responds to requests from customers and dispatches vehicles accordingly, so the empty vehicle movements can be modeled and tracked.

Collaboration and Coordination with Other Institutions

- Partner: NREL
  - Support processing and analysis of CAVs-relevant data
  - Developed RouteE model for energy intensity calculation
  - Developed a novel mode choice model, and working with UCR to integrate it into the BEAM platform
- Collaboration with other universities and national labs
  - LBNL: work closely with Tom Wenzel, Colin Sheppard and BEAM development team on BEAM modeling and future collaboration
  - UIC/ANL: discuss transferability modeling with Ramin Shabanpour and Thomas Stephens
  - California PATH: collaborate on demo and test along El Camino Real
- Collaboration with agencies and industry
  - Southern California Association of Governments
  - City of Riverside, City of Carson
  - Leidos
  - Crash Avoidance Metrics Partners LLC (CAMP)
  - Volvo Truck
  - Honda

Remaining Challenges and Barriers

- The CAV Efficiency Database still relies on the results from micro-simulation, as most of current CAV field experiments and deployments only represent limited scenarios, e.g. low CAV penetration rate, low automation level, and lack of information from other vehicles on the same road.
- Lack of real world data to calibrate the mode choice model that considering induced demand from new mobility technologies, as most travel surveys such as National Household Travel Survey (NHTS) only cover the trip that was finally made.
- It is impossible to build a single agent-based model with all the details on travel demand and travel activities for the entire state. An extrapolation approach is needed to extract information from highly detailed regional level model and transfer that to the state level.

Proposed Future Research

- Further fine-tune the parameters in the proposed mode choice model, and develop discrete choice models to characterize the induced demand effect
- Define multiple scenarios that could represent the various stages of new mobility technologies in the future
- Evaluate the regional energy impact of CAV and shared mobility for Riverside and Bay Area using the proposed BEAM-based model
- Evaluate the potential effects of proposed policies to mitigate adverse energy outcomes
- Extrapolation to the state level:
  - Estimate the energy change rate per person using the output from the regional models, and cluster them using socio-demographic information
  - Generate synthetic population of the state using the NHTS samples and census level survey data
  - Evaluate the statewide energy impact by applying the energy change rate per person to the population of the state

Any proposed future work is subject to change based on funding levels

Summary

- ***This Project:***
  - Collects data from vehicles with CAV and shared mobility technologies (primarily deployed in California)
  - Develops a comprehensive framework for evaluating energy efficiency opportunities from large-scale CAVs and shared mobility systems
  - Addresses key barriers by quantifying the transportation system-wide energy impacts from new mobility technologies using real-world data
- ***Technical Accomplishments and Progress:***
  - Completed CAV data collection and created CAV efficiency database
  - Built Riverside model, the first BEAM model in Southern California
  - Developed RouteE model for energy estimation considering CAV effect
  - Developed novel mode choice model for new mobility technologies
- Solid collaboration with universities, national labs, agencies and industry
- Future research to tackle remaining challenges

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Thank You

Technical Back-Up Slides

Publications

- Chao, W., Hou, Y., Barth, M. (2019). Data-Driven Multi-step Demand Prediction for Ride-hailing Services Using Convolutional Neural Network, Computer Vision Conference (CVC) 2019. Link
- Ye, F., Hao, P., Wu, G., Esaid, D., Boriboonsomsin, K., Barth, M. (2019). An Advanced Simulation Framework of an Integrated Vehicle-Powertrain Eco-Operation System for Electric Buses. Accepted by 2019 IEEE Intelligent Vehicles Symposium.
- Wei, Z., Hao, P., Barth, M. (2019). Developing an Adaptive Strategy for Connected Eco-Driving under Uncertain Traffic Condition. Accepted by 2019 IEEE Intelligent Vehicles Symposium.

- The research team members are also working on multiple papers for The International Conference on Intelligent Transportation Systems (ITSC) 2019, Transportation Research Board (TRB) and journals.

Critical Assumptions and Issues

- This project focused on the transportation-related impact on energy efficiency due to CAV and shared mobility. The land use or economy development change is not considered in this project.
- The mode choice model define a set of variables that travelers consider for mode choice decisions in any transportation mode. We assume the model calibrated from existing modes is applicable to new/novel travel modes
- In the current BEAM Riverside model, we assume the CAV penetration rate as a constant value for all the links as CAVs share the same mode with conventional vehicle in he model. We will work with BEAM development team to assign a new mode for CAVs and calculate the real penetration rate based on the number of CAVs at each link.
- When transferring the finding from the regional model to the entire state, we assign socio-demographic characteristics and area wide infrastructure attributes to each agent and group them into clusters.