Project ID#: EEMS081
Pillar(s): Connected and Automated Vehicles

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

Nationwide energy and mobility impacts of connected and automated vehicle technologies

David Gohlke, Thomas Stephens; ANL
Alicia Birky, Jeff Gonder, Jake Holden, Bingrong Sun; NREL
Paul Leiby, Zhenhong Lin; ORNL
2019 Vehicle Technologies Office Annual Merit Review
June 11, 2019

OVERVIEW

Timeline

Project start: 1 Sep 2018

Project end: 30 Sep 2019

Percent completed: 55%

EEMS Barriers

The EEMS Program must address numerous barriers to achieve its Goals, fulfill its Mission, and realize its Vision. This project addresses:

- Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles
- Computational difficulty of accurately modeling and simulating large- scale transportation systems

Budget

FY 2018: $260k

FY 2019: $0

(100% DOE)

Partners

- Interactions / Collaborations
  – Argonne National Laboratory
  – Oak Ridge National Laboratory
  – National Renewable Energy Laboratory
- Project lead: D. Gohlke, Argonne

RELEVANCE

Objectives:

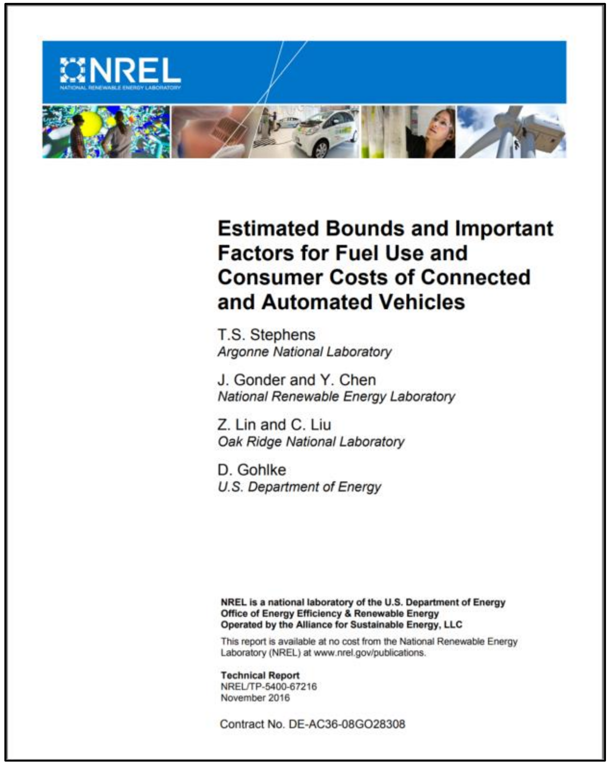
Update 2016 review and synthesis of findings on the **national-level mobility and energy impacts and costs of CAVs**

Develop improved **upper and lower bounds** of these impacts

Explore **interactions between different key factors** driving total energy consumption

Relevance for DOE:

The previous bounding report, published nearly 3 years ago, has been frequently cited, both by DOE/EERE and other governmental organizations, and in the academic literature. The original report found potential changes in light-duty vehicle fuel consumption ranging from +200% to -60%, based on literature available at the time. The current work updates data sources and methodology to better estimate changes from CAVs technology.



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles

T.S. Stephens
Argonne National Laboratory

J. Gonder and Y. Chen
National Renewable Energy Laboratory

Z. Lin and C. Liu
Oak Ridge National Laboratory

D. Gohlke
U.S. Department of Energy

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5400-67216
November 2016

Contract No. DE-AC36-08GO28308

Stephens et al., 2016.
https://www.osti.gov/biblio/1334242

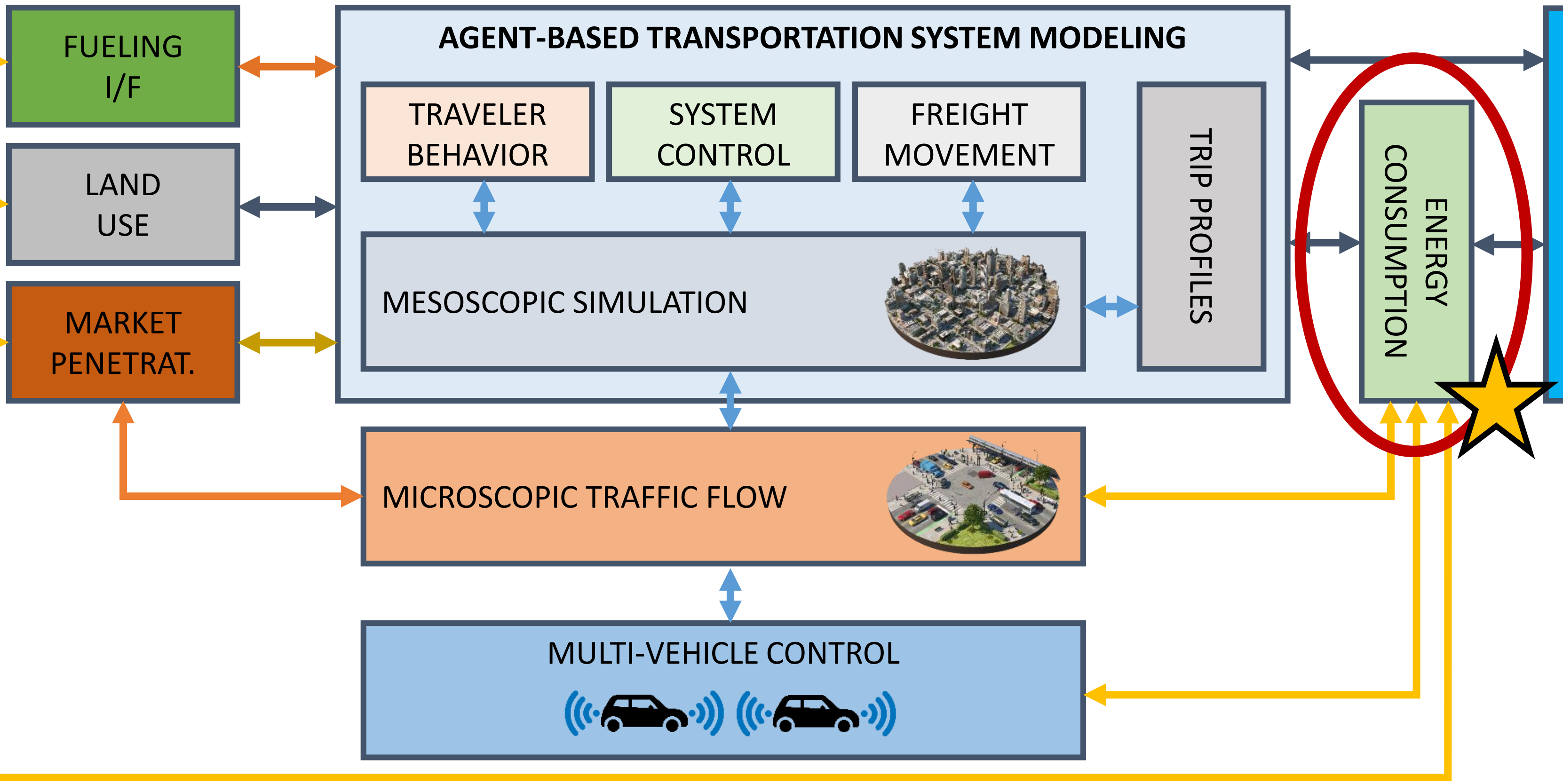
MILESTONES

Month/year	Description	Status
Sep 2018	Initial scoping of technologies and use cases to explore	Complete
Dec 2018	Summarized literature review of updated bounds and outputs from FY16-18 SMART projects and external research	Complete
Mar 2019	Improve methodology to quantify synergies and interactions between different variables	Complete
Jun 2019	Presentation to DOE on preliminary results for CAVs impacts	On track
Sep 2019	Finalization of report documenting improved estimates of bounds for metrics related to energy consumption and mobility	On track

APPROACH

- Review relevant literature about factors which may impact energy consumption in light-duty connected and automated passenger vehicles, including peer-reviewed articles, laboratory reports, and gray literature, focusing on results derived from SMART Mobility research projects.
- Synthetize and harmonize factors from disparate sources to estimate changes in travel demand and fuel efficiency due to CAVs technologies in different scenarios
- Identify upper and lower nationwide bounds of vehicle miles traveled and fuel consumption for light-duty CAVs.
- Estimate statistical distribution of probable energy outcomes from ubiquitous CAVs technology.
- Develop narratives and scenarios to estimate how impacts of CAVs technologies vary when considering different powertrains, ownership paradigms, and land-use changes.

END-TO-END MODELING WORKFLOW



FACTORS OF INTEREST

- 24 factors, half of which are new, have been identified for potential changes in vehicle demand and efficiency for light-duty vehicles due to connected and automated vehicle technologies

Demand

Personal mobility	1	Shifting travel patterns - sprawl	
	2	Shifting travel patterns - urbanization	New
	3	Additional travel - underserved	
	4	Additional travel - leisure travel	New
On-road travel	5	Mode shift to highway	
	6	Re-routing (eco-routing)	New
	7	Ridesharing	
	8	Empty VMT (deadhead)	
	9	Additional fueling trips	New
Commerce	10	Efficient parking	
	11	Change in shopping trips	New
	12	Commercially sponsored trips	New

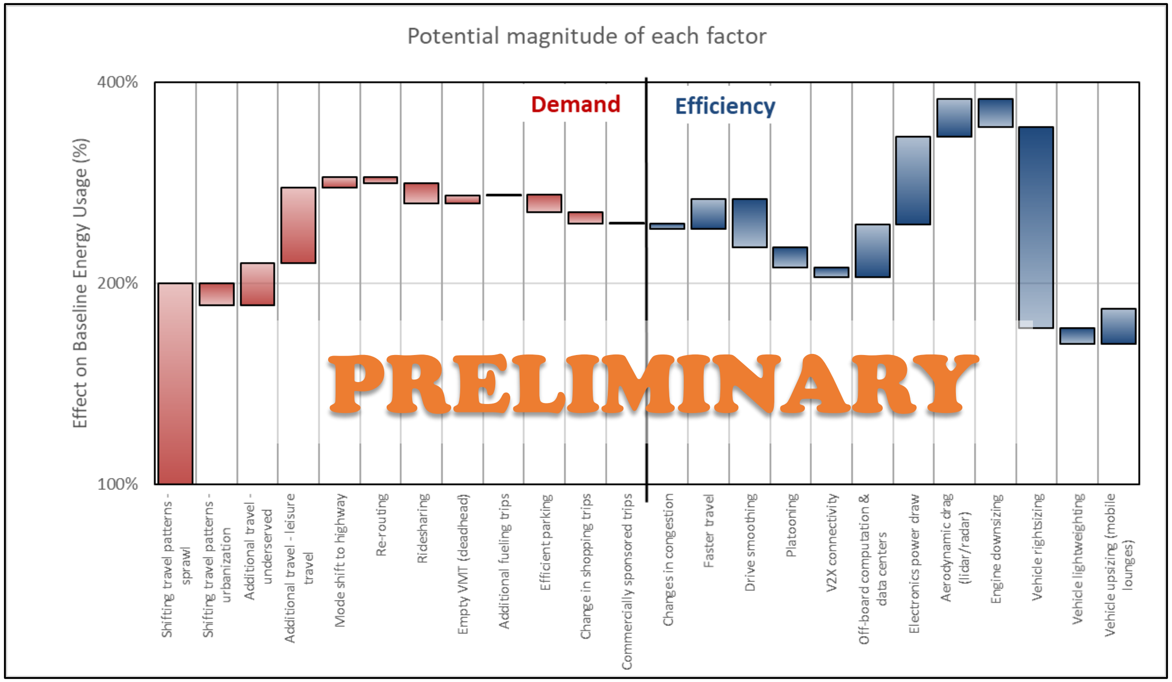
Efficiency

13	Changes in congestion		Travel changes
14	Faster travel		
15	Drive smoothing		
16	Platooning		Connectivity
17	V2X connectivity		
18	Off-board computation & data centers	New	
19	Electronics power draw	New	Vehicle design
20	Aerodynamic drag (sensors)	New	
21	Engine downsizing	New	
22	Vehicle rightsizing		
23	Vehicle lightweighting	New	
24	Vehicle upsizing (mobile lounges)	New	

ENERGY CONSUMPTION BY CONNECTED AND AUTOMATED VEHICLES

- Using same methodology as in the previous report with updated numbers and factors, we can estimate upper and lower bounds for national energy consumption for light-duty CAVs.

- Sprawl and vehicle trip rightsizing each are potentially large, with high uncertainty
- Leisure trips, auxiliary power draw, and drive smoothing are additional key factors
- Power draw from off-board computations and data servers could be large



Graphic showing maximal potential changes due to each factor

INTERACTIONS BETWEEN FACTORS

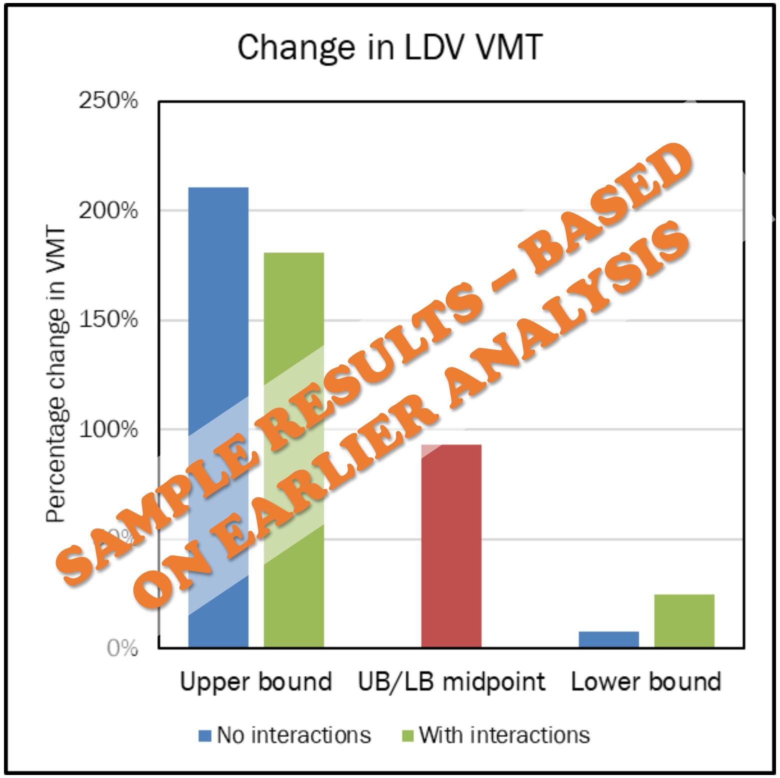
- Factors are not fully independent of each other, e.g., it is impossible to simultaneously maximize ridesharing and passenger occupancy while resizing cars to only have one seat
- To account for interplay between factors, we created adjusted factors to more accurately estimate VMT and MPG changes.
  – Each factor *f* is transformed into a new factor *g* using matrix *M, by* $\vec{g} = \overleftrightarrow{M}\vec{f}$, where the entries of the matrix, M_{ij} represent the effect of the magnitude of factor *j* on the value of factor *i*.
- Magnitude of interactions depends on the specific pair of factors in question
  – Many demand factors are assumed to be independent of efficiency factors – if a change in vehicle design does not impact the ride quality, then consumers will not drive more because of it
  – Changes in congestion have a negative feedback relationship with demand – if there is less congestion and faster travel, people will be inclined to travel more

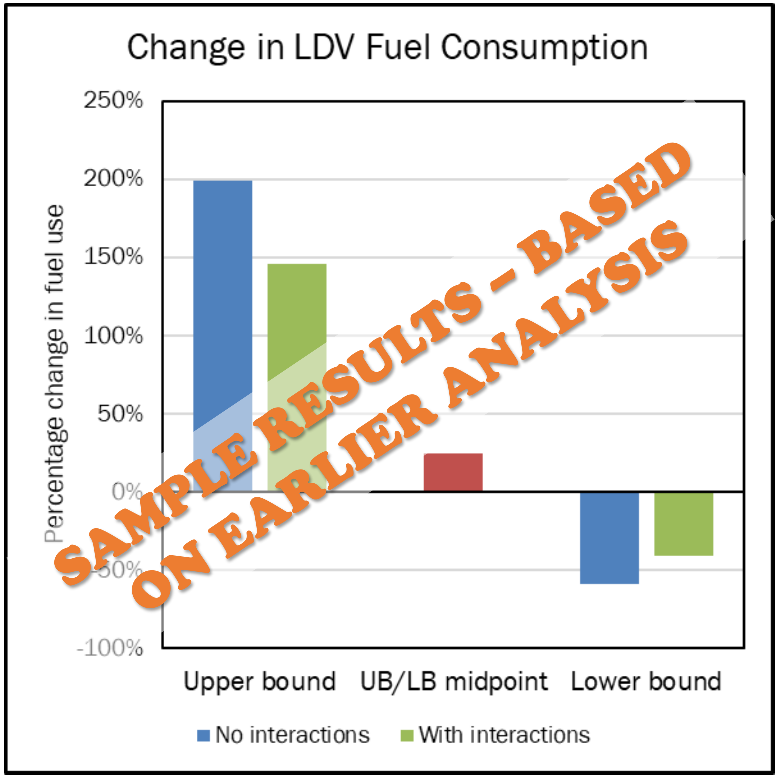
		Effect **of** factor *j*																							
	Effect **on** factor *i*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Shifting travel patterns - sprawl	x	0	0	0	0	0	0	0	0	0	0	0	-0.6	0.5	0.3	0	0	0	0	0	0	0	0	0.3
2	Shifting travel patterns - urbanization	0	x	0	0	0	0	0.2	0	0	0.1	0	0	-0.2	0	0	0	0	0	0	0	0	0	0	0
3	Additional travel - underserved	0	0	x	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0
4	Additional travel - leisure travel	0.2	0	0.2	x	0	0	0	0	0	0.2	0	0.2	-0.5	0.1	0	0	0	0	0	0	[illegible]	0	0	0.1
5	Mode shift to roads	0	0	0	0	x	0	0	0	0	0.2	0	0	-0.2	0.2	0	0	0	[illegible]	0	0	0	0	0	0
6	Re-routing (Eco-routing)	0.1	0	0	0	0	x	-0.2	-0.2	0	0	0	0	0	0	0	[illegible]	0.5	[illegible]	[illegible]	0	0	0	0	0
7	Ridesharing	-0.2	0.2	0	0	0.2	0	x	0.1	0	0	0	0	0	[illegible]	[illegible]	0	[illegible]	0.1	0	0	0	-1	0	0.1
8	Empty VMT (deadhead)	0	0	0	0	0	0.1	0	x	0	0.2	0	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	0	0	0	0
9	Additional fueling trips	0.1	0	0	0	0	0	0	0.3	x	[illegible]	0	0	[illegible]	0.1	0	0	[illegible]	0.2	0.3	0	0	-0.2	[illegible]	[illegible]
10	Efficient parking (reduced hunting)	0	-0.1	0	0	0	0	0	[illegible]	0	x	[illegible]	0	0.3	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	[illegible]	[illegible]	[illegible]
11	Reduction in shopping trips (due to deliveries)	0.3	0	0	0	0	[illegible]	[illegible]	0	[illegible]	-0.2	x	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
12	Commercially sponsored trips	0	0	0.2	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0.2	[illegible]	x	0	[illegible]	0	0	0	[illegible]	[illegible]	0	0	0	0	0.2
13	Changes in congestion	0.8	0.2	[illegible]	[illegible]	[illegible]	0	-0.5	0.3	[illegible]	[illegible]	-0.2	[illegible]	x	0	-0.5	[illegible]	[illegible]	0	[illegible]	0	0	0	0	0
14	Faster travel	[illegible]	[illegible]	[illegible]	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	0	0	-0.2	x	[illegible]	[illegible]	[illegible]	0	0	-0.2	0	0.1	0.1	0
15	Drive smoothing	[illegible]	[illegible]	0	0	0	0.2	[illegible]	[illegible]	[illegible]	0	0	[illegible]	[illegible]	0	[illegible]	0	0.4	0	0	0	0.1	0	0	0
16	Platooning	0.2	0	0	0	0	0.1	0	0	0	[illegible]	[illegible]	0	[illegible]	[illegible]	0.1	x	0.1	0.2	0	0	0	-0.3	0	0
17	V2I / V2V	0	0	0	0	0	0.2	0	[illegible]	[illegible]	0.5	[illegible]	[illegible]	0	0	0	0	x	0	0	0	0	0	0	0
18	Off-board computation & data centers	0.1	0	0.4	0.1	0	[illegible]	0	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0.2	0.3	x	0.3	0	0	0	0	0
19	Electronics power draw	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	-0.1	0	0	0.2	x	0	0	0	0	0.3
20	Aerodynamic drag (lidar/radar)	0	0	0	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	0.1	0.3	-0.2	0	0	0	0	x	0	0	0	0
21	Engine downsizing (performance de-emphasis)	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	0.1	0	0.1	0	0.1	0	x	0.1	0	0
22	Vehicle rightsizing	-0.1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0
23	Vehicle lightweighting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0
24	Vehicle upsizing (mobile lounges)	0.3	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0.1	0.1	x

SAMPLE DATA – NOT FOR CALCULATIONS

PRELIMINARY INTERACTIONS BETWEEN FACTORS

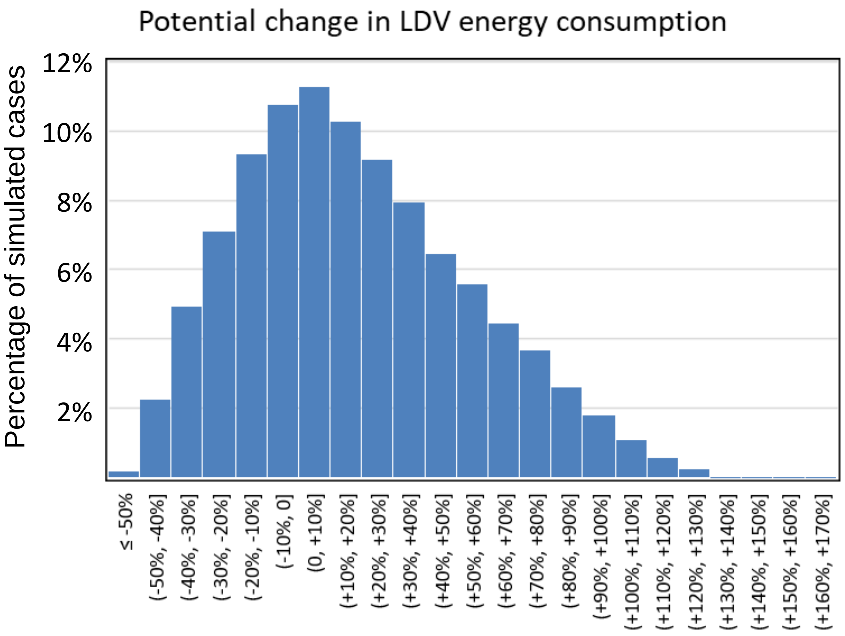
- Looking at extreme bounds from previous report, interactions largely work to temper most extreme cases, bringing VMT and fuel consumption closer to the midpoints

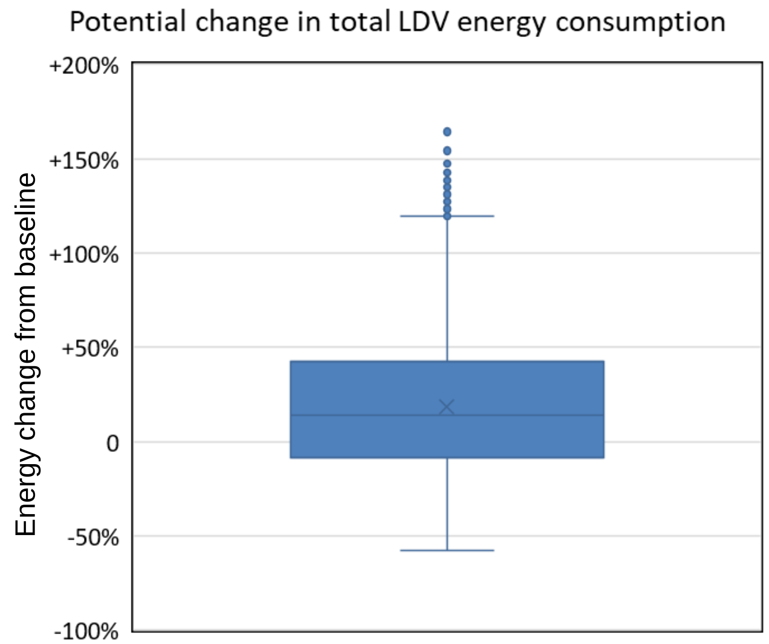




UNCERTAINTY ANALYSIS

- Bounding study gives extreme values, but future likely to end up between bounds
- Monte-Carlo simulation selecting each factor from a uniform distribution within previously defined bounds finds 98% of scenarios were found to change total fuel consumption by less than a factor of 2x, as compared with a factor of 3x using the bounds





RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- This project was not reviewed in 2018

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- This project is being done jointly by researchers from Argonne National Laboratory, the National Renewable Energy Laboratory, and Oak Ridge National Laboratory
  – Dave Gohlke, Tom Stephens; ANL
  – Alicia Birky, Jeff Gonder, Jake Holden, Bingrong Sun; NREL
  – Paul Leiby, Zhenhong Lin; ORNL
- Inputs for analysis are informed by DOE'S SMART Mobility laboratory consortium, with research from aforementioned institutions as well as Idaho National Laboratory and Lawrence Berkeley National Laboratory
- Analysis will be compared with ongoing complementary approaches for energy consumption being developed within SMART Mobility

REMAINING CHALLENGES AND BARRIERS

- Gaps in robust numbers for each factor / Need to quantify specific numbers to harmonize values from different studies
- Adjustment of literature values for one specific scenario into other factors
- Refine interactions between factors based on studies which examine relative elasticities of these parameters

PROPOSED FUTURE RESEARCH

- FY2019 research:
  - Improvement of values and distributions of each factor impacting CAVs energy consumption
  - Development and examination of additional scenarios with more narrative value, rather than just extreme bounding cases
  - Quantification of statistical distributions of values for each factor

- FY2019 research will be accomplished through further literature review and engagement with SMART Mobility PIs and other experts on specific topics

- Potential research for FY2020 and beyond:
  - What happens with non-passenger travel (e.g., freight)?
  - When will this happen (e.g., how to account for fleet turnover)?
  - What are the energy implications of CAVs during the fleet transition?

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

SUMMARY SLIDE

- **Relevance**
  - Important to understand energy implications of CAVs
- **Approach**
  - Review relevant literature
  - Synthetize and harmonize factors from disparate sources
  - Identify upper and lower nationwide bounds of VMT and fuel consumption for light-duty CAVs.
  - Estimate statistical distribution of probable energy outcomes from ubiquitous CAVs technology.
  - Develop narratives and scenarios
- **Technical Accomplishments**
  - Identification of factors and initial values from literature and engineering judgment
  - Methodology development
    - Quantification assuming independent factors
    - Incorporation of interactions between factors
  - Monte-Carlo analysis of uncertainty
- **Future Work**
  - Refinement of values of each factor
  - Scenario development
  - Statistical distributions

TECHNICAL BACK-UP SLIDES

MATHEMATICAL QUANTIFICATION OF CHANGES IN VEHICLE MILES TRAVELED AND FUEL CONSUMPTION

- For each scenario, explore the energy consumption under four road types, labeled *k*: uncongested city; congested city; uncongested highway; congested highway
  - These road types were selected based on the availability of studies relevant for each factor
- For each road type, assign a value for the multiplicative change in total fuel consumption (based on changing demand or efficiency) due to each factor, labeled *i*. The set of all factors is denoted by $f_{i,k}$ and individual values come from literature and engineering judgment
- In the absence of explicit interactions between the factors, the total fractional change to VMT (on road type *k*) is given by $\prod_{i \in \{\text{demand}\}} f_{i,k}$ where *i* is in the set of factors directly related to VMT, the percent change in the average fuel economy (on road type *k*) is $\prod_{i \in \{\text{efficiency}\}} f_{i,k}$ where *i* is in the set of factors directly related to MPG, and the total fractional change to fuel consumption is the product of all factors: $\prod_i f_{i,k}$
- To introduce interactions between factors, new terms are introduced. The value of each element $\overleftrightarrow{M}_{i,j}$ represents the change in factor f_j caused by factor f_i. For example, if $\overleftrightarrow{M}_{i,j} = +1$ and f_i were at its maximal value, then f_j would be transformed the equivalent amount as from its lower bound to its upper bound, while if $\overleftrightarrow{M}_{i,j} = 0$, then the magnitude of factor f_i does not affect factor f_j. (This can lead to factors being outside their originally defined bounds.) Each factor is adjusted by $g_j = \overleftrightarrow{M}_{i,j} \times f_i$ and the complete equation is $\vec{g} = \overleftrightarrow{M}\vec{f}$
- As above, for the adjusted factors $g_{i,k}$ the total change in fuel consumption is the product $\prod_i g_{i,k}$