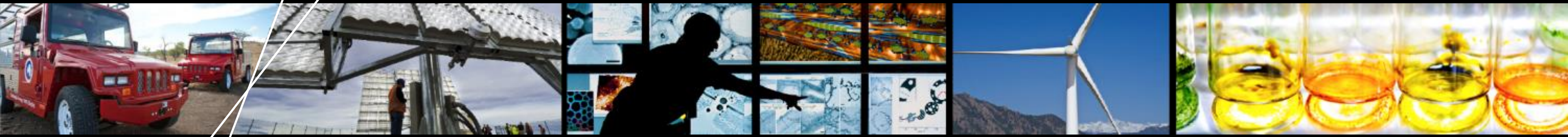
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL Research and Thoughts on Connected and Automated Vehicle Energy Impacts



Jeff Gonder, Austin Brown, Eric Wood, Mike Lammert
Transportation and Hydrogen Systems Center (THSC)
National Renewable Energy Laboratory (NREL)

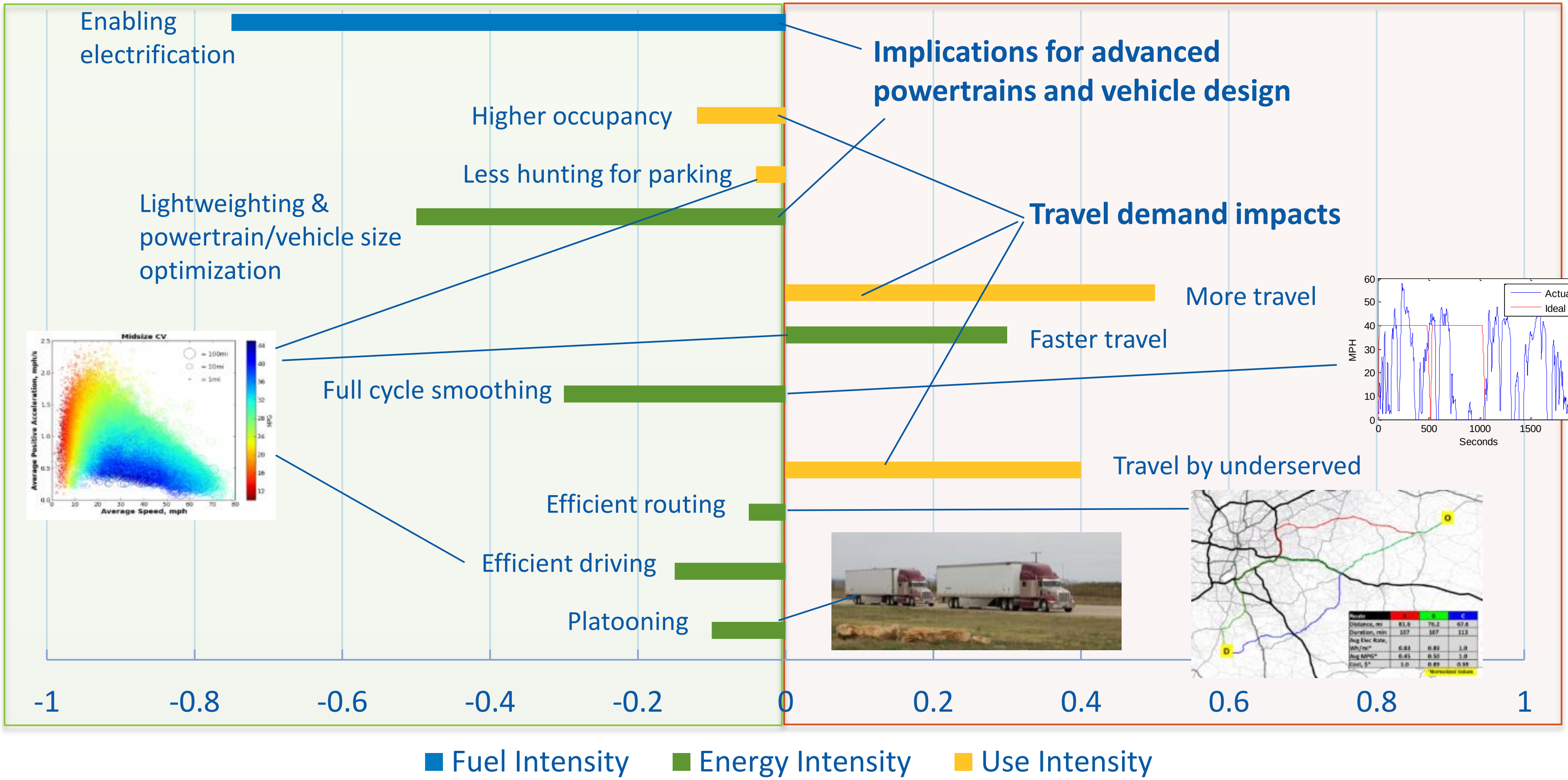
Remarks at EPA Mobile Sources Technical Review Subcommittee (MSTRS) Meeting
December 9, 2014; New Orleans, LA

Connected/Automated Vehicle (CAV) Topics

- **Comprehensive energy impact assessment (positive and negative)**
- Data collection and analysis
- Enabled energy efficiency opportunities
- Synergy with vehicle electrification

"Bookending" CAV Energy Impact Analysis

- **Identified dramatic potential energy impacts** (across automation levels)
  - Informed by related NREL work and literature review
  - Significant uncertainties remain; further research is warranted



Brown, A.; Gonder, J.: Repac, B. (2014). "An Analysis of Possible Energy Impacts of Automated Vehicles." Chapter 5, Societal and Environmental Impacts. Meyer, G., ed. *Lecture Notes in Mobility: Road Vehicle Automation.* Berlin: Springer.

Some Further Research Recommendations/Plans

- **Refine energy impacts analysis**
  - Reduce input uncertainties—including potential behavior changes (inform from surveys and present-day approximations such as car sharing, managed lanes, etc.)
  - Adjust calculation framework to better capture system interactions
- **Fully define multiple specific scenarios**
  - Identify corresponding energy outcome sensitivities/tipping points
- **Further energy-focused data collection, analysis and partnering on early CAV development, demonstration and deployment programs**
  - Feed best available data into refined analysis for informing stakeholders

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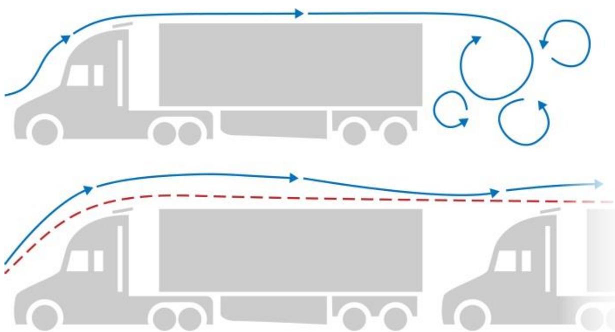
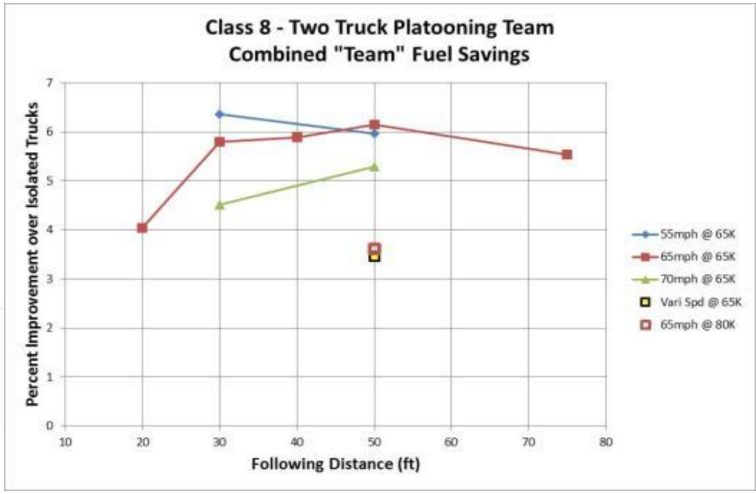
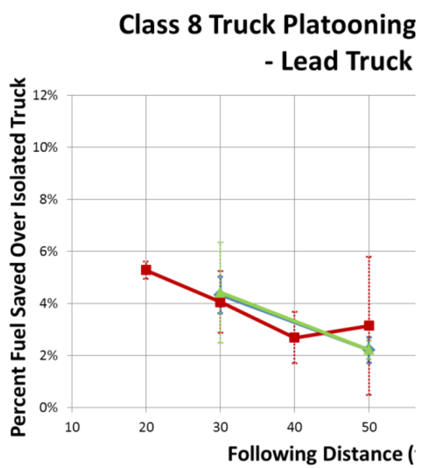
Evaluating Truck Platooning Efficiency Benefits

- **Also potential safety and comfort benefits**
- **Many factors can influence**
  - Vehicle spacing
  - Cruising speed
  - Speed variation
  - Baseline aerodynamics
  - Vehicle loading
  - Engine loading







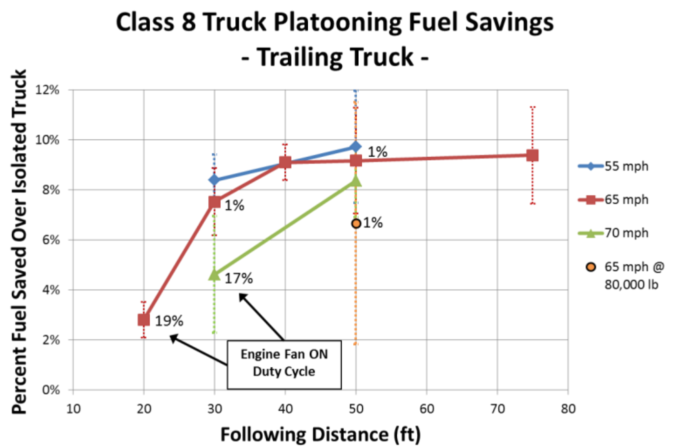



Photo from Mike Lammert, NREL

Results from SAE Type II track testing of Peloton Technology system over a variety of conditions

Lammert and Gonder poster: www.nrel.gov/docs/fy14osti/62494.pdf
Lammert, et al. *SAE Int. J. Commer. Veh.*: www.nrel.gov/docs/fy15osti/62348.pdf

Real-World Data for Transportation Decision-Making

Secure Access Paired with Expert Analysis and Validation

Alternative Fuels Data Center (AFDC)
Public clearinghouse of information on the full range of advanced vehicles and fuels

National Fuel Cell Technology Evaluation Center (NFCTEC)
Industry data and reports on hydrogen fuel cell technology status, progress, and challenges

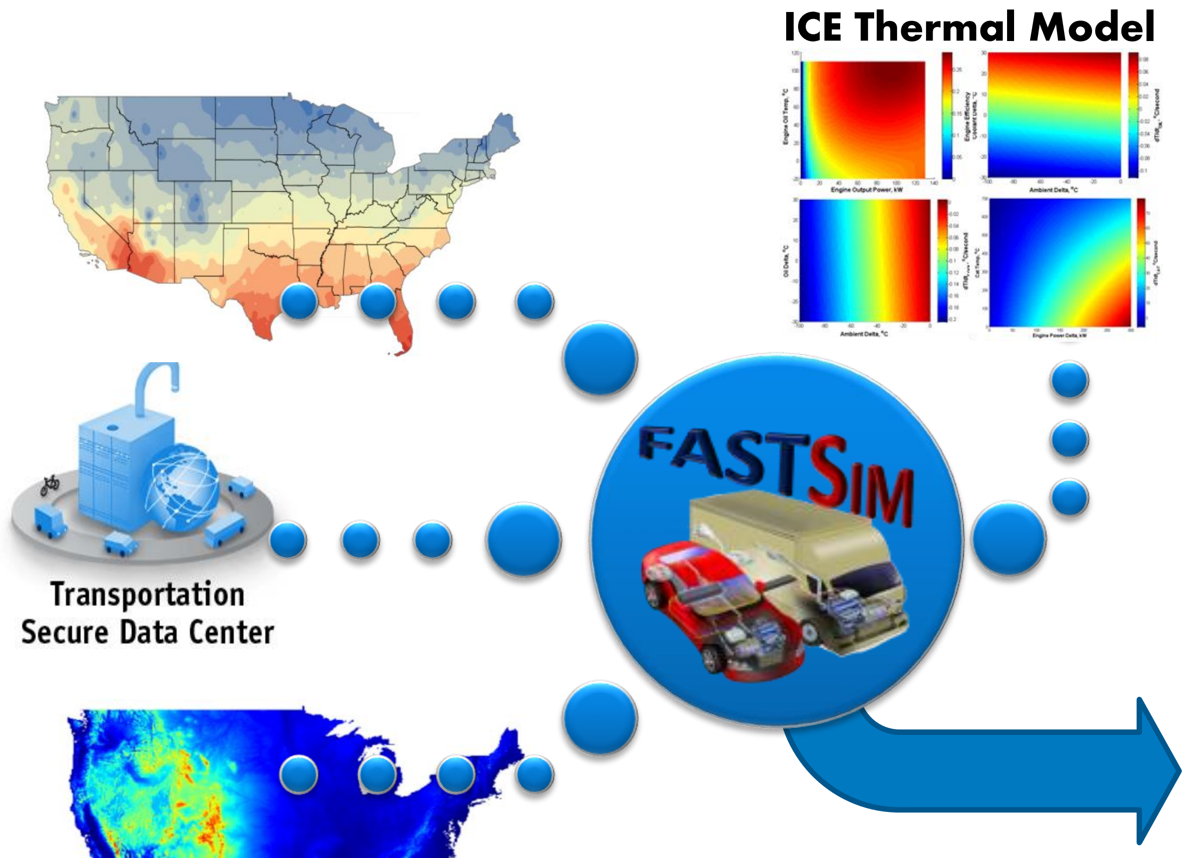
Transportation Secure Data Center (TSDC): *Detailed fleet data, including GPS travel profiles*

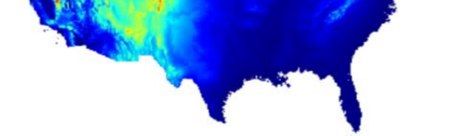
Fleet DNA Data Collection
Medium- and heavy-duty drive-cycle and powertrain data from advanced commercial fleets

FleetDASH: *Business intelligence to manage Federal fleet petroleum/alternative fuel consumption*

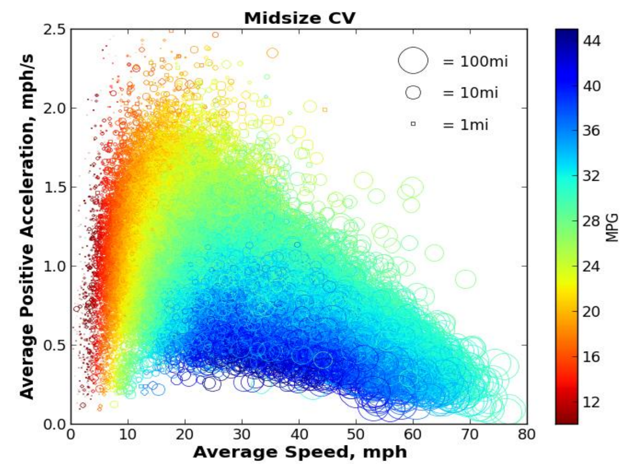
Features	AFDC	NFCTEC	TSDC	Fleet DNA	Fleet DASH
Securely Archived Sensitive Data		Y	Y	Y	Y
Publicly Available Cleansed Composite Data	Y	Y	Y	Y	
Quality Control Processing	Y	Y	Y	Y	Y
Spatial Mapping/GIS Analysis	Y	Y	Y	Y	Y
Custom Reports		Y		Y	Y
Controlled Access via Application Process			Y		
Detailed GPS Drive-Cycle Analysis			Y	Y	

Merging Datasets to Support Real-World Analyses





Vehicle use conditions from disparate datasets can be merged in a common environment to investigate the interplay of conditions (thermal, drive cycle/ routing, grade, etc.)



Data Element	Source	Notes
Drive Cycles/ Trip Distributions	NREL Transportation Secure Data Center	The TSDC houses hundreds of thousands of real-world drive cycles from vehicles across the country.
Climate Data	NREL National Solar Radiation Database	Home to TMYs from hundreds of U.S. locations, each containing hourly climate data.
Elevation/ Road Grade	USGS National Elevation Dataset	Raw USGS elevations are filtered to remove anomalous data and produce smooth road grade curves.

USGS = United States Geological Survey
TDSC = Transportation Secure Data Center
TMY = Typical Meteorological Year
FASTSim – Future Automotive Systems Technology Simulator

Discussion Point: Many CAV technologies may require such a real-world/off-cycle assessment approach

- **E.g., efficient routing, cycle smoothing and adaptive control technologies**
- **Assess energy benefit from potential real-world change, and frequency of occurrence**
- **Could utilize existing pathway for demonstrating off-cycle credit beyond pre-defined table of technologies**

Demonstrations not Based on 5-Cycle Testing

In cases where the benefit of a technological approach to reducing CO_2 emissions cannot be adequately represented using 5-cycle testing, manufacturers will need to develop test procedures and analytical approaches to estimate the effectiveness of the technology for the purpose of generating credits. These provisions were

TABLE II–22—OFF-CYCLE TECHNOLOGIES AND CREDITS AND EQUIVALENT FUEL CONSUMPTION IMPROVEMENT VALUES FOR CARS AND LIGHT TRUCKS

Technology	Adjustments for cars		Adjustments for trucks	
	g/mi	gallons/mi	g/mi	gallons/mi
+High Efficiency Exterior Lights* (at 100 watt savings)	1.0	0.000113	1.0	0.000113
+Waste Heat Recovery (at 100W)	0.7	0.000079	0.7	0.000079
+Solar Panels (based on a 75 watt solar panel)**;				
Battery Charging Only	3.3	0.000372	3.3	0.000372
Active Cabin Ventilation and Battery Charging	2.5	0.000282	2.5	0.000282
+Active Aerodynamic Improvements (for a 3% aerodynamic drag or Cd reduction)	0.6	0.000068	1.0	0.000113
Engine Idle Start-Stop;				
w/ heater circulation system#	2.5	0.000282	4.4	0.000496
w/o heater circulation system	1.5	0.000169	2.9	0.000327
Active Transmission Warm-Up	1.5	0.000169	3.2	0.000361
Active Engine Warm-up	1.5	0.000169	3.2	0.000361
Solar/Thermal Control	Up to 3.0	0.000338	Up to 4.3	0.000484

*High efficiency exterior lighting credit is scalable based on lighting components selected from high efficiency exterior lighting list (see Joint TSD Section 5.2.3, Table 5–21).
**Solar Panel credit is scalable based on solar panel rated power, (see Joint TSD Section 5.2.4). This credit can be combined with active cabin ventilation credits.
#In order to receive the maximum engine idle start stop, the heater circulation system must be calibrated to keep the engine off for 1 minute or more when the external ambient temperature is 30 deg F and when cabin heat is demanded (see Joint TSD Section 5.2.8.1).
+This credit is scalable; however, only a minimum credit of 0.05 g/mi CO_2 can be granted.

NATIONAL ARCHIVES AND RECORDS ADMINISTRATION
LITTERA SCRIPTA MANET
1985

FEDERAL REGISTER

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Pages 62623–63200

Part II

Environmental Protection Agency
40 CFR Parts 85, 86, and 600

Department of Transportation
National Highway Traffic Safety Administration
49 CFR Parts 523, 531, 533, *et al.and 600*
2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule

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- Comprehensive energy impact assessment (positive and negative)
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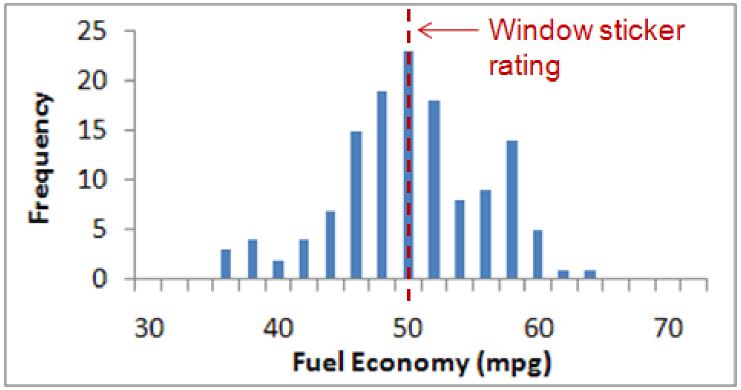
- **Enabled energy efficiency opportunities**
- Synergy with vehicle electrification

Notes from Driver Feedback Fuel Savings Project

Motivation

- "Your mileage will vary"
  - Based on driving conditions & <u>style</u>
- Improve efficiency of <u>existing vehicles</u>

2010 Prius Fuel Economy Histogram for 133 Drivers



Approach

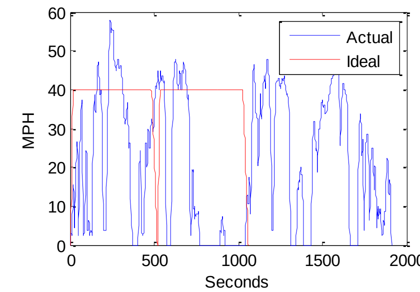
- Quantify savings from cycle changes
  - Vehicle simulations & cycle analysis
  - On-road experiments over repeated routes
- Identify/understand behavior influences
  - Literature review & expert consultation
  - On-road observations
- Assess feedback methods
  - Survey existing examples
  - Evaluate based on project's other findings

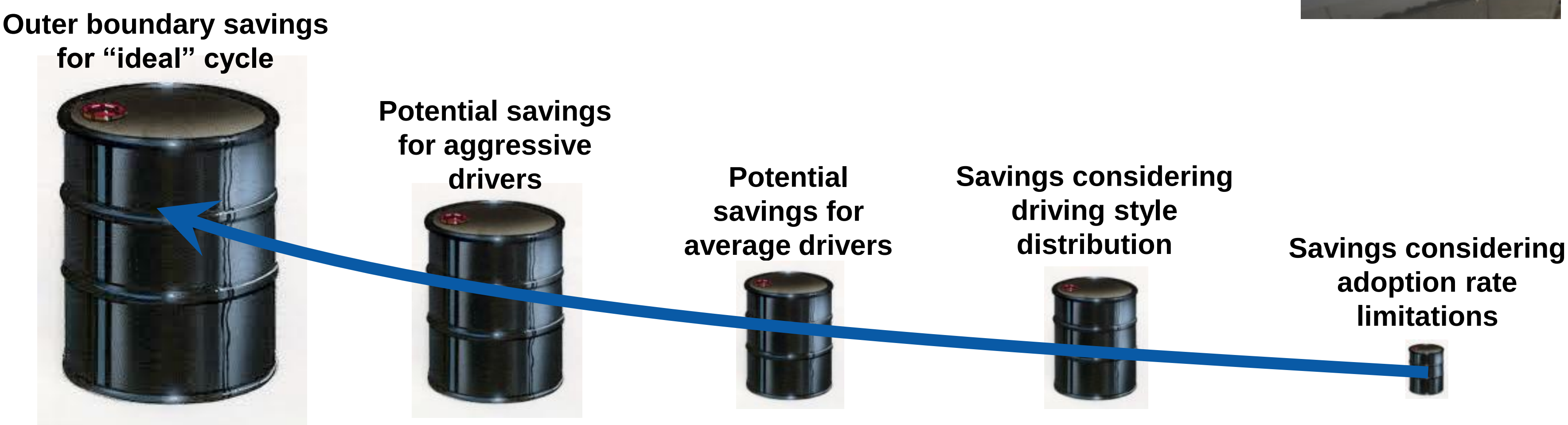
Midsize Conventional Vehicle Assumptions

Engine = 123 kW	CD = 0.30
Curb mass = 1473 kg	Crr = 0.009
FA = 2.27 m^2	

Driver Feedback Analysis Project: Key findings

- **Driving changes can save fuel**
  - 30%-40% outer bound for "ideal" cycles
  - 20% realistic for aggressive drivers
  - 5%–10% for majority of drivers
- **Existing methods may not change many people's habits**
  - Other behavior influences dominate
  - Current approaches unlikely to have broad impact

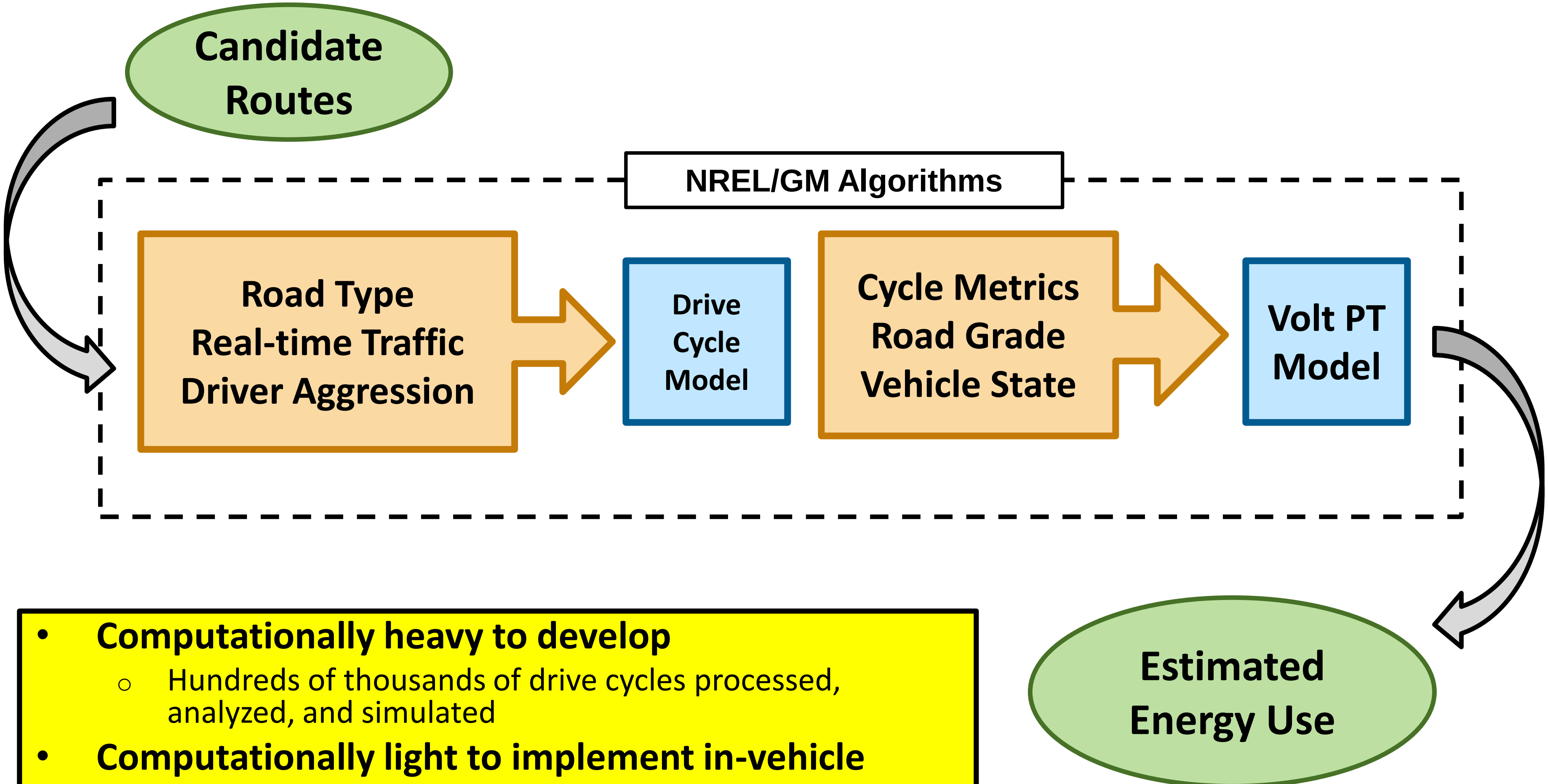




Developed several recommendations to maximize savings…

Gonder, J.; Earleywine, M.; Sparks, W. "Analyzing Vehicle Fuel Saving Opportunities through Intelligent Driver Feedback." *SAE International Journal of Passenger Cars – Electronic and Electrical Systems*, September 2012; 5:450-461.

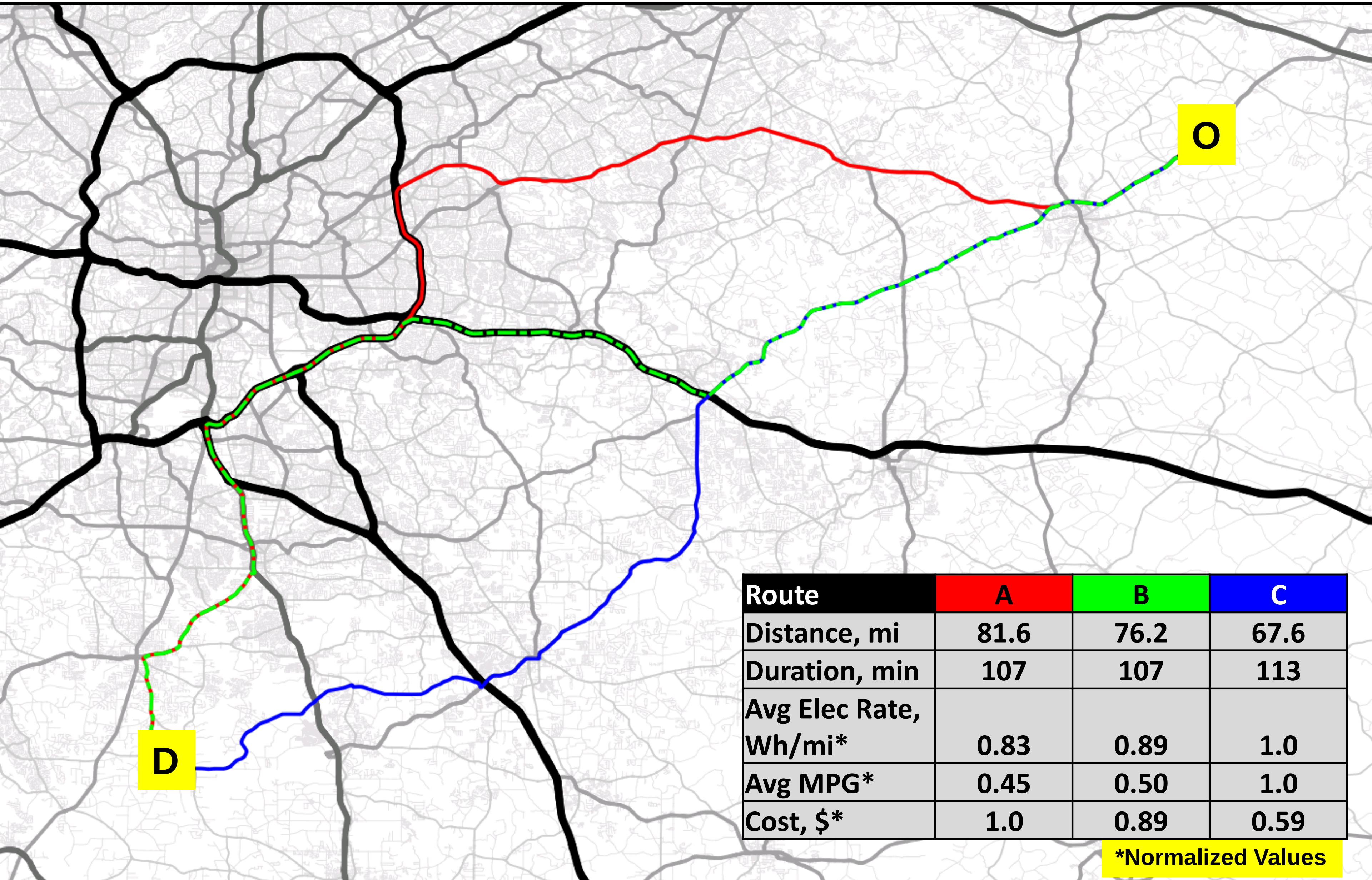
Notes from Collaborative Project on Green Routing and Adaptive Control for the Chevy Volt



- **Computationally heavy to develop**
  - Hundreds of thousands of drive cycles processed, analyzed, and simulated
- **Computationally light to implement in-vehicle**
  - Does not require determination of time/speed trace or real-time simulation of high-fidelity vehicle model

Gonder, J.; Wood, E.; Rajagopalan, S. "Connectivity-Enhanced Route Selection and Adaptive Control for the Chevrolet Volt." *Proceedings of the 21st World Congress on Intelligent Transport Systems*, Sept 2014. www.nrel.gov/docs/fy14osti/60960.pdf

Green Routing Example



Route	A	B	C
Distance, mi	81.6	76.2	67.6
Duration, min	107	107	113
Avg Elec Rate, Wh/mi*	0.83	0.89	1.0
Avg MPG*	0.45	0.50	1.0
Cost, $*	1.0	0.89	0.59

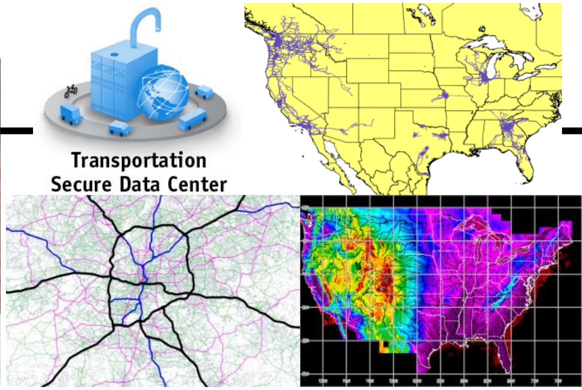
*Normalized Values

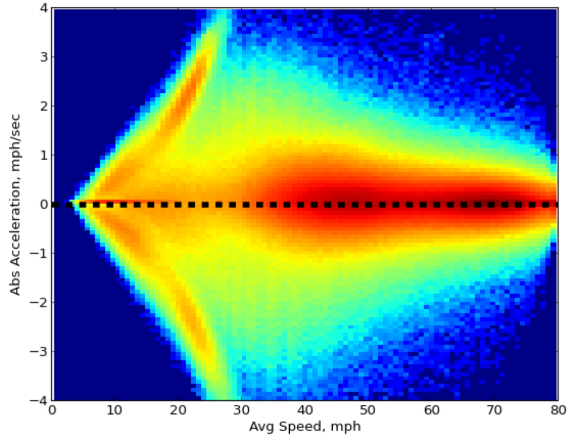
Summary

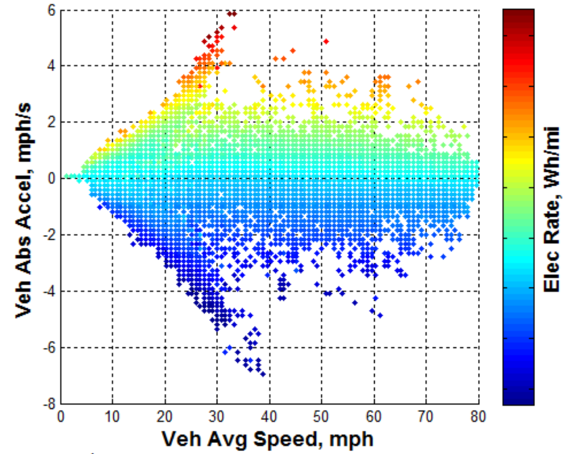
- **Demonstrated ability to model vehicle speed/accel profiles relative to road type**
- **Constructed high-level powertrain model employing cycle metrics and vehicle state as inputs**
- **Applied model using real-world distribution of O/D pairs, demonstrating:**
  - Aggregate energy savings of up to 4.6% for green routing (relative to passenger value of time)
  - Average energy savings of 3.3% for mode scheduling

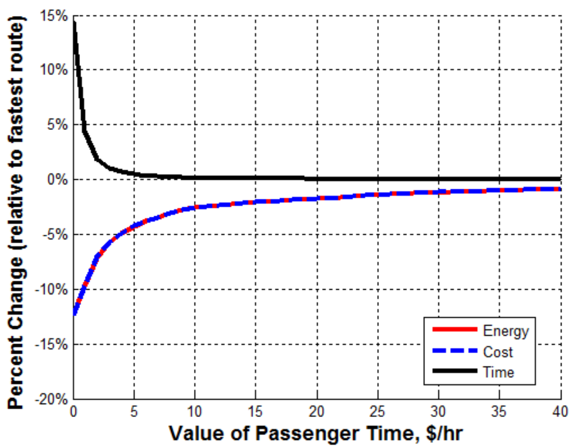
Modest aggregate savings, but may be cost-effective

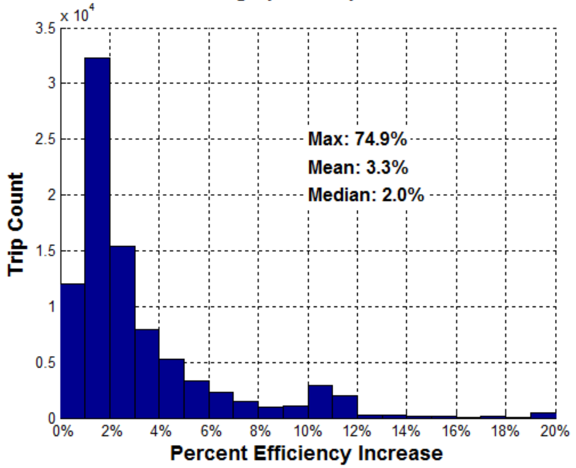
NREL IG 18563











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Thoughts on Automation/Electrification Synergy

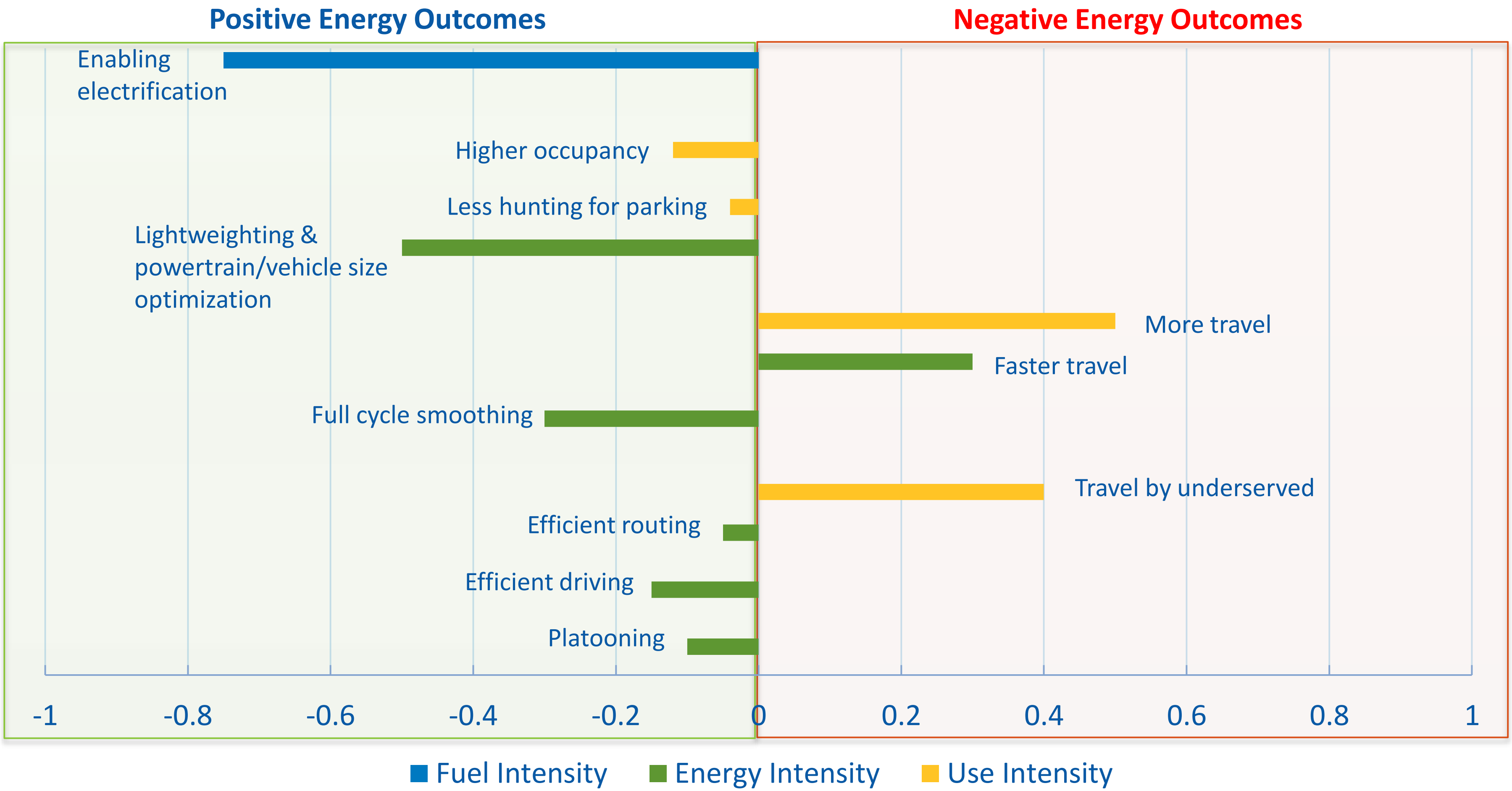
- **Automation easier with electrified driveline**
- **Information connectivity helps with vehicle/grid integration**
- **Automated alignment for wireless power transfer (WPT)**
- **Automated plug-in electrified vehicle parking/charging**
  - Value from valet anywhere, maximized electrified miles and infrastructure utilization, minimized anxiety about range and finding chargers
- **Vehicle right-sizing for trip/range**

Acknowledging some caveats

- **Can also automate conventional vehicle powertrains to obtain on-demand valet and taxi benefits**
- **Shared-use automated taxis may have lengthy daily ranges**
  - But improvements in battery cost, fast charging, WPT could still enable electrification
  - Also note operating cost/efficiency may become more important for such vehicles

CAV Assessment Summary

- **Dramatic potential energy impacts** (positive and/or negative)
  - Significant uncertainties remain; further research is warranted
  - Thoughtful policy needed to encourage desired outcomes



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Thanks! Questions?