Connected and Automated Vehicles

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ANL, INL, NREL, ORNL
2016 DOE VTO Annual Merit Review
June 8, 2016, Washington DC

Project ID: VAN022

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## Project Overview

<table>
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<tr>
<th>Timeline</th>
<th>Barriers</th>
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<tbody>
<tr>
<td>Start Date: September 2016</td>
<td>• Energy impact of connected and automated vehicles</td>
</tr>
<tr>
<td>End Date: September 2019</td>
<td>• Implication on VTO technologies and targets</td>
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<tr>
<td>Percent Complete: 10%</td>
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<table>
<thead>
<tr>
<th>Budget</th>
<th>Partners</th>
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<tbody>
<tr>
<td>Total project funding: $3M (100% DOE)</td>
<td>National Laboratories (ANL, INL, NREL, ORNL)</td>
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<tr>
<td>Funding for FY 2016: $1M</td>
<td>LLNL (VS006)</td>
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Objective: How can connectivity and automation be leveraged to reduce total energy use?

Why DOE VTO? DOE has the key expertise to provide the analysis and quantify the potential benefits of CAVs in reducing energy usage and greenhouse gas emissions:

• Vehicle technology (what are the optimal powertrain designs for automated vehicles?)
• Vehicle control (=> using information to save energy)
• Traffic flow control (speed harmonization, intersection control, smoothing, cooperative driving)
• Traveler Behavior (Where, when, how people travel?)
### Relevance

**Great Uncertainty about CAVs Effect On Energy Consumption**

#### Changes in traffic flows ⇒ Different Speeds
- Increased capacity
- Smoother speeds
- Potentially faster speeds
- Smart intersections

#### Travel behavior ⇒ +/- VMT
- Mode shifts (to/away from transit with automated shuttles)
- Increased access to mobility of underserved populations
- Changes in the value of time

#### Higher Vehicle Energy Efficiency
- Smoother driving
- Predictive energy management
- Reduced aero losses in platoons
- Downsizing (due to performance/safety)

![Energy Use Diagram]

+ Interaction with advanced powertrain technology!
Milestones

Task 1: Energy Impacts at the Individual Vehicle Level

- Energy impact of CAV-specific speed profiles
- Estimation of ACC/CACC energy impact

FY16
- Develop framework for evaluating ACC & CACC technologies

FY17
- Perform simulations to evaluate the impact of smart intersections at the regional level for advanced vehicle technologies

FY18
- Quantify the energy impact at the regional level of CAVs for VTO technologies

Task 2: Energy Impact at the Macro Level

- Fuel savings with predictive cruise control on highways
- Sensitivity of ACC/CACC to powertrain electrification

FY16
- Perform simulations to quantify the energy impact of secondary effects (e.g., VMT) at the regional level
- Quantify the impact of VTO technologies on LDVs design and energy consumption

FY17
- Quantify the impact of VTO technologies on USDrive targets

FY18
- Quantify the impact of simultaneous CAVs technologies
- Quantify how VTO technologies can mitigate potential energy multiplier
- Quantify the impact of VTO technologies on MDVs & HDVs design and energy consumption

Task 3: Secondary Energy Impact

- Fuel savings with optimal speed/powertrain control on urban/arterial roads
- Impact of platooning on energy

FY16
- Fuel savings with predictive cruise control on highways

FY17
- Sensitivity of ACC/CACC to powertrain electrification

FY18
Approach

Interactions with National Level Impact (AOI 2C) Effort

- Energy impacts of CAV technologies at vehicle-, local- and regional-levels will be analyzed by the AOI 9E team (VAN022), with guidance on cases to analyze and assumptions from this (AOI 2C – VAN020) effort.

- Results from AOI 9E analyses will be used to develop national-level estimates, to be refined as more results are available.

- This effort will identify gaps and uncertainties for improved analyses by the AOI 9E team.
Approach
Expertise of Each Laboratory Leveraged

- **ANL**
  - Vehicle energy modeling and control
  - Travel demand, flow and traveler behavior modeling
  - Vehicle [V2X] technology evaluation and analysis, dyno LD/MD
- **INL**
  - Define LD vehicle data collection requirements for model validation and identify data sources
  - On-road and on-track data collection and analysis – LD
- **NREL**
  - LD driving behavior; MD/HD on-road data collection and analysis
  - Impacts of vehicle design/operation & green routing on energy use
- **ORNL**
  - Decentralized control for optimizing traffic flow
  - Impact on VMT using geo-demographics
Approach

Different Resolution Tools Required

Evaluating new vehicle technologies, developing new vehicle controls

Developing controls for connected and automated vehicles

Analyzing the impact of new infrastructure, control and new forms of transportation

Single Vehicle
- Eco-driving
- Eco-Routing
- Predictive Control

Small Network
- Connected Intersections
- V2X
- ACC, CACC & Platooning

Entire Urban Area
- Connected Intersections
- Platooning & Eco-lanes
- Low-emission zones
- VMT changes

National Level
- Evaluation at the national level

VAN022

VAN020
- Evaluating energy impacts at the national level
### Approach

**Project Organization Leverages Tool Resolution**

<table>
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<tr>
<th>Task</th>
<th>Description</th>
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<td><strong>1</strong></td>
<td>Energy Impact at the Vehicle Level</td>
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<tr>
<td>1.1.1</td>
<td>On-Road Light Duty Vehicle Evaluation (INL)</td>
</tr>
<tr>
<td>1.1.2</td>
<td>On-Road Medium &amp; Heavy Vehicle Evaluation (NREL)</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Light duty chassis dynamometer evaluation (ANL)</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Heavy Duty Powertrain Dynamometer Evaluation (ORNL)</td>
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<tr>
<td>1.3</td>
<td>Individual Vehicle Simulations (ANL)</td>
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<tr>
<td>1.4</td>
<td>Connected Vehicle Simulations (ANL)</td>
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<tr>
<th><strong>2</strong></th>
<th>Energy Impacts at the Macro Level</th>
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<tr>
<td>2.1.1</td>
<td>Larger-Scale Traffic Flow Impacts (ANL)</td>
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<tr>
<td>2.1.2</td>
<td>Green routing (NREL)</td>
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<td>2.2</td>
<td>Control for Improving Traffic Flow with CAVs (ORNL)</td>
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<th><strong>3</strong></th>
<th>Secondary Impacts that Could Enhance or Inhibit Energy Benefits</th>
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<tr>
<td>3.1</td>
<td>Travel Behavior Evolution at the Regional Level and its Energy Impact (ANL)</td>
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<tr>
<td>3.2.1</td>
<td>Evolution of Vehicle Miles Traveled at the Nat. Level (ORNL)</td>
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<td>3.2.2</td>
<td>Impacts on Heavy-Duty Freight Demand (NREL)</td>
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<td>3.3.1</td>
<td>Impact on Vehicle Design (ANL)</td>
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<tr>
<td>3.3.2</td>
<td>Impact on Vehicle Design (NREL)</td>
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Approach

Project Subtasks Dependency

**Single Vehicle**
- Task 1.1 On-Road Eval.
- Task 1.2.1 Vehicle Dyno. Eval.
- Task 1.3 Indiv. Vehicle Simu.
- Task 3.3 Vehicle Design Impact

**Small Network**
- Task 1.4 V2X Vehicle Simu.
- AOI 9C HD Aero

**Entire Urban Area**
- Task 2.1.1 Large Scale Traffic Flow Simu
- Task 2.1.2 Green Routing
- AOI 2C Nat Level
- Task 3.1 Travel Behavior Eval at Regional Level
Technical Accomplishments

Task 1.3: Energy Impact of Individual Vehicles

Process

- SSSpeed cycles
- RWDC CAV3
- RWDC CAV1
- RWDC

Results

- 3 Midsize vehicles
  - Conventional
  - HEV
  - BEV

- Database of recorded GPS traces

- 35 to 50% potential fuel savings at low vehicle speed
- BEVs have biggest potential at low vehicle speed
Technical Accomplishments
Task 1.4: Connected Vehicles Simulations
Started Development of Multi-Vehicle Simulation Framework Using Autonomie

Truck platoon example
Technical Accomplishments

Task 1.4: Connected Vehicles Simulations

Longitudinal vehicle dynamic control - ACC concept

- **ACC**
  - Vehicles are equipped with sensor(s) to measure
    - The inter-vehicle gap
    - The preceding vehicle speed

- **ACC controller**

Aerodynamic data for following trucks provided by LLNL (VS006)
Technical Accomplishments

Task 1.4: Connected Vehicles Simulations

Longitudinal vehicle dynamic control - CACC concept

- CACC
  - Vehicles are equipped with sensor(s) to measure
    - The inter-vehicle gap
    - The preceding vehicle speed
    - The leading-vehicle gap
    - The leading vehicle speed

- Simplified CACC controller

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<table>
<thead>
<tr>
<th></th>
<th>Vehicle longitudinal controller</th>
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<tbody>
<tr>
<td>CACC gap sp</td>
<td>CACC controller +</td>
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<tr>
<td>ACC gap sp</td>
<td>ACC controller +</td>
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<tr>
<td></td>
<td>Accel. dem. + trq. dem.</td>
</tr>
<tr>
<td></td>
<td>Brake [%]</td>
</tr>
<tr>
<td></td>
<td>Accel. [%]</td>
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Gap measure $\varepsilon_i$

Aerodynamic data for following trucks provided by LLNL (VS006)
Technical Accomplishments

Task 1.4: Connected Vehicles Simulations

Developed Adaptive Cruise Control Algorithms

Grade robust ACC for line haul
Technical Accomplishments
Task 2.1.1: Large Scale Traffic Flow Impact

Developed a linkage between MA3T outputs that allows fleet definition using Autonomie vehicles.

MA3T (ORNL Market Penetration Tool)

Fleet distribution
Technical Accomplishments

Task 2.2: Control for Improving Traffic Flow with CAVs

- Developed a scalable optimization framework for coordinating CAVs to optimize traffic flow in designated transportation segments, e.g., intersections, merging roadways.

- Formulated the centralized control problem for CAVs merging at highway on-ramps. Developed the decentralized control framework that will allow each vehicle to solve the optimal control problem independently.

**Optimization Problem:**

\[
\min J = \min_{u_{j,i}} \frac{1}{2} \sum_{j=1}^{m} \sum_{i=1}^{n} \int_{0}^{T_j} u_{j,i}^2 dt
\]

Subject to:

\[
\begin{align*}
\dot{x}_{j,i} &= v_{j,i} \\
\dot{v}_{j,i} &= u_{j,i}
\end{align*}
\]

- Safety Constraints
  - Rear-end collision avoidance
  - Lateral collision avoidance
Technical Accomplishments

Task 3.1: Travel Behavior Evolution at the Regional Level and its Energy Impact

- Preliminary analysis of potential range of secondary effects at the regional level
- Simplified models of behavioral and traffic flow response to CACC deployment:
  - Changes in travel behavior come only from assumed changes in value of time (ranges drawn from literature)
  - Modeled by reducing travel time parameters in the utility functions for destination choice, mode choice, etc.
  - ex: \( V_{in} = \beta_T T_{in} (1 + \gamma_{vt}) + \cdots \), where \( V_{in} \) = utility, \( \beta_T \) = travel time parameter, \( \gamma_{vt} \) = % change in travel time value
  - Traffic flow impacts modeled as link capacity changes for given penetration level derived from literature review:

- Analyzed over a range of market penetration values
- CACC technology randomly distributed to drivers according to penetration level
- Link capacity changes uniformly applied across network
Technical Accomplishments

Task 3.1: Travel Behavior Evolution at the Regional Level and its Energy Impact

- Baseline model + 18 scenarios evaluated, including:
  - 3 with only capacity changes
  - 6 with only value of travel time changes at different penetration levels
  - 9 with all effects, including turning off intersection control at 100% penetration

- Wide range of potential outcomes:
  - Difference largely driven by VOTT
  - Worst case of ~80% increase in VMT at high deployment/low VOTT

- Preliminary model with several potential behavioral responses unaccounted for and simplified impact of CACC on traffic flow
Collaboration and Coordination with Other Institutions

The project has been developed with collaboration in mind due to the multiple partners:

- Decentralized control for optimum traffic flow
- Impact of VMT using geo-demographics
- LD driving behavior; MD/HD on-road data collection and analysis
- Impacts of vehicle design/operation and green routing on energy use
- Data collection requirements
- On-road and on-track data collection and analysis for light duty
- Vehicle Energy Consumption
- Transportation system simulation
- Vehicle [V2X] technology evaluation, dyno

Numerous other projects leveraged including:

- LLNL (Aero. VS006)
- MTC FOA (Data VS173)
- TARDEC (Advanced controls)
- CERC (MaaS)
- Detroit (Transportation system modeling)
- FTA (Transit modeling)
- ARPA-E TRANSNET (Connected traveler)
**Future Work**

FY16

- Collect data requirements for model validation and determine possible data sources, and contact data owners to find out if data can be shared.
- Complete ACC, CACC control impact along with the new multi-vehicle framework.
- Quantify the benefits of CAVs in fuel consumption in merging at highways on-ramps.
- Assess the impact of CAVs at the regional level to quantify positive (e.g., platooning, green routing) as well as negative impacts (e.g., VMT evolution).

FY17

- Perform data availability gap analysis.
- Design on-road evaluation program using AVTA resources to fill gaps.
- Assess the energy impact of CAVs for multiple technologies at different scales including uncertainties.
- Collect data and determine resources specific traffic scenario of heavy-duty vehicles for model validation.
Connected and automated vehicles (CAVs) have the potential to disrupt the transportation system as it currently stands. While a significant amount of work has been reported related to safety, only limited qualitative analysis has been performed so far related to energy. This multi-year multi-national laboratory project expands existing expertise related to energy consumption, GHG and cost for CAVs. Multi-scale approach (single vehicle, small network, region and nation) combined with vehicle test data already showed promising results. Project currently being expanded to be part of Smart Mobility which will include decision science, infrastructure, multi-modal and urban in addition to CAVs.
ADDITIONAL SLIDES
Current State of Research

• Current focus has been on safety and feasibility
  – Autonomous vehicles demonstrated for automated features (i.e., GM supercruise, Magna EYERIS…) as well as for self-driving cars (i.e., Google car, DARPA grand challenge…)
  – Regarding connected vehicles,
    • DSRC rule making is in progress. Cars will likely soon be equipped with V2V communications capabilities (ANPRM out).
    • Safety pilot performed at University of Michigan

• Government agencies, led by DOT/AERIS, universities and research institutions (i.e., ITS America) have performed preliminary work related to CAVs energy consumption potential. Several programs also on-going in Europe (i.e. amitran, compass4D) and Japan (i.e. nedo).

Qualitative foundational work performed so far for energy
Researchers have performed *preliminary* estimations of *some* benefits

### Examples of DOT/AERIS - *Estimations per Vehicle*

<table>
<thead>
<tr>
<th>Technology</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Eco Approach &amp; Departure</td>
<td>• 5-10% fuel reduction for an uncoordinated corridor</td>
</tr>
<tr>
<td></td>
<td>• Up to 13% fuel reduction for a coordinated corridor</td>
</tr>
<tr>
<td>Eco-Traffic Signal Timing</td>
<td>• 5% fuel reduction when optimizing for the environment (e.g., CO2)</td>
</tr>
<tr>
<td></td>
<td>• 2% fuel reduction when optimizing for mobility (e.g., delay)</td>
</tr>
<tr>
<td>Eco-Traffic Signal Priority</td>
<td>• Eco-Transit Signal Priority provides up to 2% fuel reduction benefits for transit vehicles</td>
</tr>
<tr>
<td></td>
<td>• Eco-Freight Signal Priority provides up to 4% fuel reduction benefits for freight vehicles</td>
</tr>
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The accelerated introduction of advanced vehicle technologies will allow for mobility optimization => **advanced technologies allow us to decouple energy from mobility**

While safety benefits can be extrapolated, **energy benefits cannot be generalized as they completely depend on the network and scenario**

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Limitations of Current Research – Energy Benefits

A long list of next steps has already been identified by leading researchers, focusing on:

- **Different fleet distributions** (i.e., “More aggressive assumptions of electric and hybrid fuel vehicles could be considered in future modeling efforts”)
- **Improved algorithms** (i.e., “Trajectory planning algorithm used to make priority determinations can be improved to better estimate the arrival time of buses at intersections”)
- **Different travel demand and traffic flow** (i.e. “Additional modeling [for EcoSignal] could be considered on different corridor demand configurations (e.g., a corridor with higher demands on the side streets, an urban grid, etc.)”)
- **Larger networks** (i.e., “Evaluate [benefits of connected EcoDriving] on a larger network (interconnected arterial and freeway segments)”)
- **Integration of multiple benefits** (i.e. “Integrate modeling of the Eco-Approach and Departure Application with other Eco-Traffic Signal Applications to determine composite benefits”)

Quotes from AERIS Program Webinars
Limitations of Current Research – Energy Benefits

Energy consumption analysis

**Current Research Limitations**

- Vehicle energy consumption based on average values (VMT), on vehicle speed binning (MOVES) or simplified vehicle models.
- These methodologies can be limited, especially for advanced vehicles.
- Connectivity (X2X) not consistently leveraged for vehicle control optimization (AERIS sponsored “glide-path” research at Turner Fairbanks).

**Leveraging DOE Expertise**

Leverage high fidelity vehicle simulation tool to estimate:

- Advanced control benefits
  - Include full vehicle connectivity (i.e. V2V, V2I, I2V, V2G)
  - Take into account advanced controls (i.e. trucks use variable target speeds when going up & down grades)
  - Assess route based control
- Take into account powertrain specificities (i.e. different vehicles have different optimum speeds).
- Impact on vehicle design:
  - Component downsizing (i.e., impact on battery sizing due to efficient driving)
  - Light weighting
  - Impact of aerodynamic / thermal management for platooning
Limitations of Current Research – Energy Benefits

Travel Behavior, Traffic Flow Simulation & Fleet Definition

**Current Research Limitations**

- Rely on microscopic traffic flow simulations (very data hungry & hard to calibrate)
- Focus on small portions of roads (i.e. urban, highway) rather than the network
- Shift in travel behavior unaccounted (i.e. multi-modal, vehicle ownership models, demographic changes...)
- Leverage today’s fleet distribution for their baseline
- Estimations based today’s vehicle technologies (i.e. focus on anti-idling gains)

**Leveraging DOE Expertise**

- Leverage mesoscopic traffic flow simulators designed for ITS
- Leverage market penetration tools to estimate future fleet distribution
- Leverage expertise to define behavioral models of individual decision-maker
- Leverage expertise to estimate increased VMT, behavioral shift (i.e. mode shift...)

In addition, several of the benefits have not been quantified (i.e., Eco-traveler information, Eco-Smart Parking, Wireless Charging...