EEMS 064
Project ID# 7A.1.4
CAVs Pillar

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Modeling Connected and Automated Vehicles (CAVs) Transitions Dynamics and Identifying Tipping Points

Principal Investigators: Brian Bush and Jeff Gonder
Presenter: Jeff Gonder
National Renewable Energy Laboratory
2019 Vehicle Technologies Office Annual Merit Review
10 June 2019

Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · BERKELEY LAB · OAK RIDGE National Laboratory · NREL NATIONAL RENEWABLE ENERGY LABORATORY

OVERVIEW

Timeline

- *Project start date:* March 2017
- *Project end date:* June 2019
- *Percent complete:* 85%

Budget

- *Total project funding:* $315,000
  - *DOE share:* $315,000
  - *Contractor share:* $0
- *Funding for fiscal year 2017:* $115,000
- *Funding for fiscal year 2018:* $200,000
- *Funding for fiscal year 2019:* $0

DOE = Department of Energy
LBNL = Lawrence Berkeley National Laboratory
NREL = National Renewable Energy Laboratory
ORNL = Oak Ridge National Laboratory
LANL = Los Alamos National Laboratory
MA3T = Market Adoption of Advanced Automotive Technologies

Barriers

- New tools, techniques & capabilities needed to understand most important levers for improving energy productivity of future mobility systems.
- Potential rapid and uncertain evolution of vehicle and mobility technologies.
- Difficulty accurately modeling large-scale, interrelated transportation systems.

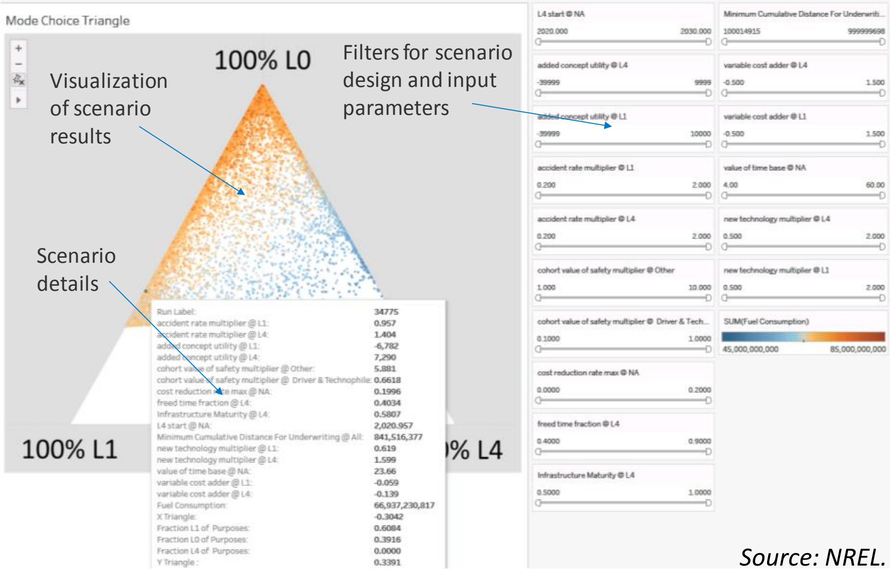
Partners

- *Traveler behavior data:* Whole Traveler Survey team (LBNL and NREL)
- *Modeling discussions:* MA3T (ORNL)
- *Statistics:* Joanne Wendelberger (LANL)
- *Workflow:* SMART Workflow Task Force
- *Project lead:* NREL

RELEVANCE

- Objectives
  - Determine how the transition and end state for connected and automated vehicles (CAVs) adoption and energy outcomes depend on cost, technology, and behavior in the interaction between numerous stakeholders.
  - Develop a semi-quantitative "CAV scenario generation" model to identify behavioral, cost, and technical influences on adoption, energy, and influential data gaps for future research, including stakeholders who can accelerate or impede CAV adoption and affect energy use.

- Impact
  - Supports efforts to estimate potential energy and mobility impacts of CAVs at both a national level and in 50+ metropolitan regions.
  - Delivers a nimble analytic tool for generating numerous scenarios for CAV adoption under a variety of conditions.
  - Enables stakeholders to understand the range of effects of CAVs and the circumstances likely to lead to particular CAV outcomes.



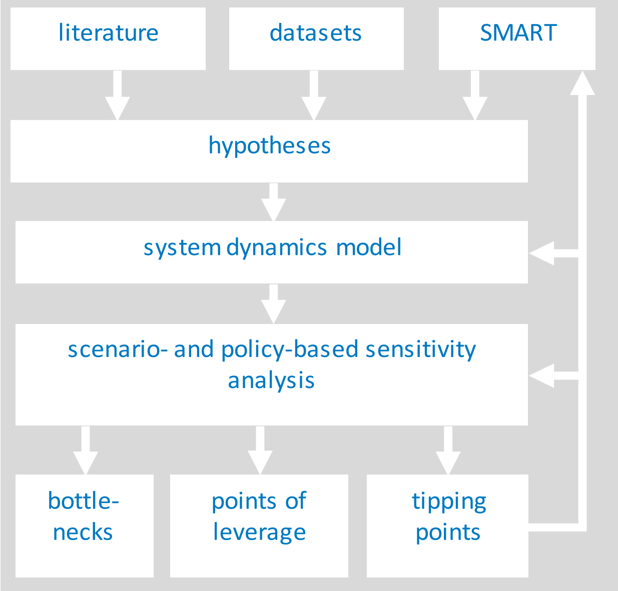
Source: NREL.

MILESTONES

Year	Quarter	Milestone	Status
Fiscal Year 2018	Quarter2	*Go/No-Go:* Confirm initial transition modeling efforts are providing sufficient fidelity and insights to justify continuing; decide whether to focus or broaden scope.	Complete
	Quarter3	Provide plan and briefing on opportunity for integration with other SMART models and datasets.	Complete
	Quarter4	Report quantifying energy/environmental implications of CAV transition and tipping points.	Complete
Fiscal Year 2019	Quarter1	Revise traveler cohorts based on WholeTraveler and National Highway Traffic Safety Administration (NHTSA) 2017 datasets; conceptualize delivery submodel.	Complete
	Quarter2	Execute sensitivity study for all CAV concepts, including local delivery for 50+ metropolitan regions.	Complete
	Quarter3	Document analysis results in manuscript for journal and prepare model for open-source release.	On track

APPROACH

- Develop system dynamics simulation to model the circumstances and dynamics of transitions from predominantly individual ownership of non-CAVs to various future scenarios of high connectivity/automation.
- Identify/quantify tipping-point hypotheses.
- Evaluate known and hypothetical situations with possibly adverse effects.
- Analyze sensitivities for CAV scenarios.

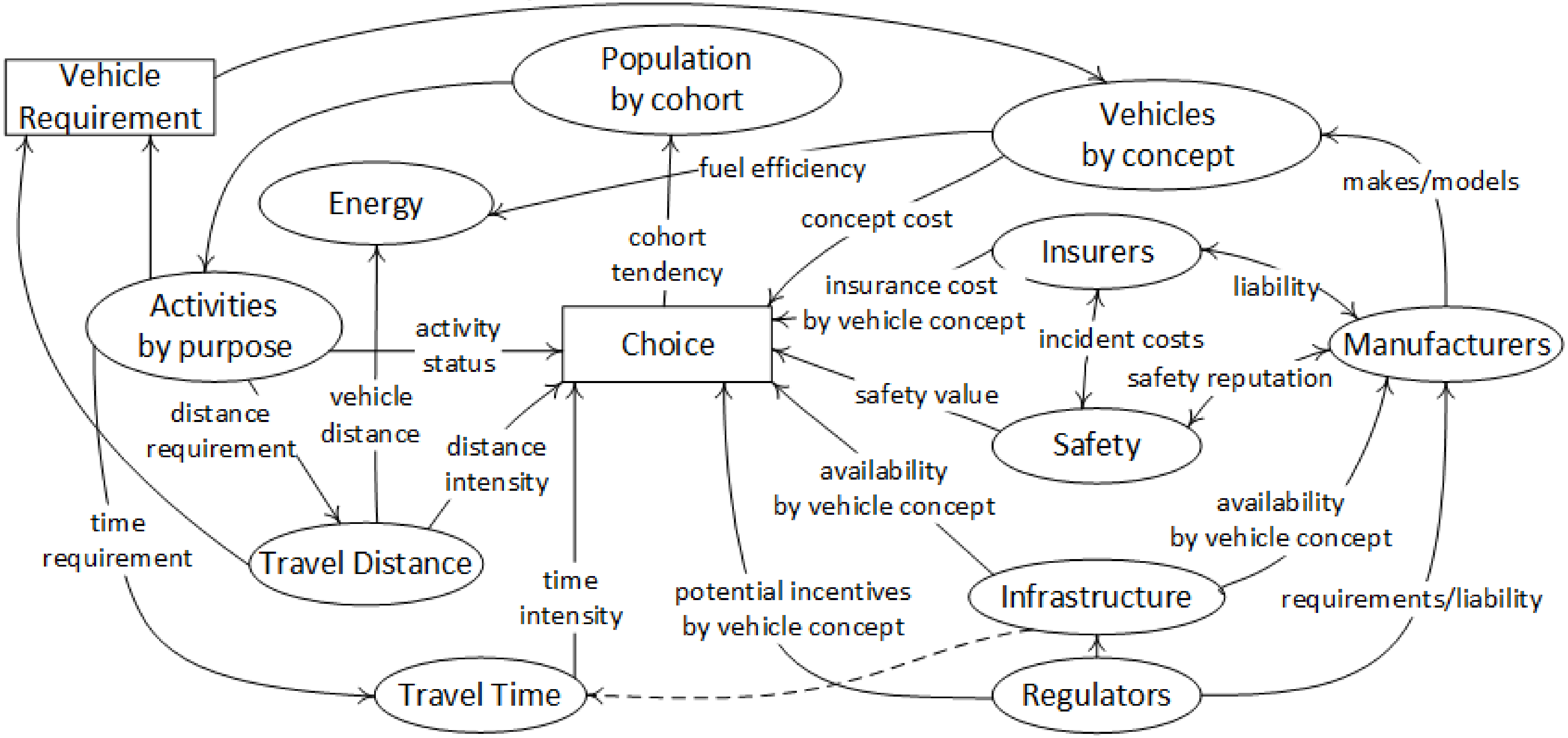


Source: NREL.

Vehicles	Services	Level of Detail	Regionality
Light-Duty Vehicles	Personal Transportation	Conceptual	National
Medium- and Heavy-Duty Vehicles	Freight Transportation	Semi-Quantitative	Regional
All Vehicle Types	All Transportation Services	Quantitative	Full Regional Flexibility

APPROACH

System modeling represents influences and feedbacks determining CAV adoption and energy consumption.



Source: NREL.

APPROACH

Sector representations enable model objectives.

Stakeholder	Modeling Objective
Travelers	Represent traveler preferences, value of safety, and time requirements.
Vehicle Owners	Compare alternative ownership models (e.g., Mobility as a Service).
Manufacturers	Include self-insurance during technology development and research and development (R&D) investment.
Regulators	Represent potential for regulatory lag and backlash due to safety concerns.
Insurers	Represent need for data before underwriting, discounts and surcharges, vehicle-type-specific accident rates.
Infrastructure Providers	Incorporate infrastructure constraints, investment, and development.
Energy	Account for effects on energy use.

Dimensionality captures primary differentiators.

Population Cohorts	CAV/Travel Concepts	Activity Purposes
Time-Sensitive: Value time highly and propensity for online shopping	Telecommuting: telecommuting substitutes for travel	Work
Automation-Prone: Propensity for using automation	Non-Motorized: pedestrian and bicycle travel	Shopping
Sharing: Propensity for ride-hailing and car-sharing	CAV 0–5: levels based on SAE International definitions (see backup slides for detailed subcategories)	Errands
Traditional: No propensity for automation or sharing	Local Delivery	School
Non-Driver: Unable or unwilling to drive		Social
		Other

* Population Cohorts informed by Lawrence Berkeley National Lab's recent Whole Traveler Survey.
* *Travel concepts are based on Shladover & Greenblatt (2018), "Connected and Automated Vehicle Concept Dimensions and Examples," DOI:10.1080/15472450.2017.1336053.*
* Activity categories based on the 2017 National Household Travel Survey.

APPROACH

Scenario-screening analyses identify influential factors for CAVs adoption and energy consumption.

Screening Study (FY 17): broad exploration of stakeholder interactions and CAV-adoption futures.
Energy Study (FY 18): assessment of factors leading to variability in total energy consumption.
Comprehensive Study (FY 19): quantification of interactions of stakeholder and energy factors.

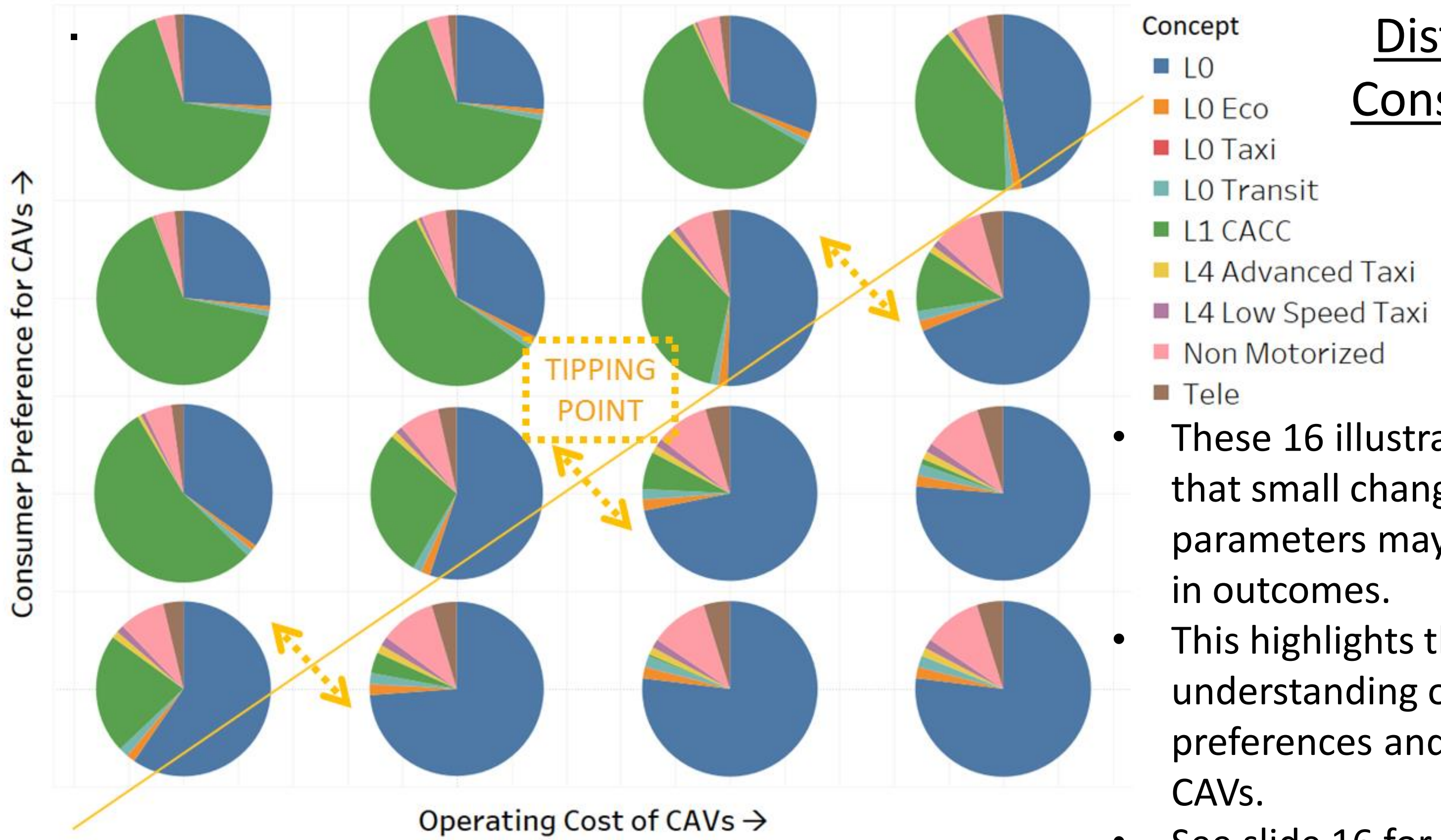
- The three studies use Latin hypercube sampling (LHS) or Sobol experimental designs for 50,000 to 100,000 simulation runs each.
  - See back-up slides for ranges of input assumptions used under each study

- Visualization, statistical, and machine-learning techniques identified sensitivities, correlations, leverages, bottlenecks, and tipping points.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Relatively small changes in combinations of assumptions may rapidly separate end states of CAVs adoption.

SCREENING STUDY: *November 2018*



Source: NREL.

Distribution of Fuel Consumption in 2040

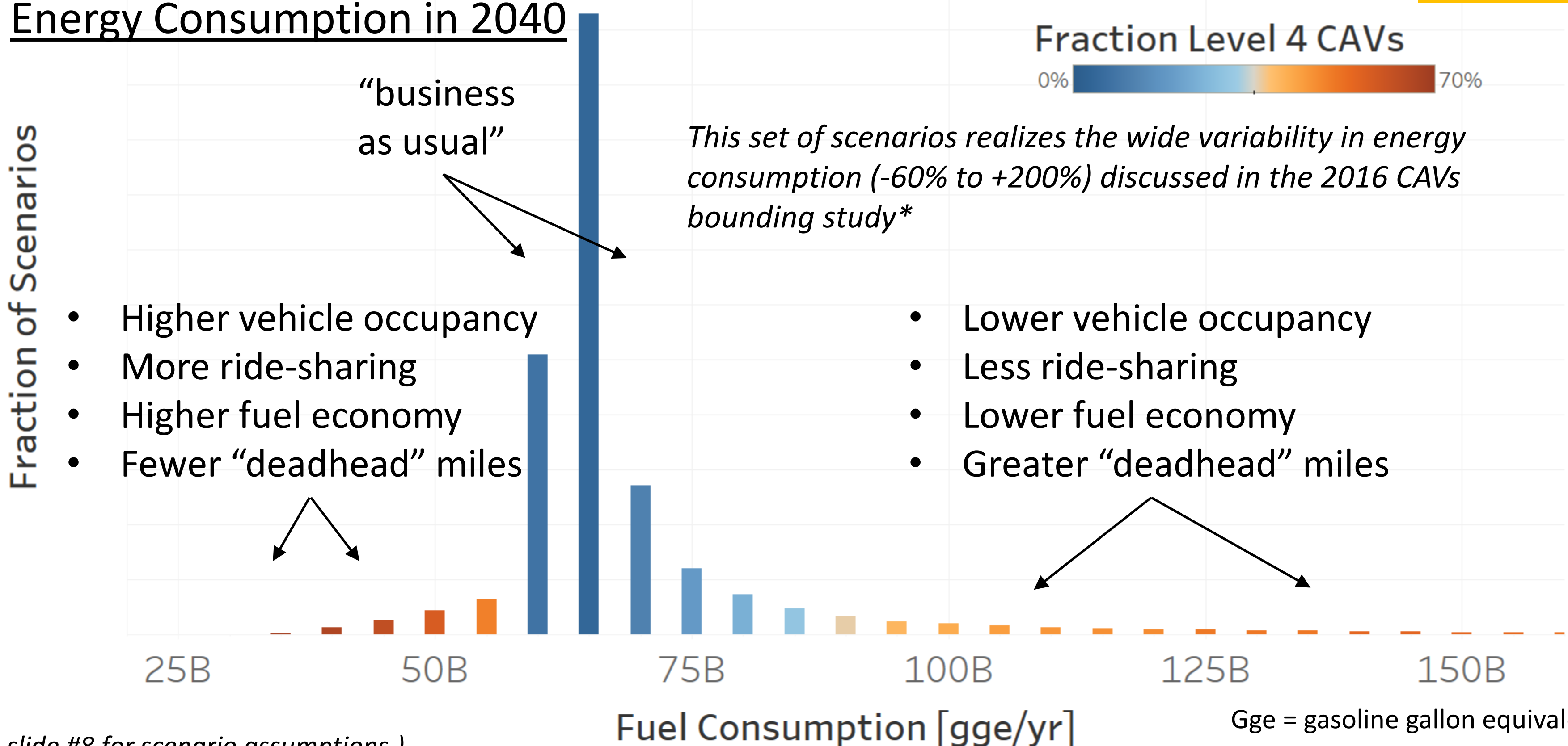
- These 16 illustrative scenarios suggest that small changes in model input parameters may result in large changes in outcomes.
- This highlights the need for quantitative understanding of both consumer preferences and also operating costs for CAVs.
- See slide 16 for related findings.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Varying assumptions regarding CAV usage may result in either very high or very low system-wide energy usage.

ENERGY STUDY:
April-July 2018

Energy Consumption in 2040



Gge = gasoline gallon equivalent

(See slide #8 for scenario assumptions.)

Source: NREL.

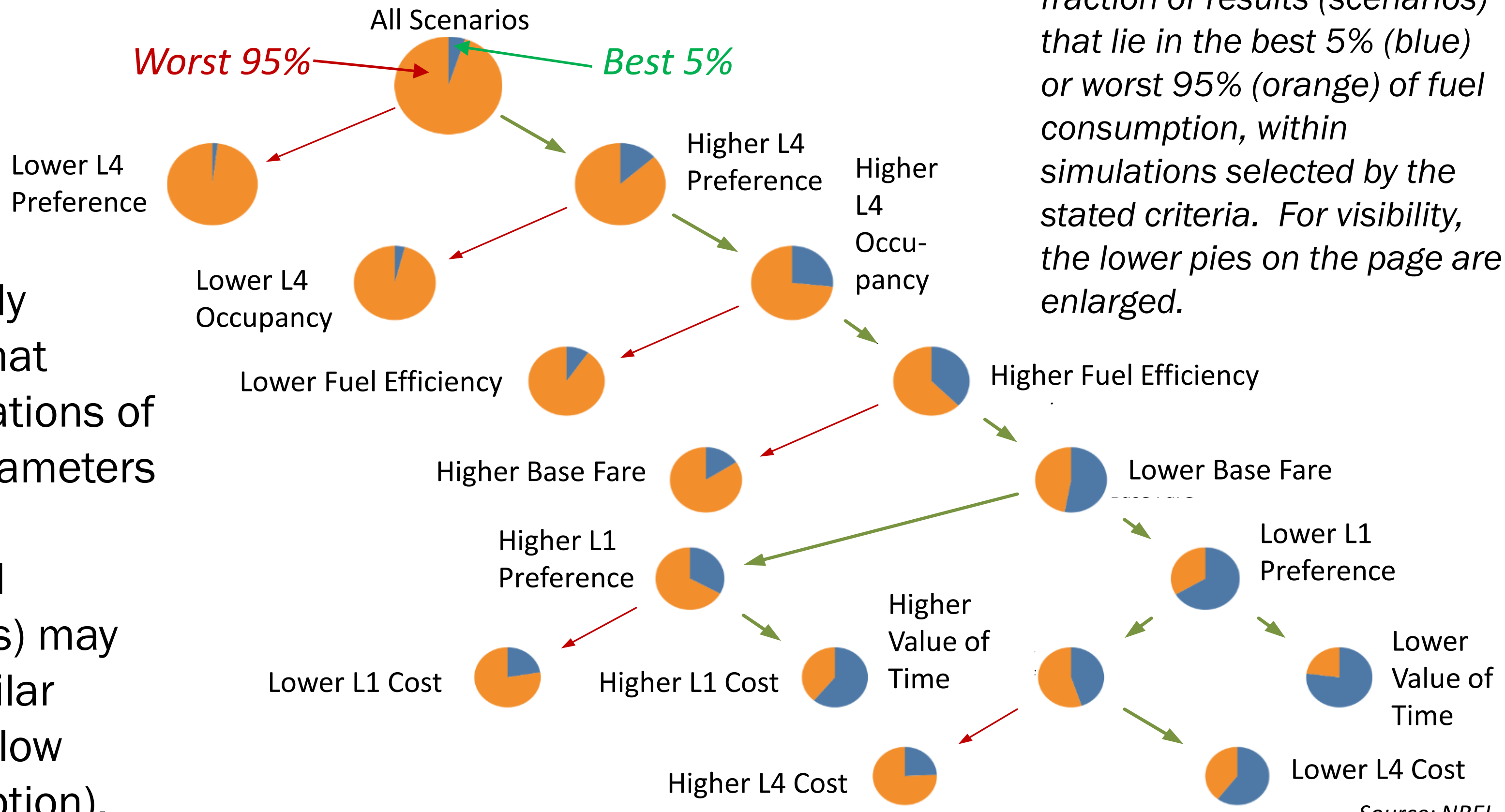
Stephens, Gonder, Chen, Lin, Liu & Gohlke (2016), "Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles," DOI:10.2172/1334242.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Consumer preference, time valuation, and technology costs most greatly influence low fuel consumption.

ENERGY STUDY:
April-July 2018

Mode Choice and Energy Consumption in 2040



Each pie chart shows the fraction of results (scenarios) that lie in the best 5% (blue) or worst 95% (orange) of fuel consumption, within simulations selected by the stated criteria. For visibility, the lower pies on the page are enlarged.

This energy study demonstrates that disjoint combinations of model input parameters (e.g., consumer preferences and technology costs) may lead to very similar outcomes (e.g., low energy consumption).

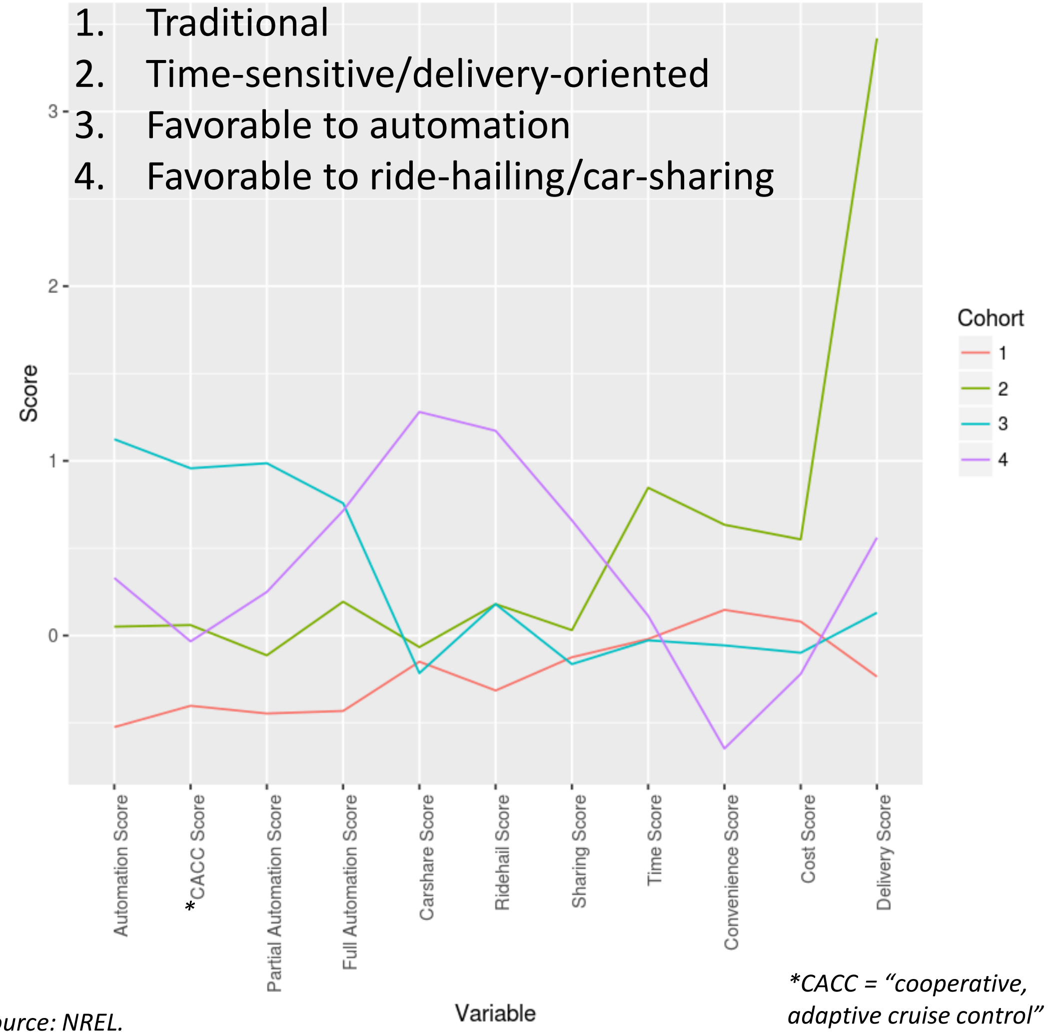
Source: NREL.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Cohorts of CAV travelers were computed via analysis of LBNL's WholeTraveler Survey results.

- Clustering analysis of WholeTraveler (WT) Survey yields cohort definitions.
- Cohort membership is predicted based on Classification and Regression Tree analysis for variables common to WT Survey and National Household Travel Survey (NHTS)

COMPREHENSIVE STUDY:
October 2018-April 2019



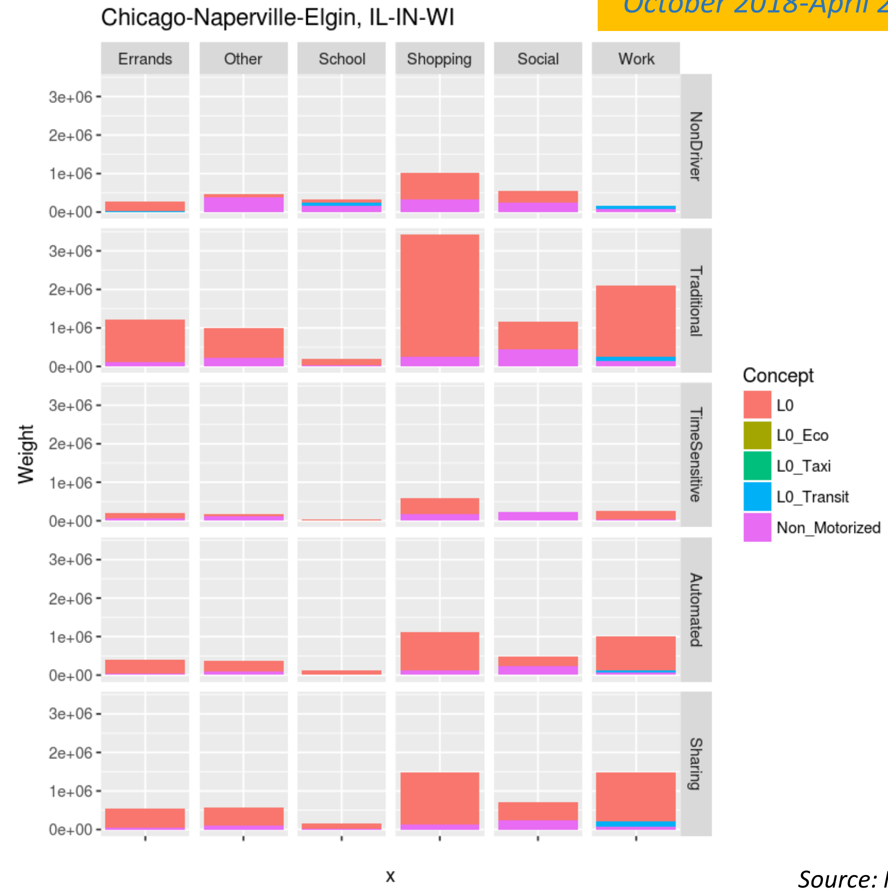
Source: NREL.

**CACC = "cooperative, adaptive cruise control"*

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

The CAV adoption model is calibrated to WholeTraveler- and NHTS-informed traveler cohorts, trip mixes, local deliveries, and mode splits in 50+ metropolitan regions.

COMPREHENSIVE STUDY:
October 2018-April 2019

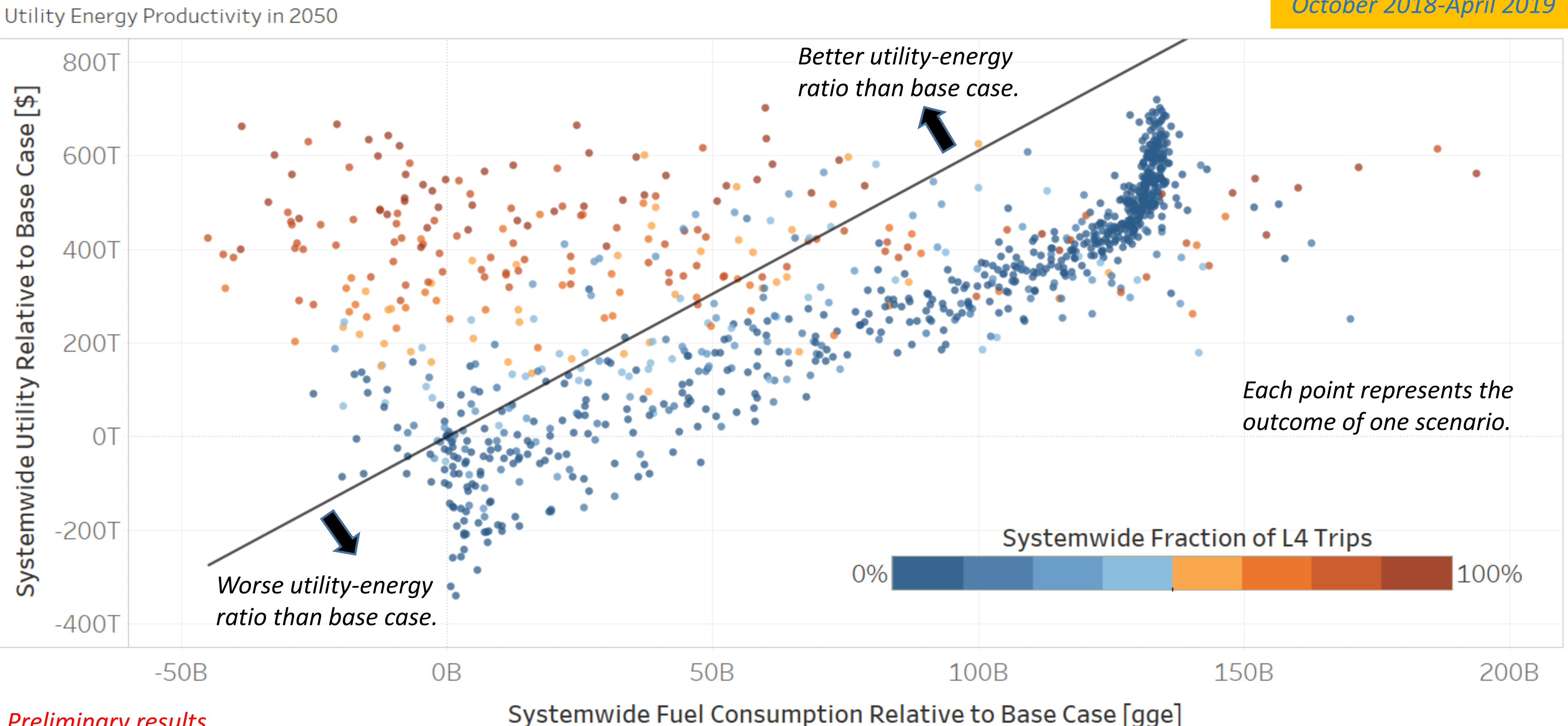


Source: NREL.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Outcomes with higher “traveler satisfaction” (system-wide utility) tend to require more fuel consumption unless CAV level 4 travel concepts predominate.

COMPREHENSIVE STUDY:
October 2018-April 2019

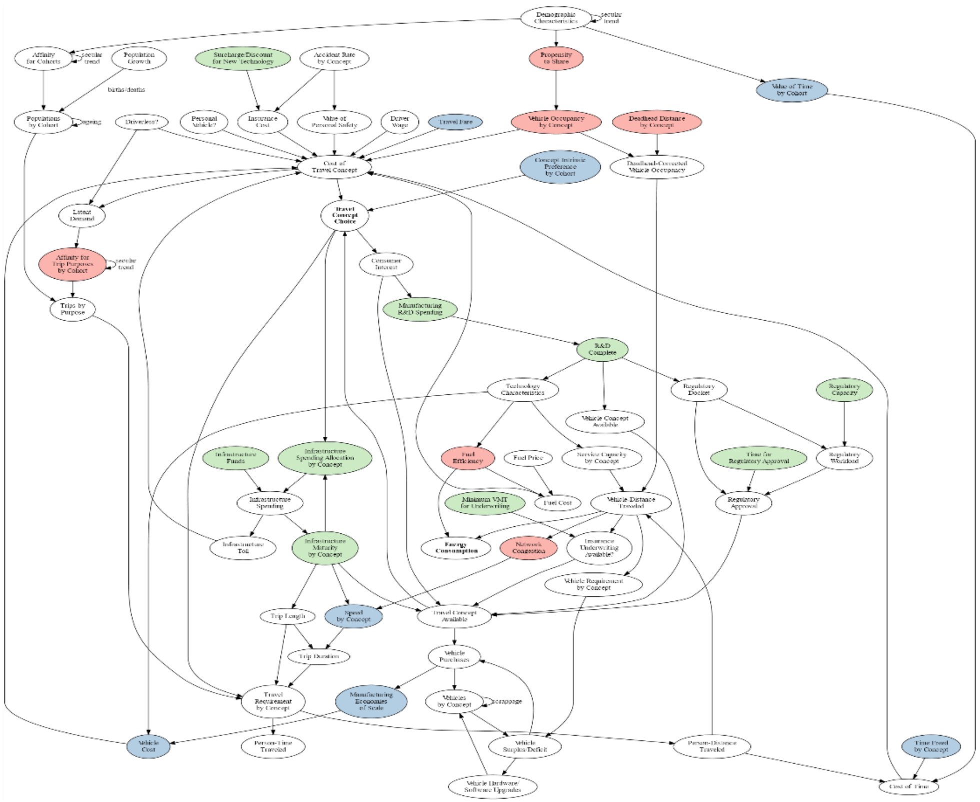


Preliminary results.

Source: NREL.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Overall, this project has identified and classified leverage points and causal relationships across the CAVs adoption system, distinguishing necessary conditions from accelerators for adoption and energy efficiency improvement.



Source: NREL. *A legible version of this figure is provided with the poster.*

Findings of Key Leverage Points

- *Green:* prerequisite or threshold for CAVs, e.g.
  - Manufacturing R&D Spending
  - Infrastructure Funds
- *Blue:* highly influential on CAVs adoption, e.g.
  - Value of Time by Cohort
  - Time freed by Concept
- *Red:* highly influential on energy use, e.g.
  - Fuel efficiency
  - Network Congestions

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Key Detailed Insights (Slide 1)

1. Massive data gaps and uncertainties regarding future travel behavior, characteristics of CAV technologies, and ownership/business models necessitate a scenario-based, semi-qualitative model of long-term CAV adoption outcomes — not a traditional, fully quantitative, choice model.
2. Points of leverage fall into three categories: (i) necessary conditions for CAV adoption, that impede adoption unless a minimum threshold of support is present; (ii) conditions that proportionately accelerate CAV adoption; (iii) conditions not strongly affecting CAV adoption, but proportionately affecting energy use.
3. It is feasible to meld the WholeTraveler survey with the NHTS to synthesize traveler cohorts, trip mixes, local deliveries, and mode splits nationally and in the largest metropolitan regions.
4. Scenario-screening analyses can identify influential factors for CAV adoption and energy consumption.
5. The model can be used to identify the conditions necessary to reach extremes of technology penetration.
6. Technological and behavioral assumptions lead to qualitatively different end states for CAVs and energy.
7. CAV adoption faces a complex landscape of overlapping stage gates where stakeholders block or accelerate.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Key Detailed Insights (Slide 2)

8. Small changes in combinations of assumptions may rapidly separate end states of CAV adoption.
9. Multiple evolutionary pathways can converge on similar outcomes for specific metrics, as well as scenarios that yield disparate mobility systems.
10. Consumer preference, time valuation, and technology costs most greatly influence low fuel consumption.
11. Varying assumptions regarding CAV usage may result in either very high or very low systemwide energy usage.
12. High adoption of level 4 may be relatively rare (fewer than 30% of scenarios modeled), given wide ranges of plausible input assumptions regarding traveler propensities (ownership preference, attitude towards automation, and value of time) and technology characteristics.
13. Outcomes with higher "traveler satisfaction" (system-wide utility) tend to require more fuel consumption unless CAVs level 4 travel concepts predominate.
14. System-wide utilities show qualitatively different scenario patterns between high and low L4 CAV adoption.
15. Although local-delivery concepts may shift significantly, their energy impact relative to changes in personal travel patterns remains relatively minor.

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

This project was not presented or reviewed at a previous Annual Merit Review.

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- Whole Traveler Survey (WTS) team (LBNL and NREL)
  - Commented on WTS questionnaire and data collection.
  - First external user of WTS survey results.
  - Methodological discussions on melding WTS and NHTS and clustering traveler behavior in WTS.
  - Used WTS to calibrate this CAVs adoption model.
- MA3T (ORNL)
  - Methodological discussions on data sources, representing choice, mode split, etc.
- Joanne Wendelberger (LANL)
  - Methodological discussions and plans for collaboration on identifying extremes of CAV adoption and energy use, design of computer experiments, and sequential sensitivity analyses.
- SMART Lab Consortium, and SMART Workflow Task Force (WTF)
  - Detailed data dictionary for inputs and outputs of this CAV adoption model.
  - Could use this CAV adoption model for selecting WTF scenarios and factors

REMAINING CHALLENGES AND BARRIERS

- **Data Gaps:** Empirical data about current transportation system attributes and transport behaviors is lacking for many key topics that could inform modeling improvements. For example, the number, type, and use of vehicles used to accomplish commercial delivery is largely unknown. In another example, the groundbreaking Whole Traveler Survey developed data for one metropolitan region that would be helpful to have nation-wide.

This project has identified major data gaps that impede CAV modeling and has provided this list to the "Livewire" EEMS data project.

- **Uncertain Future:** Future CAV scenarios are inherently uncertain. Evolving the model and data inputs to continue to reflect uncertainty is an ongoing challenge.

This project has sought to make appropriate use of available data, assign ranges to uncertain parameters for scenario analysis, and thus not over-specify the modeling and results relative to data availability and certainty.

- **Stakeholder Outreach:** This project developed a high-level model. We think many stakeholders could use this model for their own purposes, but this would pose communication and decisional challenges to make these applications effective.

We have developed descriptions of this model that distinguish it from other tools. We have published the model with city-specific datasets and basic documentation.

- **Coordination:** This project could ingest assumptions from many other parts of SMART, but extensive, precise, and synchronous alignment across all would require a more concerted effort.

This project attempted to align with numerous assumptions across the project through communications with the Workflow Task Force.

PROPOSED FUTURE RESEARCH

This project concludes following June 2019 with the completion of:

- Reporting scenario and sensitivity analysis results in a manuscript for submission to a peer-review journal.
- Open-source release of the CAV adoption model and technical manual via *github.com*.

This multifarious CAV-adoption scenario model enables exploration of questions such as the following:

- What are the likely effects of transportation strategies on energy use changes associated with CAV deployment?
- What are the most effective strategies to leverage CAV deployment to decrease energy use?
- How might effective strategies vary among different metropolitan regions?

ANY PROPOSED FUTURE WORK IS SUBJECT TO CHANGE BASED ON FUNDING LEVELS.

SUMMARY

Objective

- Determine how the transition and end state for CAV adoption and energy outcomes depend on cost, technology, and behavior in the interaction between numerous stakeholders.
- Develop a semi-quantitative "CAV scenario generation" model to identify behavioral, cost, and technical influences.

Impact

- Supports efforts to estimate potential energy and mobility impacts of CAVs at both a national level and in 50+ metropolitan regions.
- Delivers a nimble analytic tool for generating numerous scenarios for CAVs adoption under a variety of conditions.
- Enables stakeholders to understand the range of effects of CAVs and the circumstances likely to lead to particular CAV outcomes.

Approach

- Develop system dynamics simulation to model the circumstances and dynamics of transitions from predominantly individual ownership of non-CAVs to various future scenarios of high connectivity/automation.
- Identify/quantify tipping-point hypotheses.
- Evaluate known and hypothetical situations with possibly adverse effects.
- Analyze sensitivities for CAV scenarios.

Accomplishments

- Identified stakeholder-related bottlenecks and points of leverage for rapid CAV adoption.
- Ranked and quantified factors impacting systemwide energy use in CAVs adoption scenarios.
- Developed a novel clustering of travelers into cohorts related to CAVs adoption and linked that to the NHTS.
- Mapping of key influences on CAV scenarios.

QUESTIONS?

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Publication Number PR-6A20-73504

TECHNICAL BACK-UP SLIDES

APPROACH – Details on CAV concept dimensionality

Population Cohorts	CAV/Travel Concepts	Activity Purposes
Time-Sensitive Value time highly and propensity for online shopping Automation-Prone Propensity for using automation Sharing Propensity for ride-hailing and car-sharing Traditional No propensity for automation or sharing Non-Driver Unable or unwilling to drive	Telecommuting telecommuting substitutes for travel Non-Motorized pedestrian and bicycle travel CAV 0–5 levels based on SAE International definitions: • Level 0 (L0) Light-duty Vehicle • L0 Transit • L0 Taxi • L0 Eco (driver feedback) • Level 1 (L1) Guided Busway • L1 Cooperative Adaptive Cruise Control (CACC) • L1 Urban Eco Signal Control • Level 4 (L4) Automated Busway • L4 Semi Fixed Route Automated Shuttle • L4 Low Speed Automated Taxi • L4 Advanced Automated Taxi • L4 Urban Freeway Automated Driving • L4 Automated Highway Local Delivery	Work Shopping Errands School Social Other

* Population Cohorts informed by Lawrence Berkeley National Lab's recent Whole Traveler Survey.

** Travel concepts are based on Shladover & Greenblatt (2018), "Connected and Automated Vehicle Concept Dimensions and Examples," DOI:10.1080/15472450.2017.1336053.*

* Activity categories based on the 2017 National Household Travel Survey.

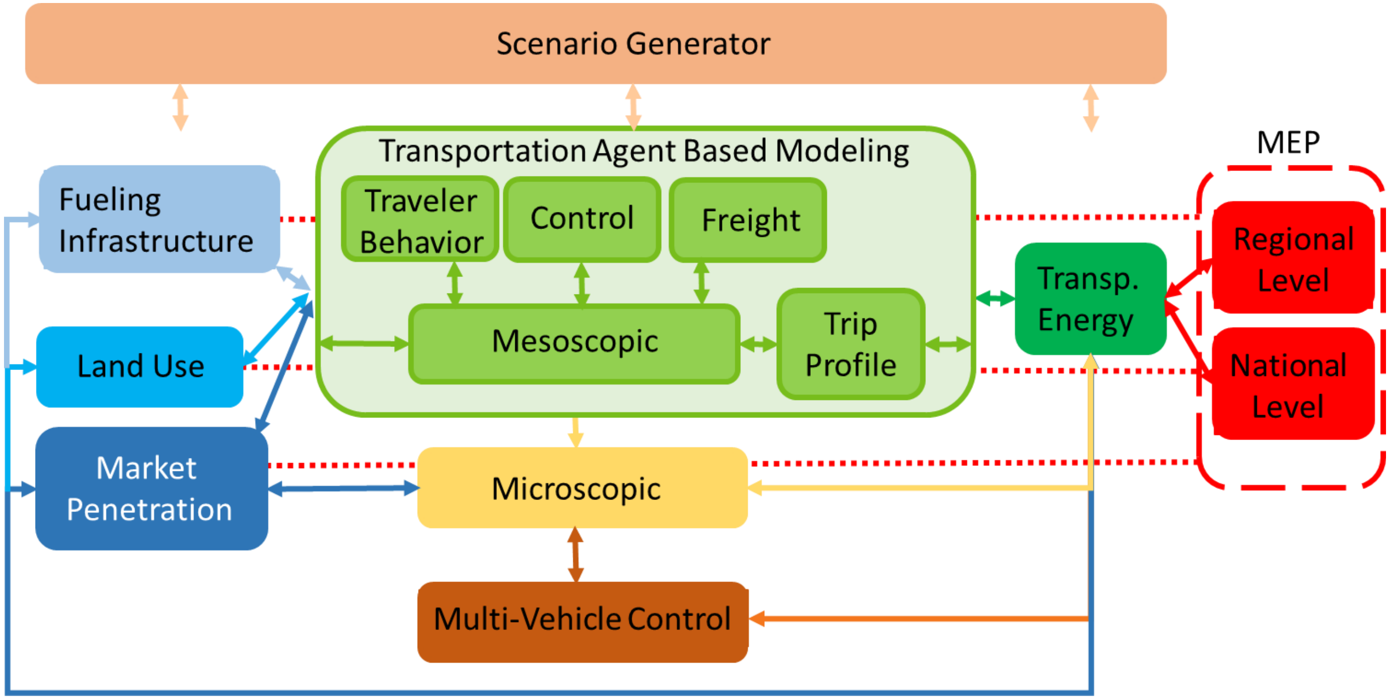
APPROACH – Ranges of Input Assumptions for Scenario Screening Analyses

- The three studies use Latin hypercube sampling (LHS) or Sobol experimental designs for 50,000 to 100,000 simulation runs each.

Variable	Range in Screening Study	Range in Energy Study	Range in Comprehensive Study
Value of time	\$4/hr to \$60/hr	\$4/hr to \$60/hr	\$4/hr to \$60/hr
Multiplier for cost of insuring CAVs	50% to 200%	Not varied	50% to 200%
Accident rate of CAVs relative to L0	20% to 200%	Not varied	20% to 200%
Consumer utility for using CAVs	-\$10,000 to +\$40,000	-\$10,000 to +\$40,000	-\$10,000 to +\$40,000
Variable cost of using CAVs relative to L0	-\$0.50/mile to +\$1.50/mile	-\$0.50/mile to +\$1.50/mile	-\$0.50/mile to +\$1.50/mile
Minimum cum. travel prior to insurance underwriting	10^8 miles to 109 miles	Not varied	10^8 miles to 109 miles
Rate of CAV cost reduction	0%/year to 20%/year	0%/year to 20%/year	0%/year to 20%/year
Initial infrastructure readiness for L4	50% to 100%	50% to 100%	0% to 100%
Fraction of passenger time freed by L4	50% to 100%	50% to 100%	40% to 90%
Valuation of safety by CAV-averse travelers	100% to 1000%	Not varied	100% to 1000%
Valuation of safety by CAV-prone travelers	10% to 100%	Not varied	10% to 100%
Multiplier for vehicle occupancy	Not varied	30% to 300%	30% to 300%
Multiplier for "deadhead" of L4	Not varied	100% to 200%	100% to 200%
Relative cost of transit to L0	Not varied	\$0.25/mile to \$3.00/mile	\$0.25/mile to \$3.00/mile
Relative cost of L0 taxi to L0	Not varied	\$0.50/mile to \$4.00/mile	\$0.50/mile to \$4.00/mile
Relative cost of non-vehicular replacements to L0	Not varied	-\$10/mile to \$0/mile	-\$10/mile to \$0/mile
Relative cost of automated highway	Not varied	Not varied	\$0/mile to \$3/mile
Multiplier for L4 fuel efficiency	Not varied	50% to 150%	50% to 150%

END-TO-END MODELING WORKFLOW

The original/long-term vision for the Workflow has been for the CAV Scenario Generation Model to evaluate a large universe of scenarios and from these suggest subsets for the more computationally- and time-intensive portion of the Workflow to explore. However, due to time limitations to operationalize the FY19 implementation of the Workflow, it was decided instead to simply prescribe a small number of scenarios to run through the Workflow rather than to have scenario selection informed by the CAV Scenario Generation Model.



*MEP = "mobility energy productivity"