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

NATIONWIDE ENERGY AND MOBILITY IMPACTS OF CAV TECHNOLOGIES

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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

OVERVIEW

- **Timeline**
  - Project start: 1 Sep 2018
  - Project end: 31 Dec 2019
  - Percent completed: 100%
- **Budget**
  - FY18/19: $260k
  - FY20: $20k (100% DOE)
- **Partners**
  - Argonne National Laboratory
    - Project lead: D. Gohlke, Argonne
  - Oak Ridge National Laboratory
  - National Renewable Energy Laboratory

- **Barriers**

  From U.S. DRIVE Roadmap for the Vehicle-Mobility Systems Analysis Tech Team (VMSATT):
  - *Future scenario visioning:* Uncertainty about the future of mobility complicates forward-looking technology evaluation and R&D prioritization.
  - *Capabilities gap analysis:* Gaps exist in estimating the impact of many new technologies and identifying priority modeling needs.

RELEVANCE

Project objective and achievements

- This project refines the justification used by VTO to highlight the importance of research on connected and automated vehicles (CAVs).
- This analysis also explores which factors have the most uncertainty in estimating CAVs efficiency and demand, identifying potential levers for future R&D to reduce nationwide fuel consumption to improve energy security.

"The Energy Efficient Mobility Systems (EEMS) subprogram supports early-stage research to support industry innovation that improves the affordability and energy productivity of the overall transportation system. Initial DOE analysis indicates that the future energy impact of connected and automated vehicles is highly uncertain and may be quite large, ranging from a potential 60% reduction in overall transportation energy use to a 200% increase in energy consumption." (page 3-1)

MILESTONES

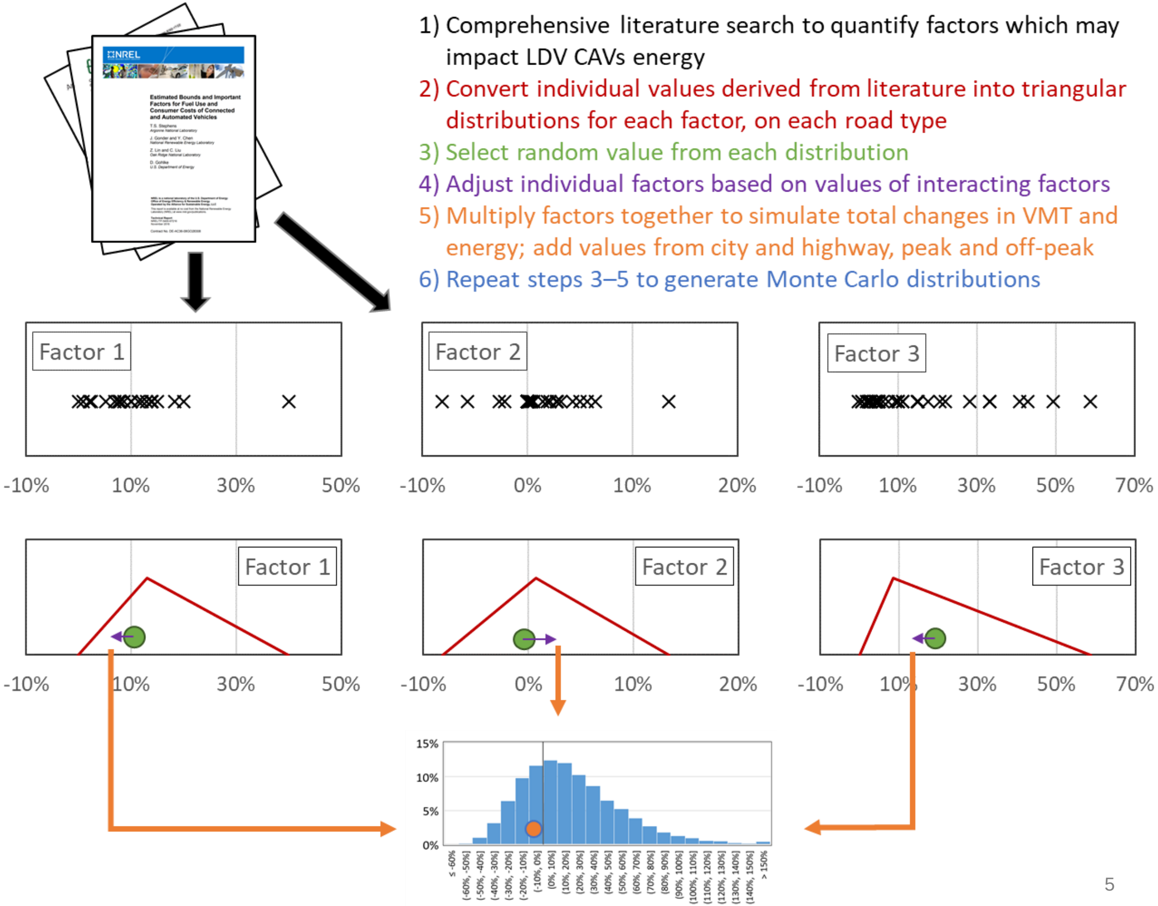
- Project carried forward from FY2019 – no new milestones for FY2020

Date	Description	Status
12/2018	Summarized literature review of updated bounds and outputs from FY16-18 SMART projects and external research	Complete
3/2019	Improve methodology to quantify synergies and interactions between different variables	Complete
6/2019	Presentation to DOE on preliminary results for CAVs impacts	Complete
9/2019	Finalization of report documenting improved estimates of bounds for metrics related to energy consumption and mobility	Analysis complete / draft report

APPROACH

- Calculate distributions of impacts due to CAVs technologies on vehicle miles traveled (VMT), fuel economy (MPG), and total energy consumption for light-duty vehicles (LDV)
  - Monte Carlo simulations
- Repeat analysis under different scenarios of how CAVs may be used

1) Comprehensive literature search to quantify factors which may impact LDV CAVs energy
2) Convert individual values derived from literature into triangular distributions for each factor, on each road type
3) Select random value from each distribution
4) Adjust individual factors based on values of interacting factors
5) Multiply factors together to simulate total changes in VMT and energy; add values from city and highway, peak and off-peak
6) Repeat steps 3–5 to generate Monte Carlo distributions



APPROACH

Factor identification and literature review

- Identified 24 factors which may cause changes in passenger vehicle travel demand or vehicle fuel efficiency which could be attributed to CAVs.
- Reviewed over 500 reports, peer-reviewed articles, technical presentations and white papers, including over 60 publications sponsored by VTO and 20 sponsored by ARPA-E.
  - Many of these reports are not directly related to CAVs, but explore scenarios which are enabled by CAV technologies.
- Generated triangular probability distributions for each factor based on literature, accounting for:
  - Road type (city vs. highway) and congestion level (peak vs. off-peak)
  - Analysis scenario

APPROACH

Factors related to changes in travel demand

Changes in personal mobility

- SHIFTING TRAVEL PATTERNS: SPRAWL
- SHIFTING TRAVEL PATTERNS: URBANIZATION
- ADDITIONAL TRAVEL: UNDERSERVED
- ADDITIONAL TRAVEL: LEISURE TRAVEL

Changes in on-road travel

- MODE SHIFT TO/FROM ROADS
- ECO-ROUTING
- RIDEPOOLING
- EMPTY VMT (DEADHEADING)
- FUELING TRIPS

Changes in commercially-linked household travel

- EFFICIENT PARKING
- HOME DELIVERY
- SPONSORED TRAVEL

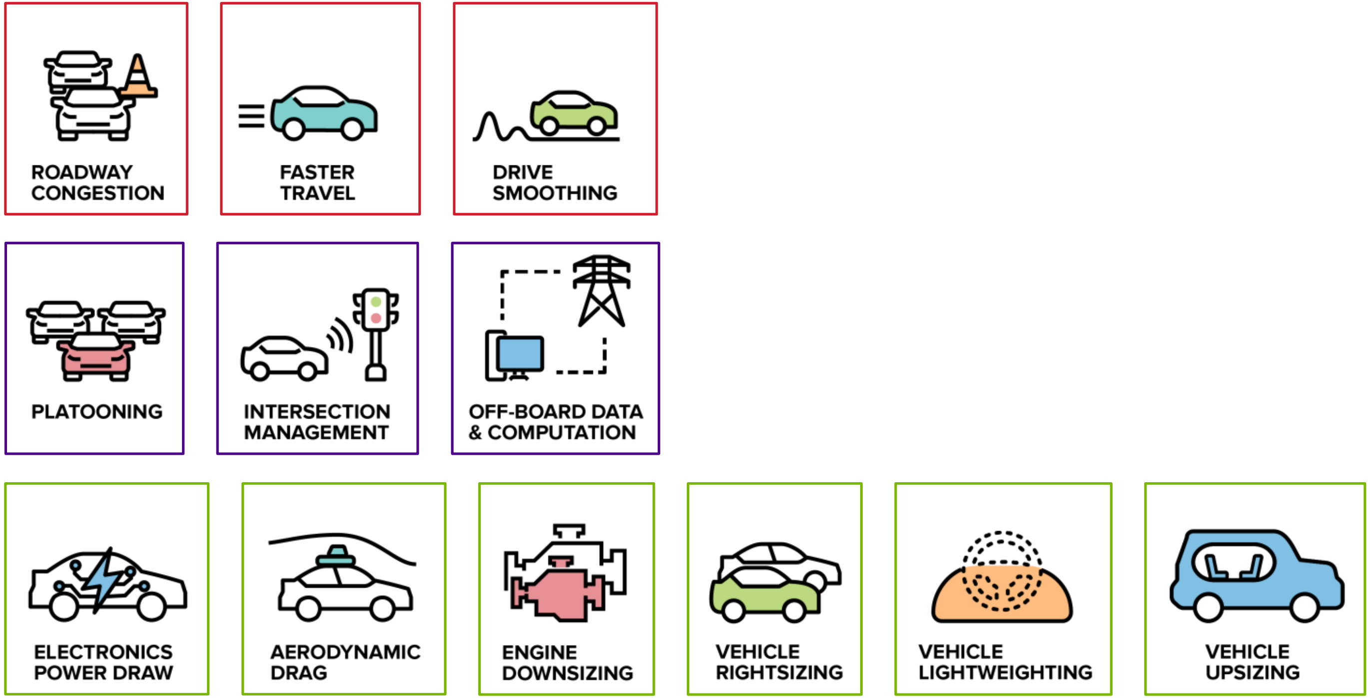
APPROACH

Factors related to changes in energy efficiency

Changes in operational fuel consumption

Changes in energy consumption due to connectivity

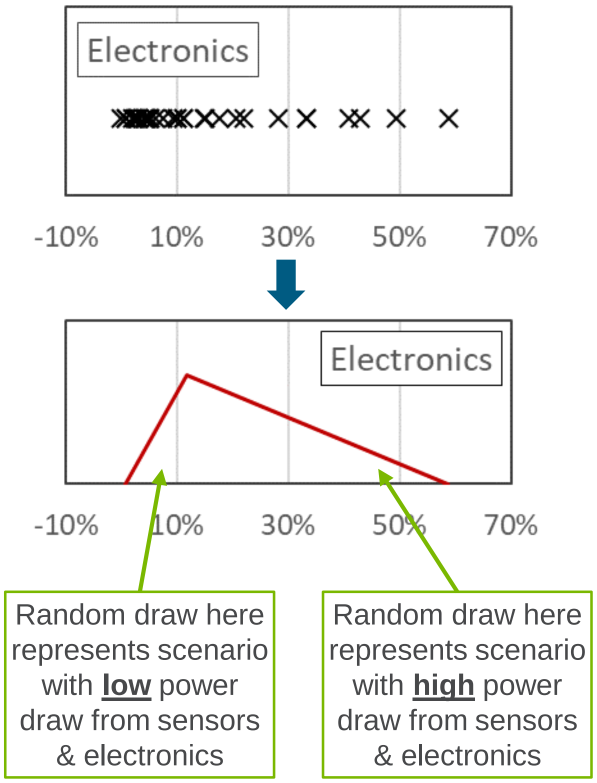
Changes in vehicle design



APPROACH

Monte Carlo simulation

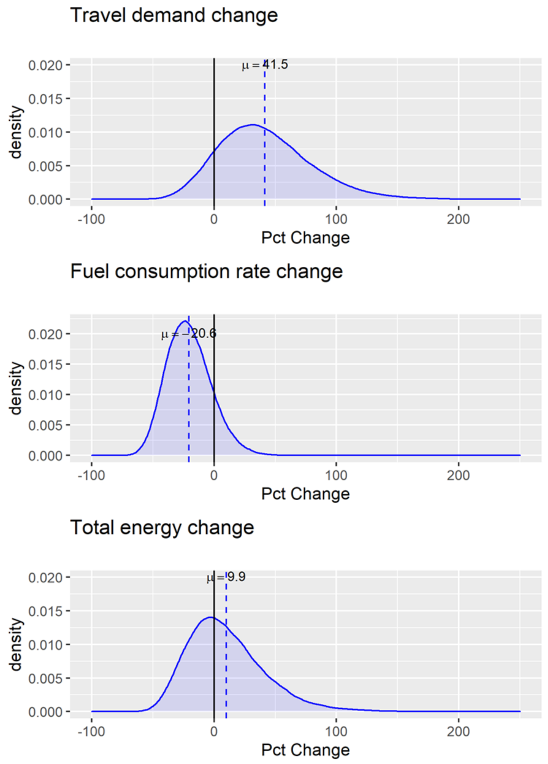
- Selected value at random from each distribution, representing a future scenario with that magnitude of change in demand or efficiency.
- Adjust values to account for interactions between factors
- Multiply adjusted factors together to find nationwide changes in vehicle travel or fuel efficiency
  - Treat each road type separately, and aggregate VMT and fuel consumption values for city & highway road types, and peak & off-peak travel.



ACCOMPLISHMENTS

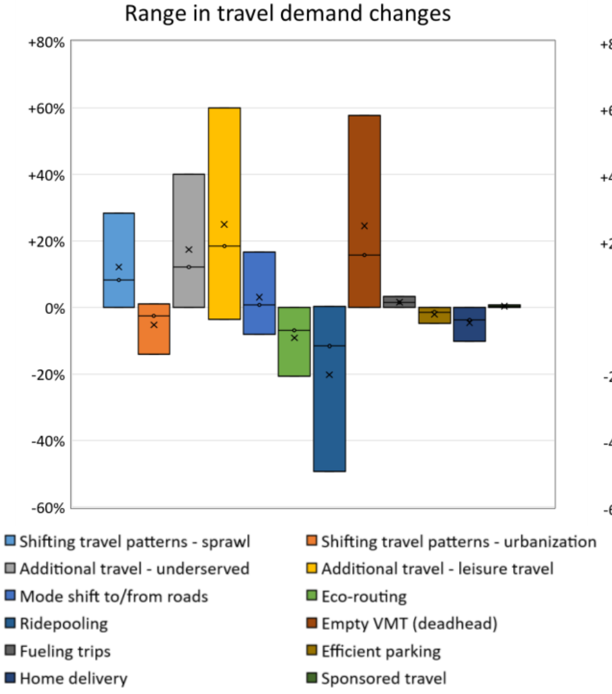
CAVs energy changes

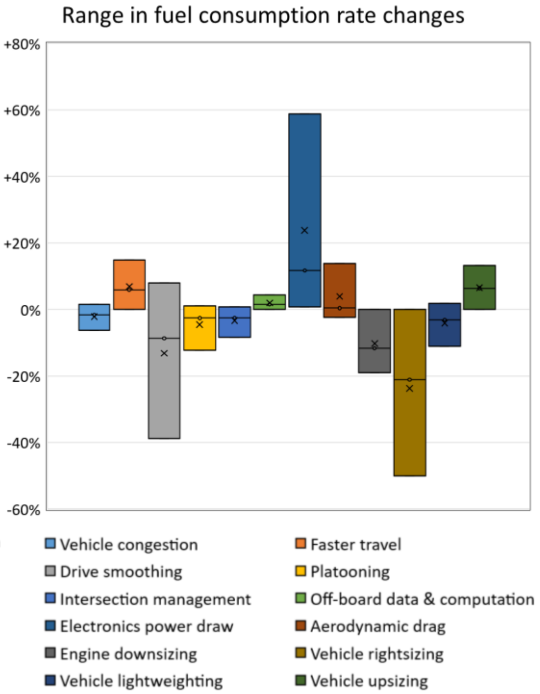
- **On average, total LDV energy use increases by approximately 10%, but with a wide distribution of possible cases.**
  - **Most common scenario has slight *decrease* in energy**
- **60% of cases lead to an increase in energy consumption and 90% of cases are between -40% and +70% energy change.**
- **Ninety percent of scenarios show an increase in VMT, with a mean increase of 40%, while the mean improvement in fuel economy is a reduction of 20% in fuel consumption.**



ACCOMPLISHMENTS

Most important and most uncertain factors



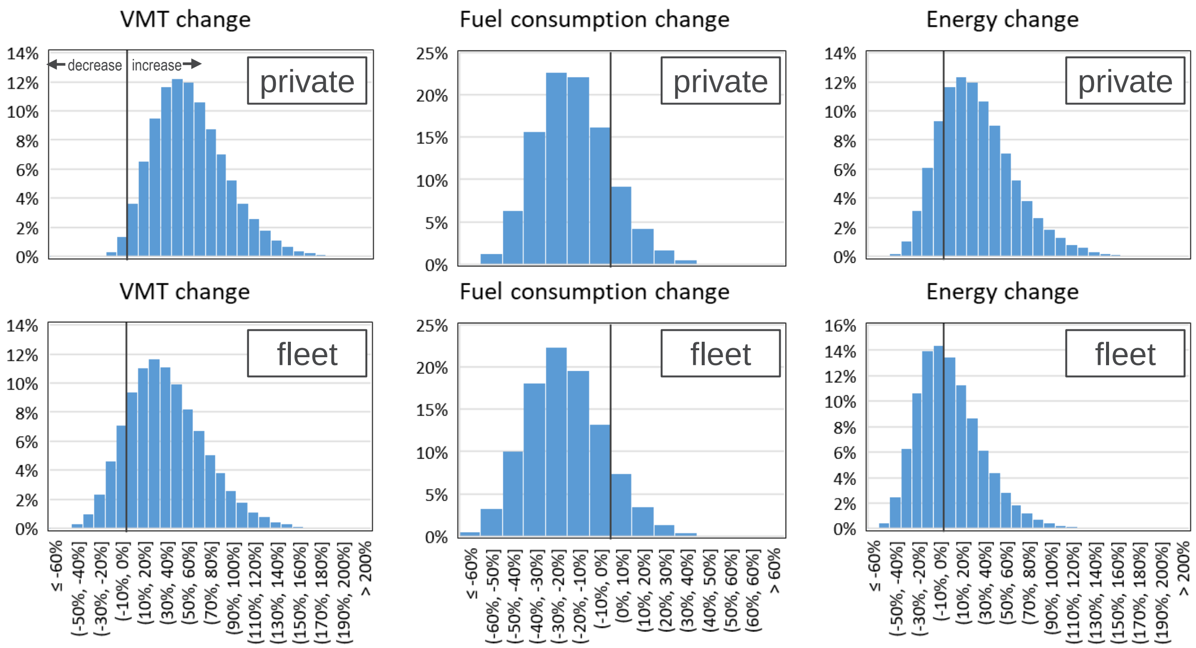


- The top factors leading to an increase in energy usage are induced travel from easier and cheaper travel, repositioning of empty vehicles, and on-vehicle electronics power draw, while the largest potential levers for reducing fuel consumption are vehicle rightsizing, ridepooling, and drive smoothing.

ACCOMPLISHMENTS

Fleet ownership vs. Private ownership

- Total LDV energy increases by 5% in the fleet-owned scenario and by 30% in the privately-owned scenario.
- Average VMT increases by 40% in the fleet-owned scenario and by nearly 60% in privately-owned



RESPONSES TO REVIEWERS

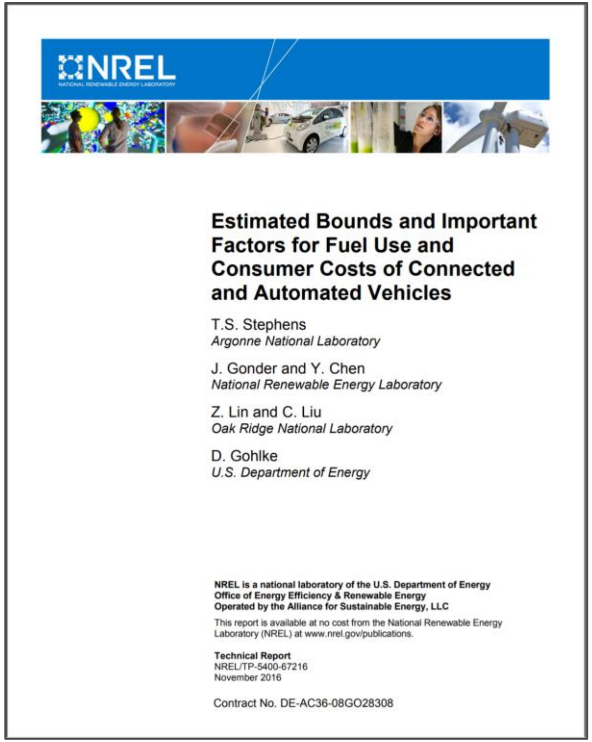
- "The reviewer commented the project's poster at AMR showed results that incorporated several new independent variables, independent variable ranges, considerations for linkages between independent variables, and Monte-Carlo simulation/analysis. Taken together, these additions significantly increase the completeness and sophistication of study conclusions when compared to the original analysis."
  - We are happy to hear the positive feedback from this reviewer. Given the expanded scope of analysis on this project, we are careful to refer to the newer study as a synthesis study, rather than a "bounding analysis".
- "The reviewer likes the proposed inclusion of scenario exercises."
  - Based on written and oral feedback, we have included 10 scenarios beyond our baseline scenario, as well as comparisons with 8 different implicit vehicle mixes.
- "There is not enough evidence of who is doing what on this project for this reviewer to evaluate how well the team is collaborating. The slides indicate that three laboratories are collaborating on the project."
  - We appreciate the reviewer concern for team collaboration. Researchers from all labs have contributed to all portions of the project. ANL is taking the lead on all aspects of the project, but NREL and ORNL have contributed substantially to literature review, methodology and analysis, and writing.
- "This work may benefit from a validation exercise that involves gaming by transportation subject matter experts [SME]. This gaming exercise would allow for relationships and assumptions to be discussed in a group environment. "
  - The reviewer proposed an interesting idea, which we were unable to explore fully. Discussions with SMEs at conferences yielded useful feedback on which factors have the most uncertainty, but no consensus on specific values for given factors.

COLLABORATION

- **Three-lab joint effort:**
  - ANL: Lead analysis, literature review, lead writing
  - NREL: Literature review, analysis methodology
  - ORNL: Analysis methodology, literature review
- Beyond formal project, references pulled from ongoing EERE-funded research, soliciting details from other PIs across the SMART Mobility laboratory consortium as necessary

REMAINING CHALLENGES & FUTURE RESEARCH

- Analysis has been finished for this project. Future steps for this project include:
  - Finalizing the technical report for publication
  - Presentation of results to interested parties
- The previous bounding report has been frequently cited, both by DOE/EERE and other governmental organizations, and in the academic literature, so we aim for a comparable public impact.


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

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Office of Energy Efficiency & Renewable Energy
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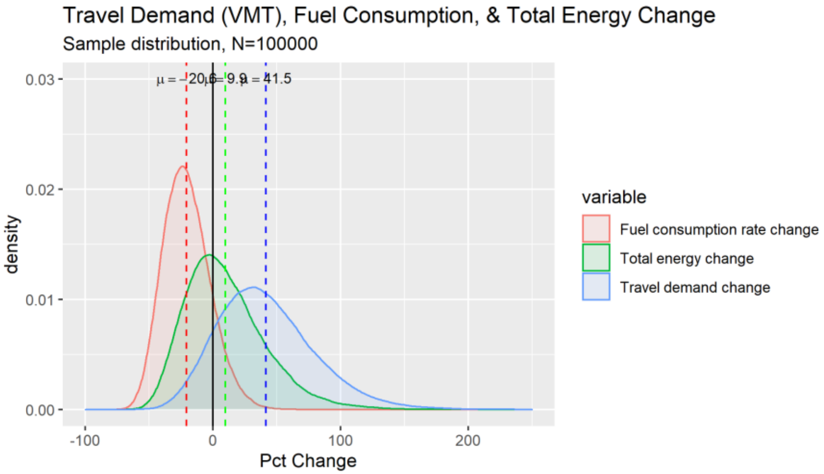
Technical Report
NREL/TP-5400-67216
November 2016

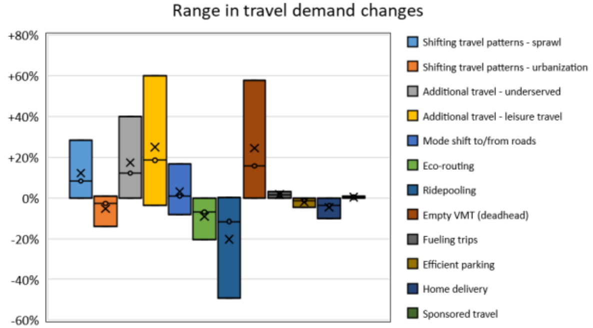
Contract No. DE-AC36-08GO28308

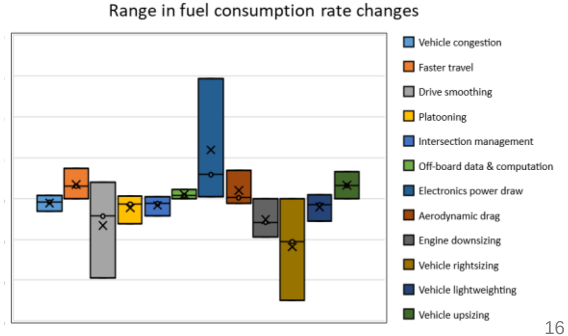
Stephens et al., 2016.
https://www.osti.gov/biblio/1334242

SUMMARY

- **Changes in energy consumption due to CAVs technologies has a wide potential range, but most scenarios show moderate changes.**
- **Factors with widest ranges are ripe for further analysis and future R&D.**







TECHNICAL BACKUP SLIDES

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TECHNICAL BACKUP SLIDE

Factors of interest (presented AMR 2019)

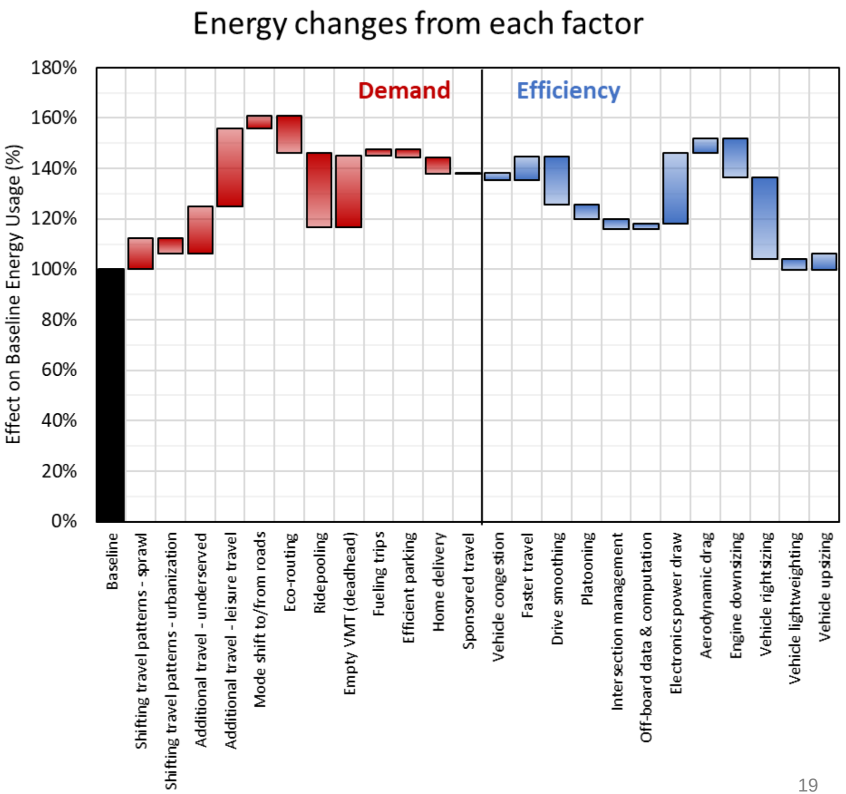
Category	#	Travel Demand	
Personal mobility	1	Shifting travel patterns - sprawl	
	2	Shifting travel patterns - urbanization	New
	3	Additional travel - underserved	
	4	Additional travel - leisure travel	New
On-road travel	5	Mode shift to/from roads	
	6	Eco-routing	New
	7	Ridepooling	
	8	Empty VMT (deadhead)	
	9	Fueling trips	New
Commerce	10	Efficient parking	
	11	Home delivery	New
	12	Sponsored travel	New

#	Energy Efficiency		Category
13	Vehicle congestion		Vehicle operation
14	Faster travel		
15	Drive smoothing		
16	Platooning		Connectivity
17	Intersection management		
18	Off-board computation & data centers	New	
19	Electronics power draw	New	Vehicle design
20	Aerodynamic drag	New	
21	Engine downsizing	New	
22	Vehicle rightsizing		
23	Vehicle lightweighting	New	
24	Vehicle upsizing	New	

TECHNICAL BACKUP SLIDE

Waterfall chart

- **A waterfall chart shows an alternative way to see which factors have the largest expected impact of energy consumption:**
  - **Leisure travel**
  - **Ridepooling**
  - **Empty VMT**
  - **Drive smoothing**
  - **Electronics power draw**
  - **Vehicle rightsizing**



TECHNICAL BACKUP SLIDE

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
- Note that graphic is sparse: many factors are assumed to be independent of each other, or there exists no data to calculate their correlation

		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	-0.5	0.14	-0.1	0	0	0	0	0	0	0	0	0.06
2	Shifting travel patterns - urbanization	0	x	0	0	0	0	0	0	0	0	0	0	-0.5	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	0	0	0	0	0	0	0	0	0	0	0
4	Additional travel - leisure travel	0	0	0	x	0	0	0	0	0	-0	0	0	-0.5	0.14	-0.1	0	0	0	0	0	0	0	0	0.06
5	Mode shift to roads	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Re-routing (Eco-routing)	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Ridepooling	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0
8	Empty VMT (deadhead)	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Additional fueling trips	0	0	0	0	0	0	0	0	x	0	0	0	0	0.07	0.34	0.07	0.05	0	0.26	0.08	0.11	0.42	0.07	0.06
10	Efficient parking (reduced hunting)	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Reduction in shopping trips (due to deliveries)	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Commercially sponsored trips	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0	0	0	0	0
13	Changes in congestion	0.13	0.09	0.18	0.29	0.13	0.12	0.44	0.26	0.02	0.02	0.05	0	x	0	0.17	0.03	0	0	0	0	0	0	0	0
14	Faster travel	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0.01	0	0	0	0
15	Drive smoothing	-0.1	-0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	-0	-0	-0	-0	0	0	x	0	0	0	0	0	0	0	0	0
16	Platooning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0	0
17	V2I / V2V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0	0	0
18	Off-board computation & data centers	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	x	0	0	0	0	0	0.25
19	Electronics power draw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	0	0.01
20	Aerodynamic drag (lidar/radar)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	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	0	0	0	0	0	0	x	0	0	0
22	Vehicle rightsizing	0	0	0	0	0	0	-0.5	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x

TECHNICAL BACKUP SLIDE

Scenario comparison

	Δ VMT			Δ GPM			Δ Energy		
	5th	Avg.	95th	5th	Avg.	95th	5th	Avg.	95th
Baseline	-13%	**42%**	110%	-48%	**-21%**	10%	-34%	**9%**	66%
Exclude outliers	3%	**42%**	90%	-52%	**-28%**	-2%	-35%	**0%**	46%
Exclude SMART	-15%	**39%**	105%	-52%	**-27%**	1%	-39%	**-1%**	49%
Fleet only	-17%	**36%**	101%	-48%	**-21%**	11%	-36%	**5%**	60%
Private only	9%	**57%**	118%	-43%	**-17%**	13%	-19%	**29%**	92%
Electrification	-17%	**38%**	107%	-42%	**-8%**	33%	-27%	**24%**	93%
No electrification	-19%	**35%**	103%	-49%	**-22%**	9%	-39%	**3%**	59%
L2 automation	-19%	**-9%**	1%	-45%	**-28%**	-11%	-49%	**-34%**	-19%
No connectivity	-17%	**35%**	98%	-31%	**-6%**	23%	-22%	**25%**	88%
Sharing is Caring	-22%	**-6%**	11%	-44%	**-25%**	-5%	-48%	**-30%**	-10%
Tech Takeover	-16%	**40%**	108%	-46%	**-18%**	14%	-33%	**12%**	70%
All About Me	23%	**72%**	134%	-41%	**-17%**	10%	-9%	**42%**	107%

Note: All percentages are relative to non-CAVs status quo, with the same vehicle types, i.e., not comparing CAV BEV to ICE

- **Developed different triangular distributions for each factor in each scenario.**
- **Privately-owned and non-connected vehicles have highest average energy increases.**