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

SAE 2016 Government/Industry Meeting
January 21, 2016

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NREL/PR-5400-65743
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
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

Positive Energy Outcomes

- Enabling electrification
- Lightweighting & powertrain/vehicle size optimization
- Full cycle smoothing
- Efficient routing
- Efficient driving
- Platooning

Negative Energy Outcomes

- Implications for advanced powertrains and vehicle design
- Travel demand impacts
- More travel
- Faster travel
- Travel by underserved

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

**Candidate Routes**

- Road Type
- Real-time Traffic
- Driver Aggression

**NREL/GM Algorithms**

- Drive Cycle Model
- Cycle Metrics
- Road Grade
- Vehicle State
- Volt PT Model

**Estimated Energy Use**

- 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

# Green Routing Example

## Table

<table>
<thead>
<tr>
<th>Route</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance, mi</td>
<td>81.6</td>
<td>76.2</td>
<td>67.6</td>
</tr>
<tr>
<td>Duration, min</td>
<td>107</td>
<td>107</td>
<td>113</td>
</tr>
<tr>
<td>Avg Elec Rate, Wh/mi*</td>
<td>0.83</td>
<td>0.89</td>
<td>1.0</td>
</tr>
<tr>
<td>Avg MPG*</td>
<td>0.45</td>
<td>0.50</td>
<td>1.0</td>
</tr>
<tr>
<td>Cost, $*</td>
<td>1.0</td>
<td>0.89</td>
<td>0.59</td>
</tr>
</tbody>
</table>

*Normalized Values*
Collaborative Project 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
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](www.nrel.gov/docs/fy14osti/62494.pdf)
Related Analysis Effort on Real-World Efficiency Benefits

• Evaluate real-world fuel-saving opportunities for technologies difficult to assess with standard certification cycles
  o DOE and regulatory bodies want to maximize real-world fuel savings
  o Manufacturers want to get credit for actual fuel savings achieved

• Strong interest from multi-lab/OEM workgroup under U.S. DRIVE; example technologies:
  o Engine encapsulation
  o Start-stop
  o High-efficiency alternators
  o High-efficiency lighting
  o Glazing technology
  o Connected vehicle applications

• DOE labs such as NREL can provide objective inputs

• Relevant existing capabilities
  o Evaluation of energy efficiency technologies
  o On-road driving data
  o 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
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*

<table>
<thead>
<tr>
<th>Features</th>
<th>AFDC</th>
<th>NFCTEC</th>
<th>TSDC</th>
<th>Fleet DNA</th>
<th>Fleet DASH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Securely Archived Sensitive Data</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Publicly Available Cleansed Composite Data</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Quality Control Processing</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Spatial Mapping/GIS Analysis</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Custom Reports</td>
<td></td>
<td></td>
<td>Y</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Controlled Access via Application Process</td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed GPS Drive-Cycle Analysis</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>
Integration with Other Large Datasets

- 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
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

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
  o 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
  o Assess specific scenarios
  o 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”)

<table>
<thead>
<tr>
<th>Focus Area</th>
<th>Future New Technologies/Models/Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility Decision Science</td>
<td>• 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.</td>
</tr>
<tr>
<td>Connectivity and Automation</td>
<td>• 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.</td>
</tr>
<tr>
<td>Multi-Modal</td>
<td>• Dynamic passenger/freight modal energy-intensity modeling with explicit consideration of consumer/market preferences and energy implications.</td>
</tr>
<tr>
<td>Urban Science</td>
<td>• Integrated city-scale models that explicitly consider energy impacts of urbanization by collecting real-world data and collaborating with local governments.</td>
</tr>
<tr>
<td>Vehicles and Infrastructure</td>
<td>• Integrated vehicle-fuel models to explore value propositions (consumer and provider), business models and opportunities for increased sustainable transportation deployment.</td>
</tr>
</tbody>
</table>
What’s the plan?

Phase 1

FY15-FY16
Foundational efforts at DOE National Labs

Phase 2
FY17
Ramped-up efforts at Labs with partners

Phase 3
FY18+
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.
Questions?

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

**Table 11-22—Off-Cycle Technologies and Credits and Equivalent Fuel Consumption Improvement Values for Cars and Light Trucks**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Adjustments for cars</th>
<th>Adjustments for trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/mi</td>
<td>gallons/mi</td>
</tr>
<tr>
<td></td>
<td>g/mi</td>
<td>gallons/mi</td>
</tr>
<tr>
<td>High Efficiency Exterior Lights* (at 100 watt savings)</td>
<td>1.0</td>
<td>0.000113</td>
</tr>
<tr>
<td>Waste Heat Recovery (at 100W)</td>
<td>0.7</td>
<td>0.000079</td>
</tr>
<tr>
<td>Solar Panels (based on a 75 watt solar panel)**</td>
<td>3.3</td>
<td>0.000372</td>
</tr>
<tr>
<td>Battery Charging Only</td>
<td>2.5</td>
<td>0.000282</td>
</tr>
<tr>
<td>Active Aerodynamic Improvements (for a 3% aerodynamic drag or Cd reduction)</td>
<td>0.6</td>
<td>0.000068</td>
</tr>
<tr>
<td>Engine Idle Start-Stop: w/ heater circulation system</td>
<td>2.5</td>
<td>0.000282</td>
</tr>
<tr>
<td>w/o heater circulation system</td>
<td>1.5</td>
<td>0.000169</td>
</tr>
<tr>
<td>Active Transmission Warm-Up</td>
<td>1.5</td>
<td>0.000169</td>
</tr>
<tr>
<td>Active Engine Warm-up</td>
<td>1.5</td>
<td>0.000169</td>
</tr>
<tr>
<td>Solar/Thermal Control</td>
<td>Up to 3.0</td>
<td>0.000338</td>
</tr>
<tr>
<td></td>
<td>Up to 4.3</td>
<td>0.000484</td>
</tr>
</tbody>
</table>

*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 CO₂ can be granted.
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**
  o 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**
  o But improvements in battery cost, fast charging, WPT could still enable electrification
  o 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...
Photo Credits

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