Assessing the Energy Impact of Connected and Automated Vehicle (CAV) Technologies

SAE 2016 Government/Industry Meeting

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Transportation and Hydrogen Systems Center (THSC)

National Renewable Energy Laboratory (NREL)

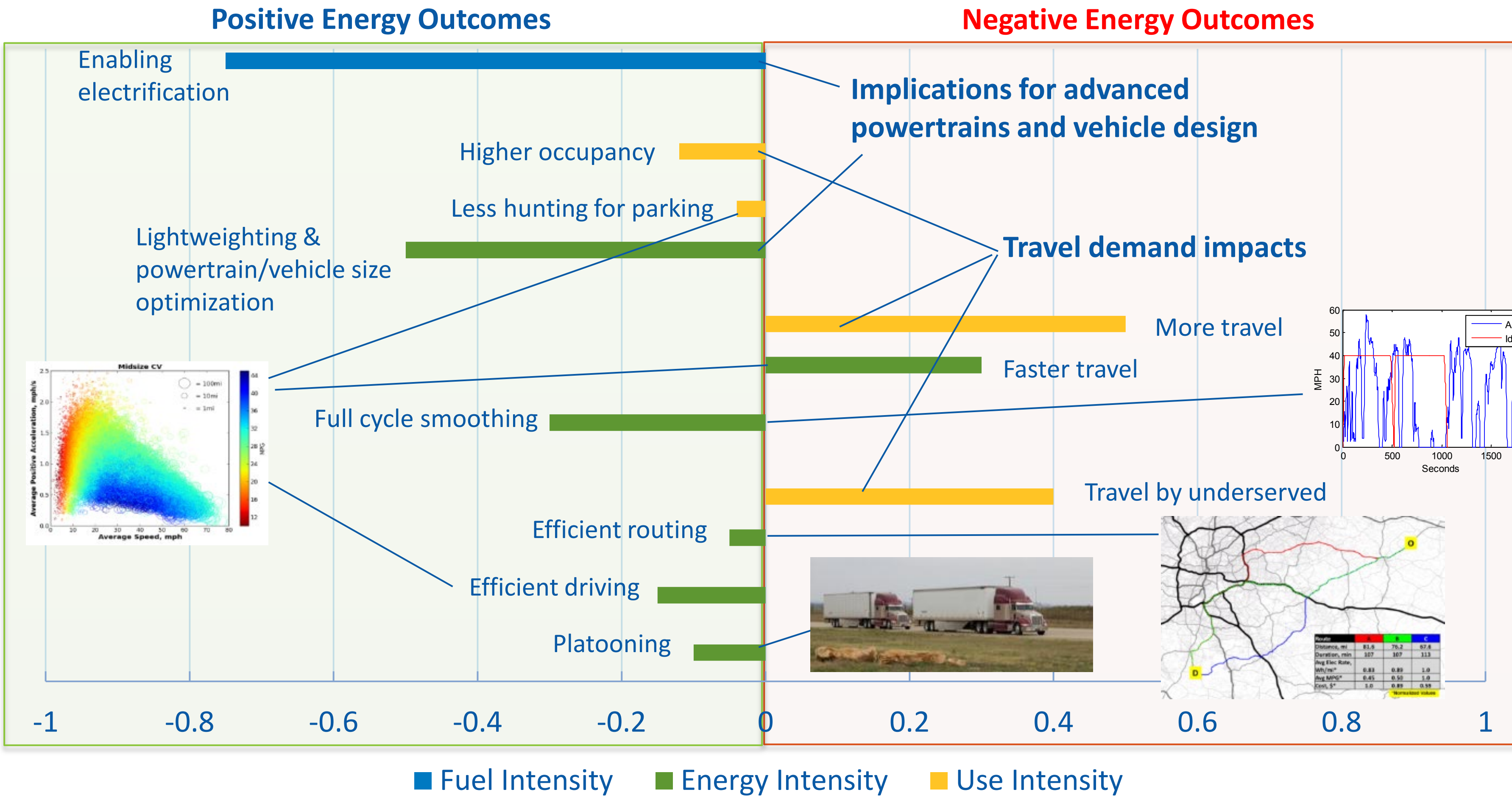
NREL/PR-5400-65743

Outline

- Overall energy impact assessment
- Example feature-level impacts
- Real-world/off-cycle benefit calculation
- On-going work by DOE and its national labs

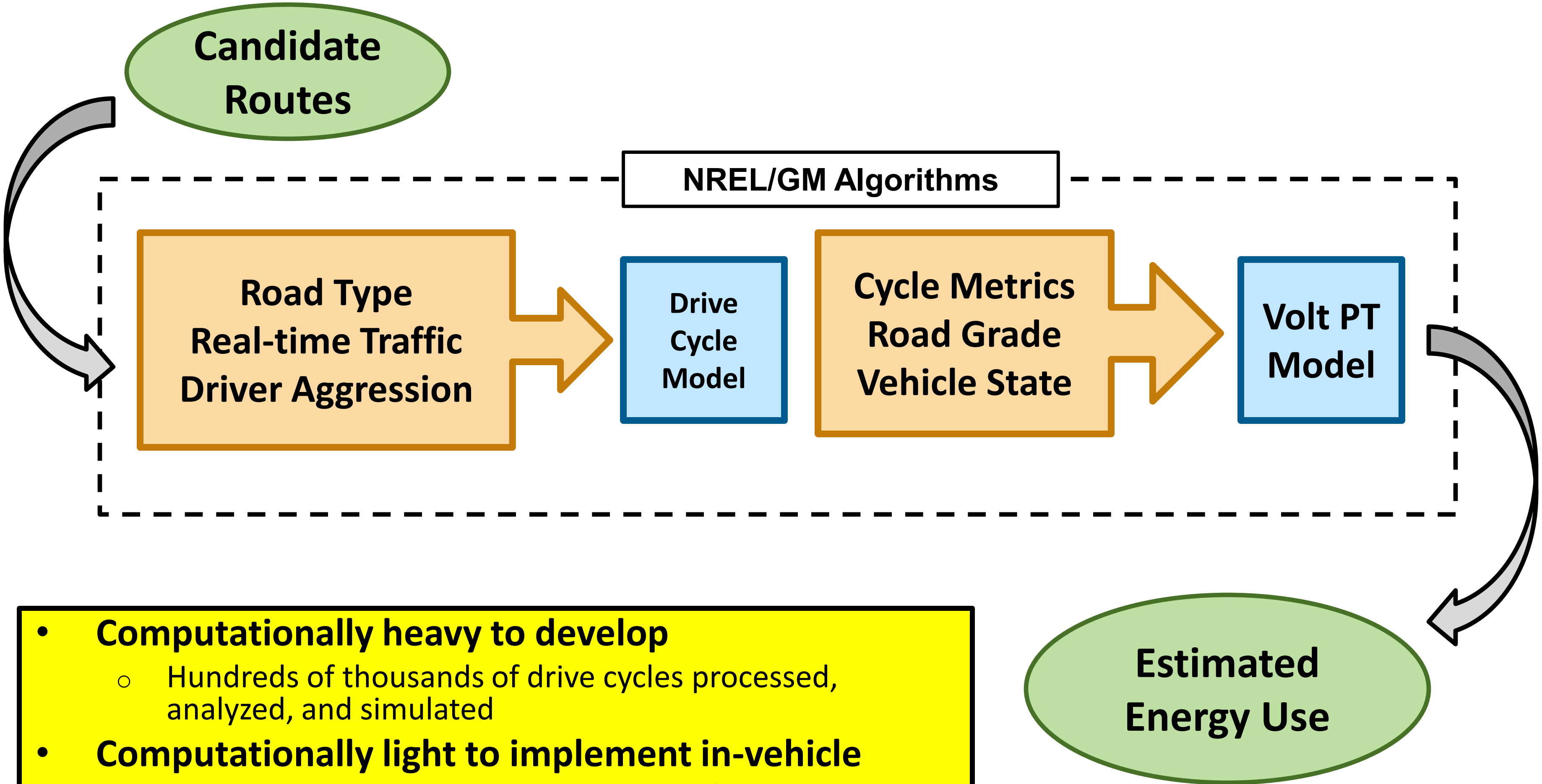
"Bookending" CAV Energy Impact Analysis

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



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.

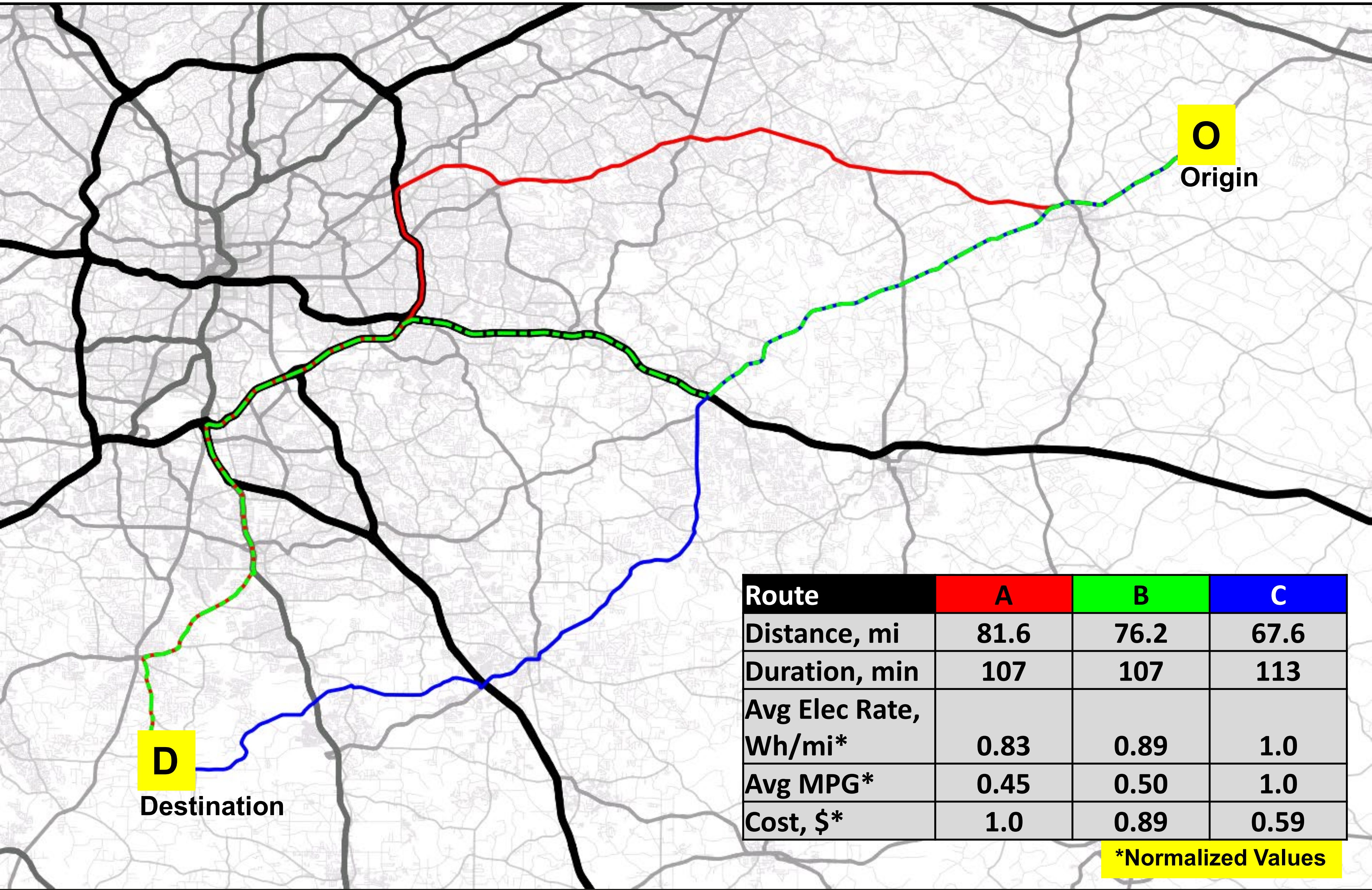
Example from Collaborative Project with GM on Green Routing and Adaptive Control for the Chevy Volt



- **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

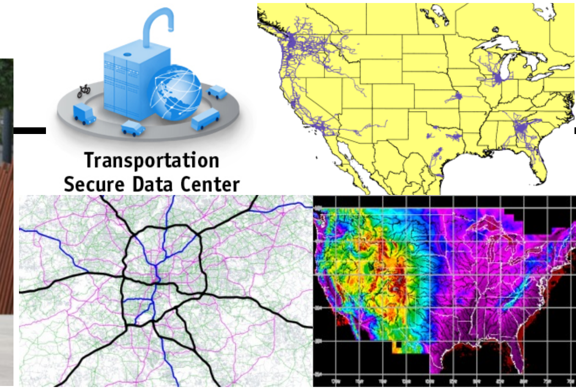


Route	A	B	C
Distance, mi	81.6	76.2	67.6
Duration, min	107	107	113
Avg Elec Rate, Wh/mi*	0.83	0.89	1.0
Avg MPG*	0.45	0.50	1.0
Cost, $*	1.0	0.89	0.59

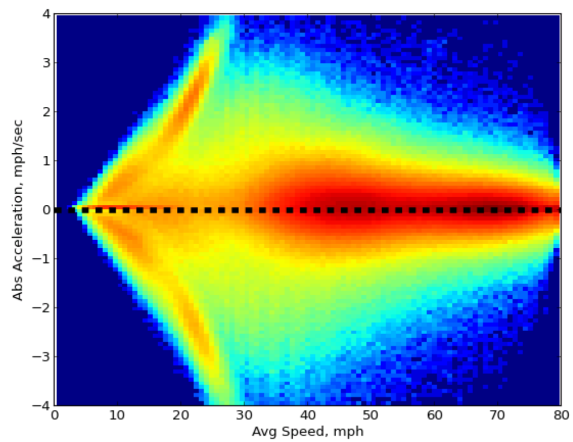
*Normalized Values

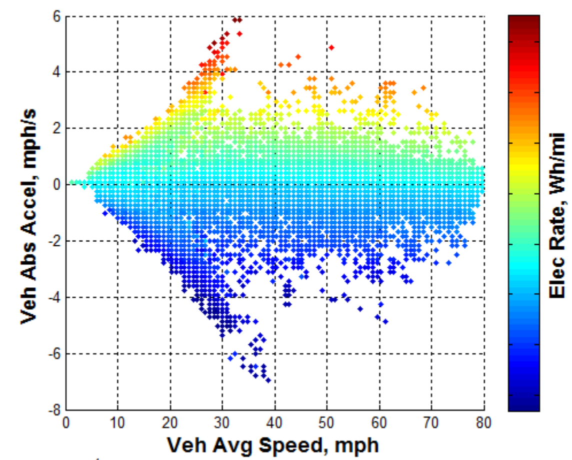
Collaborative Project Summary

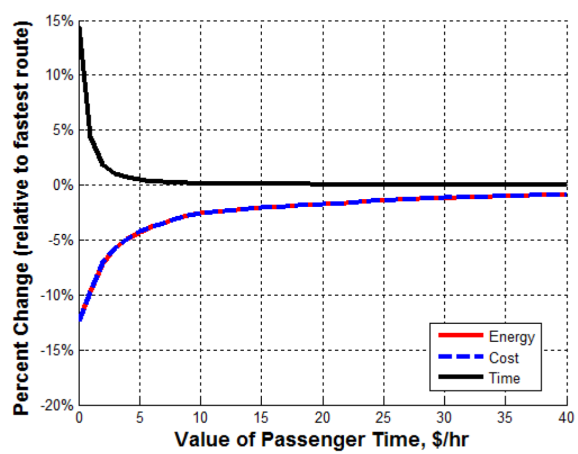
NREL IG 18563

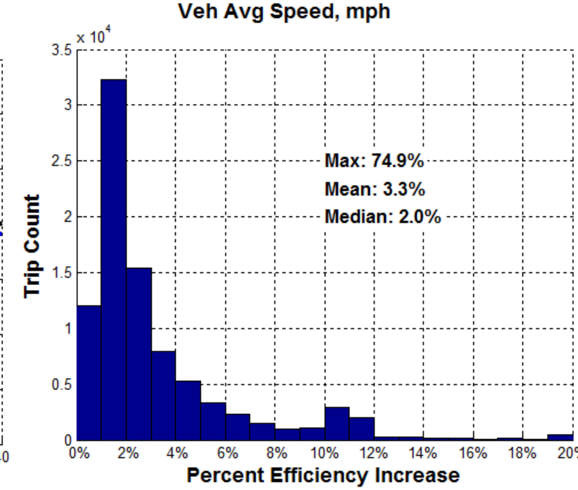


- **Demonstrated ability to model vehicle speed/accel profiles relative to road type**
- **Constructed high-level powertrain model employing cycle metrics and vehicle state as inputs**
- **Applied model using real-world distribution of O/D pairs, demonstrating:**
  - Aggregate energy savings of up to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





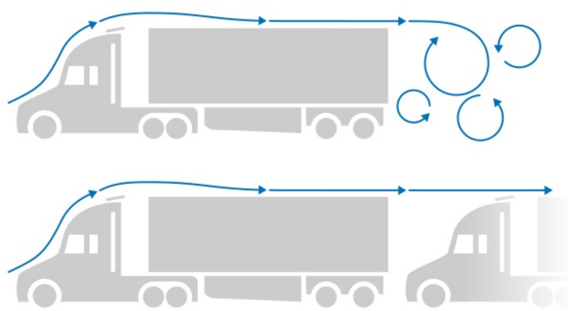


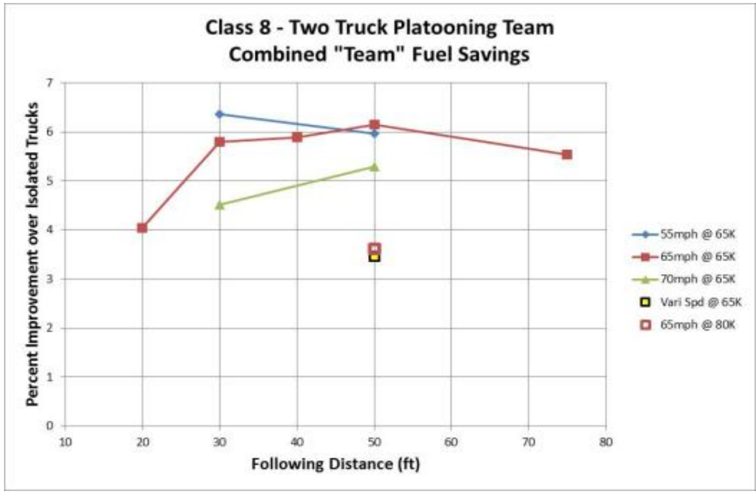


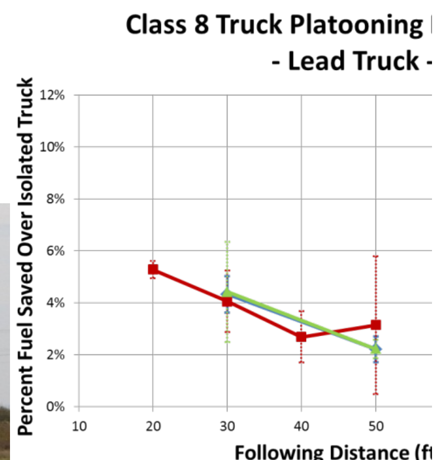
Modest aggregate savings, but may be cost effective

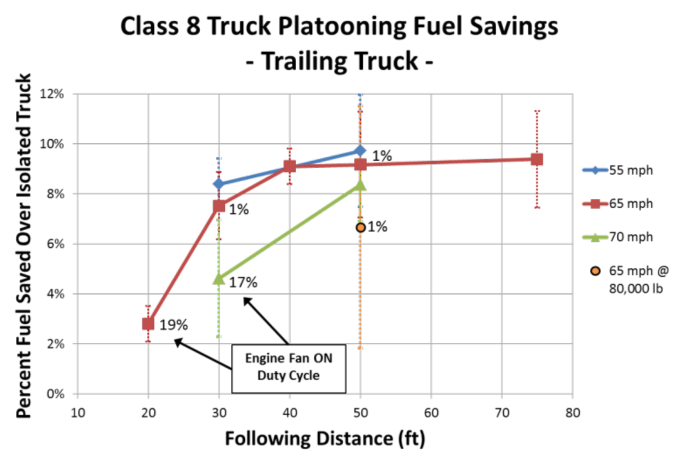
Evaluating Truck Platooning Efficiency Benefits

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









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

Related Analysis Effort on Real-World Efficiency Benefits

- **Evaluate real-world fuel-saving opportunities for technologies difficult to assess with standard certification cycles**
  - DOE and regulatory bodies want to maximize real-world fuel savings
  - Manufacturers want to get credit for actual fuel savings achieved
- **Strong interest from multi-lab/OEM workgroup under U.S. DRIVE; example technologies:**
  - **Engine encapsulation**
  - **Start-stop**
  - **High-efficiency alternators**
  - **High-efficiency lighting**
  - **Glazing technology**
  - **Connected vehicle applications**

- **DOE labs such as NREL can provide objective inputs**
- **Relevant existing capabilities**
  - **Evaluation of energy efficiency technologies**
  - **On-road driving data**
  - **Fusion of large datasets capturing range of real-world operating conditions**

OEM = original equipment manufacturer
US DRIVE = Driving Research and Innovation for Vehicle efficiency and Energy sustainability

Transportation Data Centers at NREL

Real-World Data and Analysis to Support Decision Making

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 individual travel data, including GPS profiles*

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

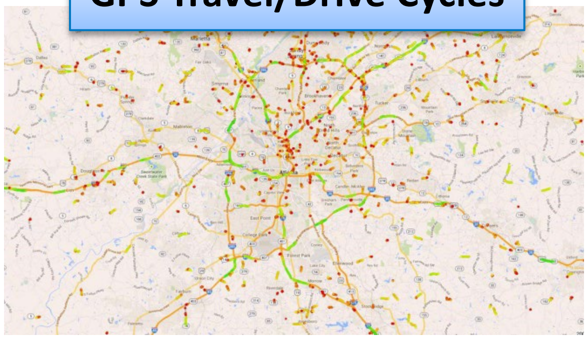
FleetDASH: *Business intelligence to manage Federal fleet petroleum/alternative fuel consumption*

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	

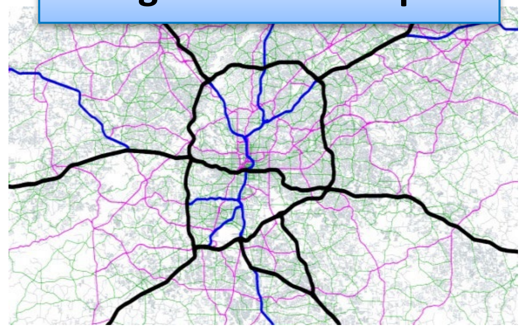
Integration with Other Large Datasets

Transportation Secure Data Center

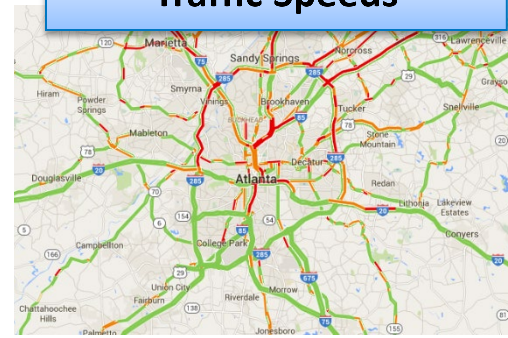
GPS Travel/Drive Cycles



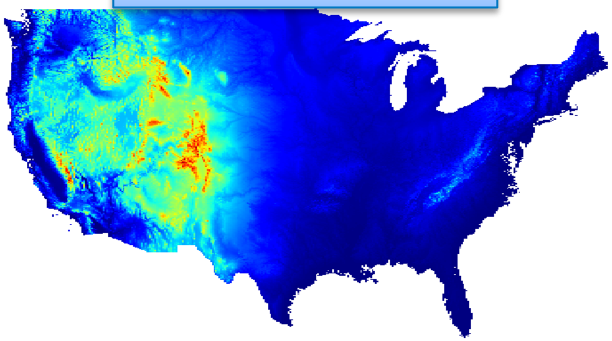
Digital Street Maps



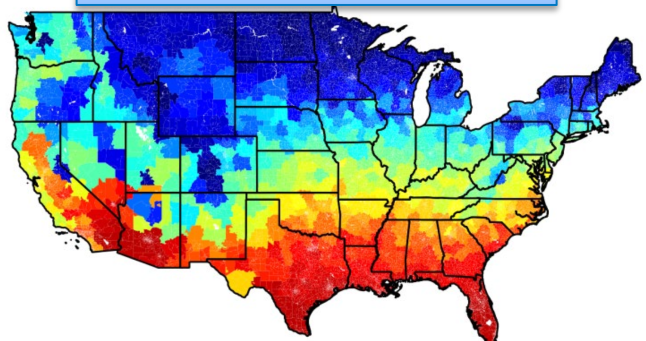
Traffic Speeds



Elevation / Grade

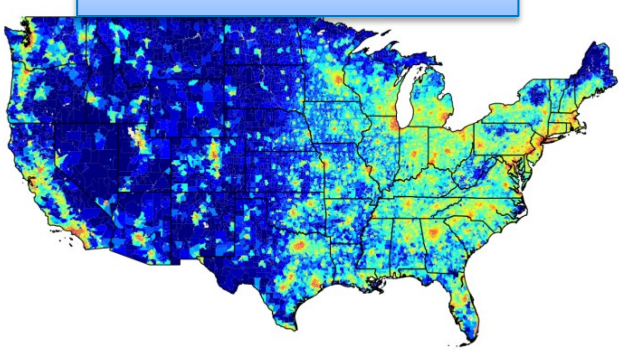


Ambient Temperature

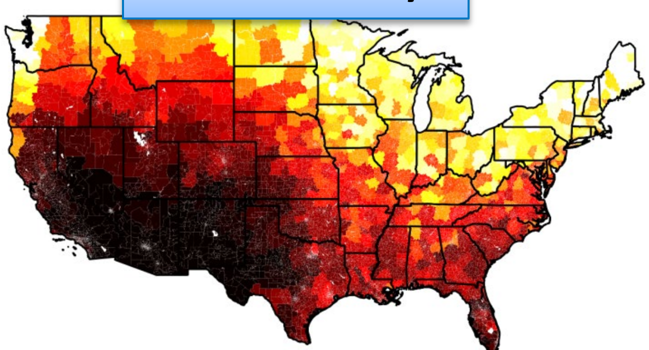


Freight Volumes

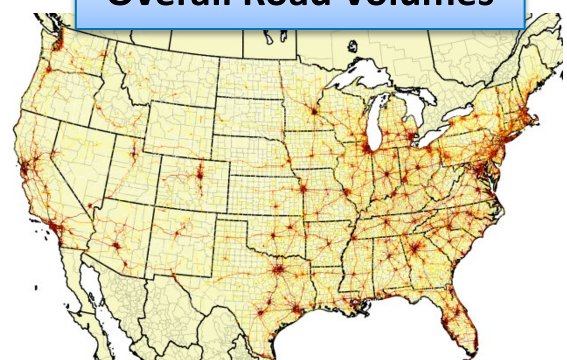
Vehicle Registrations



Solar Intensity

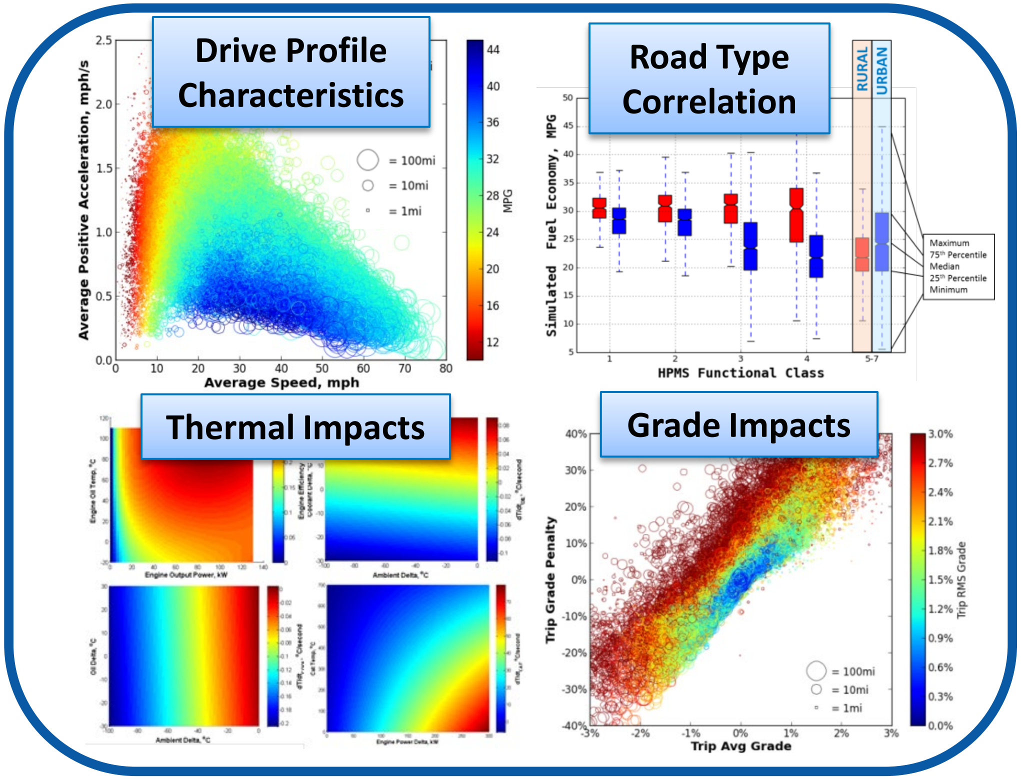


Overall Road Volumes



Prototyped Process for National-Level Aggregation of "Off-Cycle" Technology Impacts - 1

Fuel Consumption *Rates*

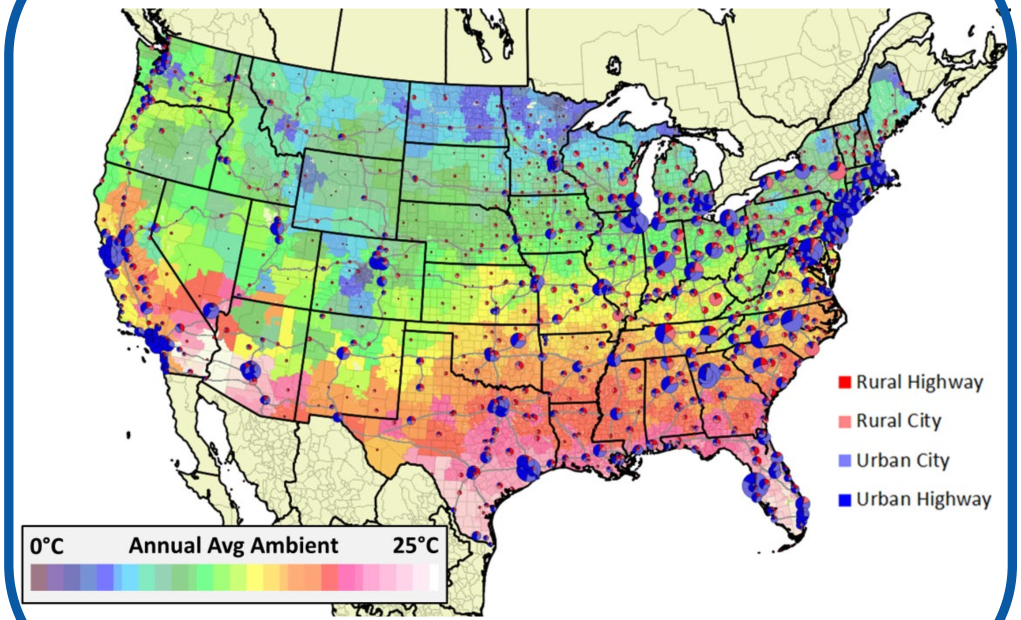


Use test data plus modeling to determine a given vehicle's fuel consumption rate over a range of driving situations

- **Consider drive profile characteristics, road grade, temperature, solar load, etc.**
- **Use large real-world driving database to correlate drive profile characteristics with road type/traffic conditions**

Prototyped Process for National-Level Aggregation of "Off-Cycle" Technology Impacts - 2

Vehicle Miles Traveled (VMT) *Volumes*

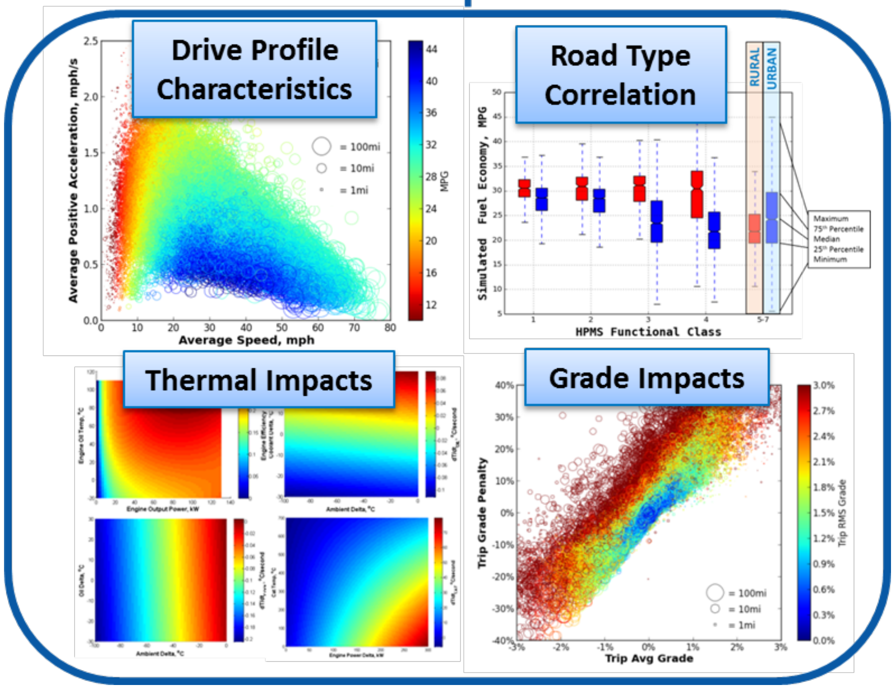


Combine national datasets on driving volumes by road type, climate conditions, road grades, etc.

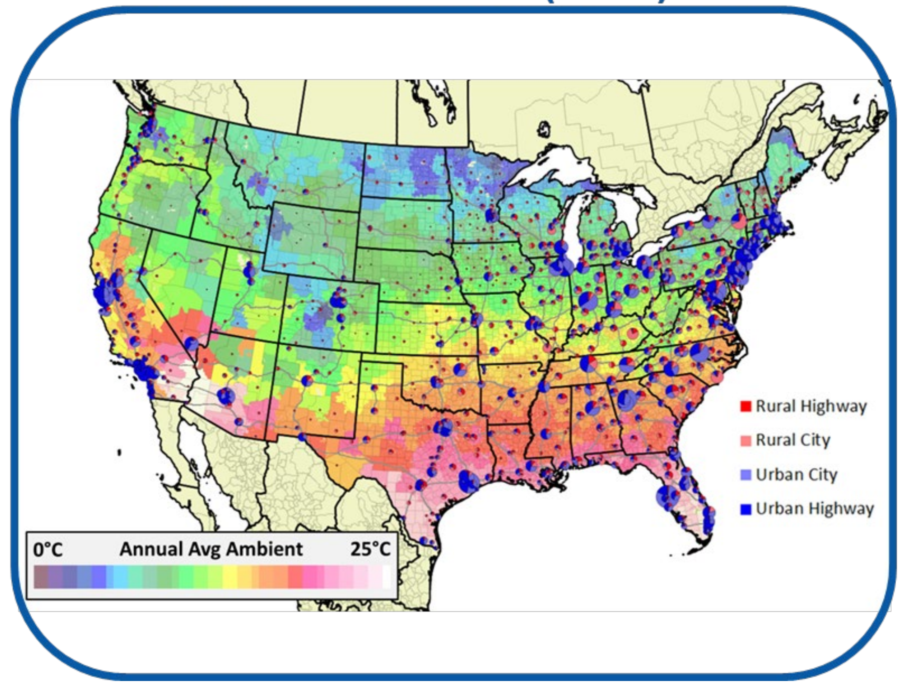
- **Proportionally weight consumption rates from different situations by the amount of driving each represents across the country and a typical meteorological year**
- **Calculate aggregated national-level fuel economy**

Prototyped Process for National-Level Aggregation of "Off-Cycle" Technology Impacts - 3

Fuel Consumption *Rates*



Vehicle Miles Traveled (VMT) *Volumes*



Repeat process with and without a given off-cycle technology enabled to calculate its national-level benefit

- **Methodology captures varying impacts a technology can have across a broad range of driving conditions**
- **Aggregation process permits the national-level A/B comparison**

Multi-Lab Project on Energy and GHG Implications from CAVs

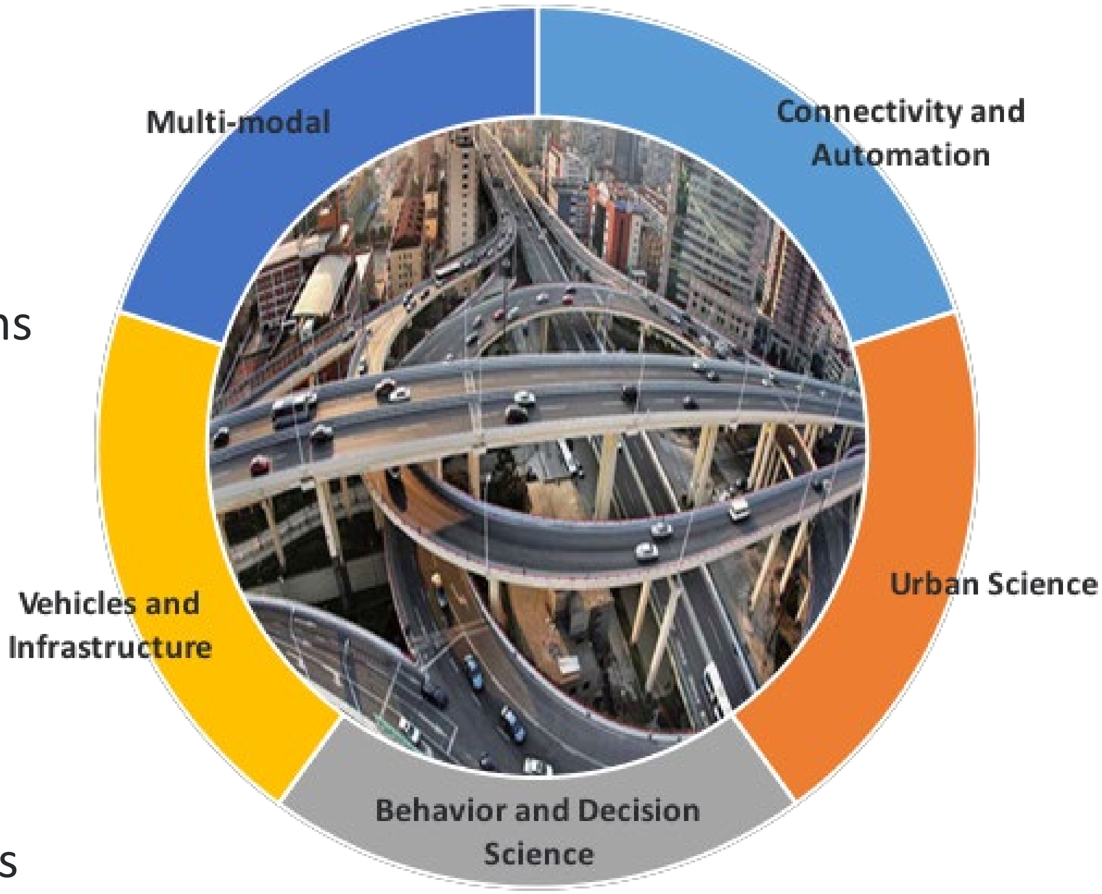
- **ANL, INL, NREL and ORNL participating**
- **Recognizing large potential impacts and uncertainties**
  - Potential disruption of travel patterns, vehicle use, ownership and even design
- **Seeking to refine bounds on potential energy consumption implications at the U.S. national level**
  - Assess specific scenarios
  - Implement/refine national-level aggregation methods
- **Identify key considerations for encouraging beneficial energy outcomes and for mitigating adverse energy outcomes**

GHG = greenhouse gas
ANL/INL/ORNL = Argonne/Idaho/Oak Ridge National Laboratories

Transportation as a System

Today:
- Vehicle-level focus
- Independent
- Unconnected
- Subject to behaviors & decisions

Tomorrow:
- System-level focus
- Connected
- Automated
- In concert
- Across modes
- Managed behaviors & decisions

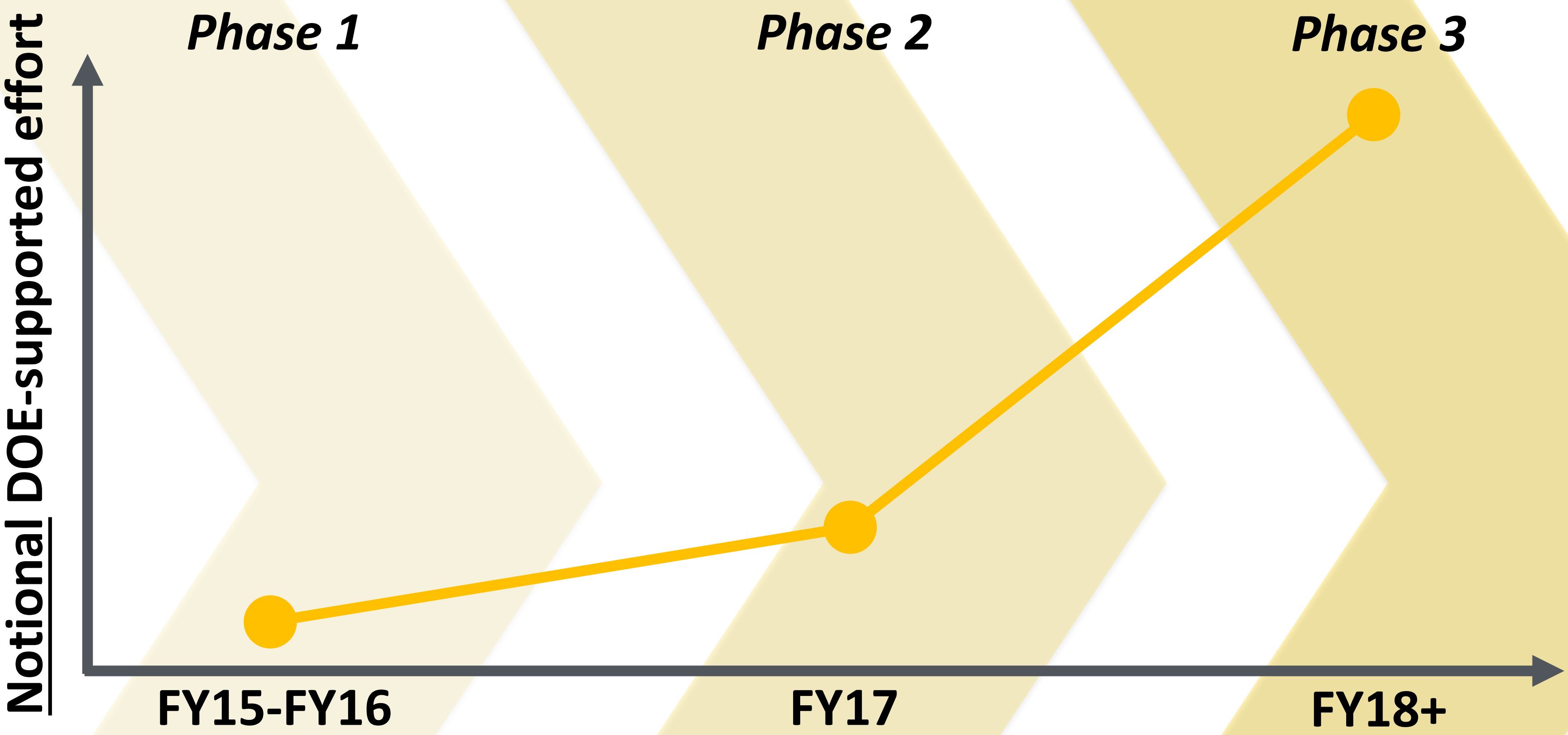


Exploring the untapped transportation system-level efficiencies

Focus Areas ("Pillars")

Focus Area	Future New Technologies/Models/Knowledge
Mobility Decision Science	• New knowledge and applications of decision science to collect and analyze real-world data on transportation decision making, electric and alternative fuel vehicle market drivers and barriers, as well as new mobility options.
Connectivity and Automation	• An increased understanding of the potential impact of connected and automated vehicles and their implications on transportation and vehicle technologies, such as electrification and overall mobility.
Multi-Modal	• Dynamic passenger/freight modal energy-intensity modeling with explicit consideration of consumer/market preferences and energy implications.
Urban Science	• Integrated city-scale models that explicitly consider energy impacts of urbanization by collecting real-world data and collaborating with local governments.
Vehicles and Infrastructure	• Integrated vehicle-fuel models to explore value propositions (consumer and provider), business models and opportunities for increased sustainable transportation deployment.

What's the plan?



Foundational efforts at DOE National Labs

Ramped-up efforts at Labs with partners

Large-scale with multiple performers

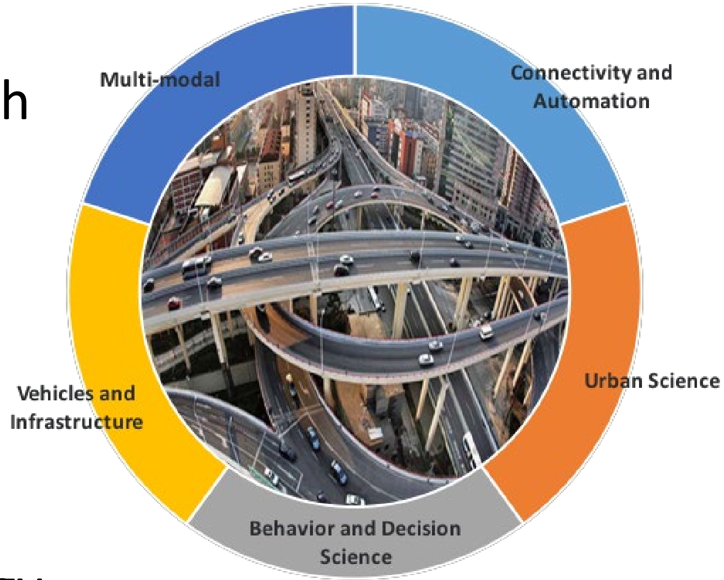
Transportation as a System: What's Next…?

DOE-funded multi-lab consortia:

1) Engage with key stakeholders, including the U.S. Department of Transportation (DOT), key universities with transportation research centers, and major cities and/or regions with ongoing DOT-funded efforts on mobility;

2) Design and execute robust analytical and foundational efforts to define and build-up constituent parts and frame DOE priority opportunities; and

3) Identify opportunities for focused technology demonstrations in conjunction with cities or states to spur commercialization and inform future activities across DOE's transportation technology portfolio.



Sustainable TRANSPORTATION

Federal POC: Jacob Ward,
jacob.ward@ee.doe.gov, 202-586-7606

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

Questions?

NREL Slides:

Jeff Gonder, jeff.gonder@nrel.gov, 303-275-4462

Appendix

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.

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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

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

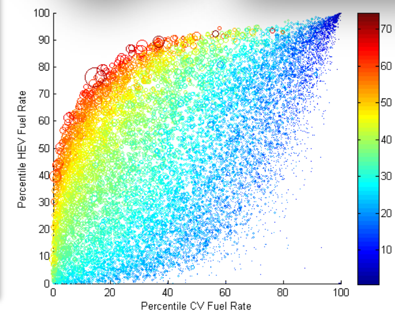
- **Can also automate conventional vehicle powertrains to obtain on-demand valet and taxi benefits; also raise efficiency baseline**
- **Shared-use automated taxis may have lengthy daily ranges**
    - But improvements in battery cost, fast charging, WPT could still enable electrification
    - Also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

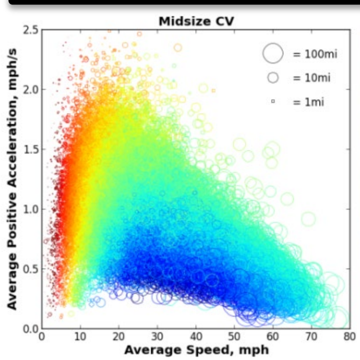
Extensive NREL Analyses with Large GPS Datasets in the TSDC

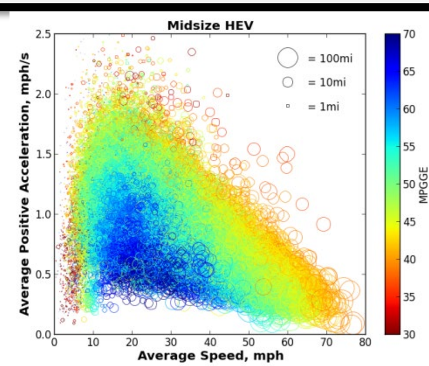
- Multi-powertrain real-world fuel economy distributions/sensitivities
- Comparing real-world driving and standardized test profile results
- Enabling road grade simulation and quantifying impacts
- Synthesis with national climate data for thermal technology evaluation
- Investigating PEV charging and alternative fuel station locations
- Developing green routing and adaptive control algorithms
- Assessing fuel saving opportunities from driver feedback…

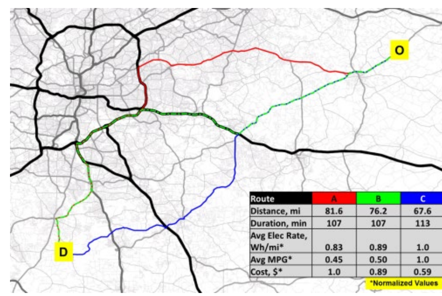
FASTSim

Transportation Secure Data Center









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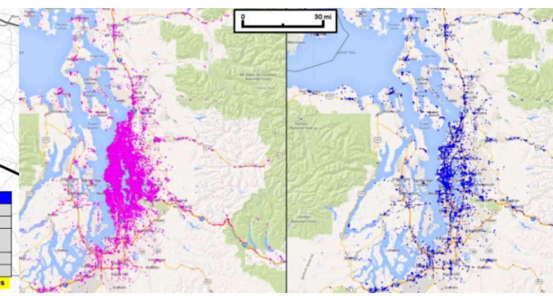

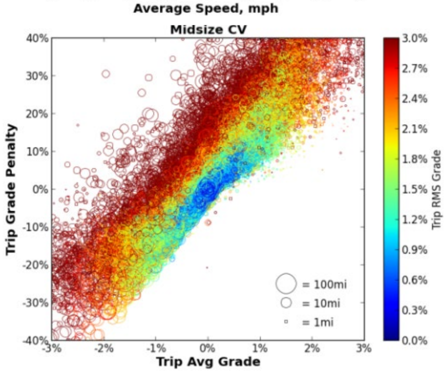

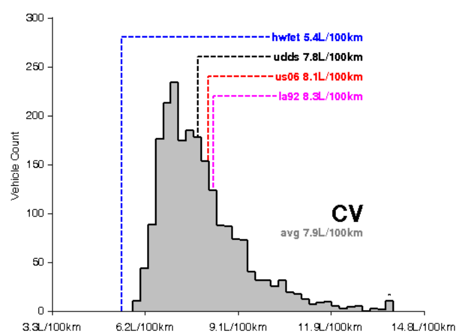

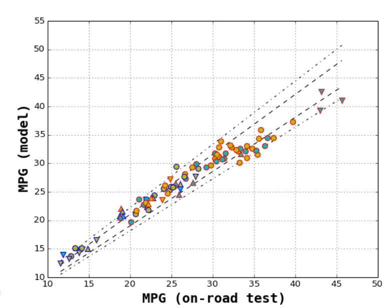

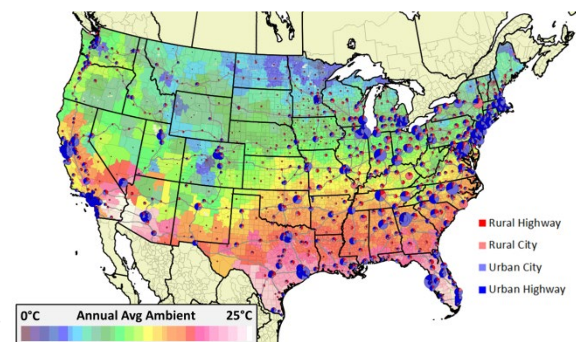

Photo Credits

- **Slides 3 and 7 – Truck photo by Mike Lammert, NREL**