Applied Analysis of Connected and Automated Vehicles

Principal investigator: Tom Stephens
Argonne National Laboratory

2016 Vehicle Technologies Annual Merit Review
June 8, 2016
Washington, DC

Project VAN020

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline
Project start: 1 Jul 2015
Project end: 30 Sep 2018
Percent Complete: 20%

Barriers
• Large uncertainty in energy and GHG implications of connected and automated vehicles
• Lack of methods for aggregating case studies and for estimating future adoption potential

Budget
FY 2015: $140k
FY 2016: $450k
– 100% DOE

Partners
• Interactions / Collaborations
  – National Renewable Energy Laboratory
  – Oak Ridge National Laboratory
  – University of Illinois at Chicago
• Project lead: T. Stephens, Argonne
Objective

• Estimate potential changes in petroleum consumption and GHG emissions due to deployment of connected and automated vehicles (CAVs)
  – Develop CAV deployment scenarios
  – Define data gaps and analysis needs to direct in-depth case studies and analysis (performed under separate effort)
  – Develop methods to estimate potential CAVs technology adoption rates
  – Develop methods to aggregate results of case studies to the national level
Vehicle Technologies Office must consider the energy and emissions implications of connected and autonomous vehicles (CAVs)

- DOE EERE Vehicle Technologies Office (VTO) develops and deploys efficient and environmentally-friendly highway transportation technologies that will provide Americans with greater freedom of mobility and energy security, while reducing costs and impacts on the environment
- CAVs are may disrupt patterns of travel patterns, vehicle use and ownership, and even vehicle design with large changes in energy consumption
- Proposed analysis of CAVs under VTO-funded project “Connected and Automated Vehicles - Modeling and Simulation” (VAN022) will provide estimated energy impacts at the local and regional levels
- The results (with other results as available) must be expanded to the national level

Key questions:
- What are the bounds on potential energy consumption implications of CAVs at the U.S. national level?
- What are the key considerations for encouraging energy beneficial outcomes and for mitigating adverse energy outcomes?
Challenges

• Drawing conclusions from current literature
  – Disparate scenarios and case studies differ in assumptions and methodologies
  – Results can’t be combined or extrapolated to national level

• Estimating future adoption levels of various CAV technologies in different vehicle applications

• Taking results of simulations and analyses at a vehicle, local or regional level and expanding estimated changes in travel, fuel use and GHG emissions to the national level
## Milestones

<table>
<thead>
<tr>
<th>Month / Year</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 2015</td>
<td>Baseline scenario established</td>
<td>Complete</td>
</tr>
<tr>
<td>Mar 2016</td>
<td>Data gaps and key uncertainties identified for CAVs in light-duty passenger travel</td>
<td>Complete</td>
</tr>
<tr>
<td>Jun 2016</td>
<td>Prioritization matrix informing CAVs focused technology demonstrations</td>
<td>In progress</td>
</tr>
<tr>
<td>Sep 2016</td>
<td>Initial synthesis of scenarios and estimates of potential ranges of energy impacts at a national level for light-duty passenger travel</td>
<td>In progress</td>
</tr>
</tbody>
</table>
Approach: Develop CAVs scenarios and analyze results from in-depth studies

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

- Results from VAN022 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 VAN022 team.
Approach: Initial literature review and assessment

• Objectives
  – Review relevant studies and assess what’s known about potential energy and market implications of CAVs for passenger travel energy use
  – Identify key knowledge gaps/uncertainties

• Scenarios considered in FY15 review:
  1) Partial Automation: NHTSA Level 1&2 Automation
  2) Full Automation: NHTSA Level 3&4 Automation
  3) Auto taxi* with no Ridesharing with full automation
  4) Auto taxi with Ridesharing with full automation

*Auto taxi = Fully automated vehicle providing transportation as a service
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Automation Level</td>
<td>N/A</td>
<td>Partial</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td></td>
</tr>
<tr>
<td>Vehicle Ownership</td>
<td>Private</td>
<td>Private</td>
<td>Private</td>
<td>Shared</td>
<td>Shared</td>
<td>Shared</td>
<td>Shared</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ridesharing</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency Improvement</td>
<td>N/A</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>VMT Demand Impact*</td>
<td>N/A</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>CAV Incremental Cost**</td>
<td>N/A</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

*Includes travel time costs (Low time cost leads to high VMT and thus higher energy use)
**Includes vehicle purchase cost

UB: Upper bound of energy impact (higher energy use)
LB: Lower bound of energy impact (lower energy use)
Assessment Structure: Main factors

Value to Consumers
- Generalized cost of personal travel
- Mobility for underserved

Change in Demand
- Travel by general public
- Travel by underserved
- Sharing
- Mode shifts

Change in Efficiency
- Faster/smooth travel
- Lower loads
- Smaller vehicles
- Platooning

Energy
Explanation of Bar Chart Format for Presenting CAV Features’ Energy and Demand Impacts:

• Reductions: for visualization, the reduction from the original attributed to each feature moves from above to below the x-axis.
• Increments: add on top of the original bar.
• The final height of the bar (in the positive region only) shows the net fuel consumption including all impacts.
Travel Demand May Increase Significantly with Full Automation

<table>
<thead>
<tr>
<th>Total VMT (Trillion)</th>
<th>2.8</th>
<th>3.1</th>
<th>2.9</th>
<th>9.5</th>
<th>3.6</th>
<th>9.5</th>
<th>3.6</th>
<th>9.0</th>
<th>3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total PMT (Trillion)</td>
<td>4.65</td>
<td>5.26</td>
<td>4.84</td>
<td>14.27</td>
<td>5.67</td>
<td>14.27</td>
<td>5.67</td>
<td>14.27</td>
<td>5.67</td>
</tr>
<tr>
<td>Average Occupancy</td>
<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
<td>1.50</td>
<td>1.59</td>
<td>1.50</td>
<td>1.59</td>
<td>1.59</td>
<td>1.85</td>
</tr>
</tbody>
</table>

- Shift from transit, air
- Repositioning (empty travel)
- Underserved
- Faster Travel, Decrease travel time cost
- Ridesharing
- Base VMT
Average Vehicle Fuel Consumption per 100 miles

<table>
<thead>
<tr>
<th></th>
<th>2.8</th>
<th>3.1</th>
<th>2.9</th>
<th>9.5</th>
<th>3.6</th>
<th>9.5</th>
<th>3.6</th>
<th>9.0</th>
<th>3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total VMT (Trillion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total PMT (Trillion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Occupancy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Average Vehicle’s Fuel Consumption per 100 miles driving (Gallon per 100 miles)

- Fast Travel
- Retained Fuel Consumption
- Collision Avoidance
- Vehicle/Powertrain Resizing
- Platooning
- Less Hunting for Parking
- Intersection V2I/I2V Communication
- Drive Profile & Traffic Flow Smoothing
### Total US LDV Fuel Consumption per Year

<table>
<thead>
<tr>
<th></th>
<th>2.8</th>
<th>3.1</th>
<th>2.9</th>
<th>9.5</th>
<th>3.6</th>
<th>9.5</th>
<th>3.6</th>
<th>9.0</th>
<th>3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total VMT (Trillion)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total PMT (Trillion)</td>
<td>4.65</td>
<td>5.26</td>
<td>4.84</td>
<td>14.27</td>
<td>5.67</td>
<td>14.27</td>
<td>5.67</td>
<td>14.27</td>
<td>5.67</td>
</tr>
<tr>
<td>Average Occupancy</td>
<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
<td>1.50</td>
<td>1.59</td>
<td>1.50</td>
<td>1.59</td>
<td>1.59</td>
<td>1.85</td>
</tr>
</tbody>
</table>

**Graph:**
- **Total US LDV Fuel Consumption (Billion Gallons per Year)**
CAVS Can Greatly Decrease Per-mile Costs for LDV Consumers

• In-vehicle time value (less travel time, less stressful, more productive) likely the main selling point to consumers
Preliminary Observations and Conclusions

• Potential energy impacts of partial automation are modest (12% decr to 9% incr)
  – Due mostly to increased mobility
• Potential energy impacts of full automation are large (x 0.2 – 3), as is potential increase in economic welfare

<table>
<thead>
<tr>
<th>Lower Energy Bound</th>
<th>Upper Energy Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low travel demand impact</td>
<td>• High travel demand impact</td>
</tr>
<tr>
<td>• Vehicle downsizing</td>
<td>• Faster travel</td>
</tr>
<tr>
<td>• Traffic smoothing</td>
<td>• Repositioning (empty travel)</td>
</tr>
<tr>
<td>• Ridesharing</td>
<td></td>
</tr>
</tbody>
</table>
Results: Key Questions/Uncertainties Identified So Far

**Light-duty passenger travel**

- How will travel demand change with CAVs?
  - Induced demand, empty vehicle travel, ridesharing
- How will CAVs be adopted (what technologies, what level)?
  - User acceptance, costs
- How will vehicle fuel economy change with CAVs (not including vehicle resizing/redesign)?
- How vehicles will be resized under CAVs scenarios?
- How to expand local/regional studies to national level?
  - By vehicle type & roadway conditions
  - By household

**Heavy-duty vehicles**

- What is energy impact of truck platooning/automation?
  - Adoption levels, fraction of truck vehicle-miles-traveled in platoons
Approach: Implement value component methods to estimate CAV adoption rates

- Quantify utility to consumers within different market segments and resulting impacts on ownership and operation decisions
- Value components:
  - Stress
  - Time
  - Energy
  - Mobility
  - Productivity
- Integrate value components into ORNL’s MA$^3$T model
- Revise MA$^3$T choice structure to include CAV
  - In addition to buy/no-buy a new LDV, add the options of buying a CAV and using AutoTaxis
Approach: Adapt consumer choice model to include CAVs purchase decision

- The choice structure in MA3T will be expanded to include the choice of buying a new ACV and choice of modes
- Nested, multinomial framework:
Increased demand from underserved population can be estimated from survey & census data using exogenous assumptions or economics approaches

- Harper (et al.) estimates total VMT will increase 12% due to increased demand from senior, non-drivers and people with medical conditions using 2009 NHTS data.
- Combing census data and literature on driving by elderly people, we can estimate future reduction in driving by the elderly.
Analysis framework: Conceptual calculation flows

1. **Quantify potential efficiency and travel behavior impacts of CAV features in different driving situations (9E)**
2. **Establish scenarios of different powertrain and CAV feature adoption rates over time**
3. **Calculate national-level roll up from aggregating driving situation impacts by the relative proportion of national VMT each represents**
4. **Transfer regional analyses to estimate national evolution of VMT distributions over time**
5. **Aggregate petroleum and GHG impacts of scenarios**
Aggregate impacts of CAV features nationally

“Rates”
CAV features to provide different fuel economy benefit in different driving situations

“Volumes”
Consider the relative proportion of national VMT represented by each driving situation

Calculate national total energy use and GHG emissions by summing VMT for the entire U.S. road network.
Approach: Use transferability modeling to expand detailed travel simulation results to the national level

- Transfer results from transportation system simulations of CAVs in a metropolitan area

Disaggregate model output:
- Socio-demographics
- Land use / built-environment
- Activity-travel information (trip rate, VMT, mode, activities)

Clustering
Clusters

Baseline regional travel demand model

Cluster analysis: Segment population based on travel variables

Transfer cluster membership and behaviors to national-level data

Calibration/Update

National-level Activity/travel patterns (trip rate, VMT, mode, activities)
Transferability permits use of rich datasets to map travel patterns

• Input data:
  – Disaggregate output from Polaris transportation system simulation
  – US Census American Community Survey
  – Census 2015 TIGER/Line geographic information system (GIS) data
  – National Household Travel Survey (NHTS) 2009

• Individual-level variables:
  – Age groups
  – Gender
  – Race/ethnicity
  – Marital status
  – Education level
  – Job category

• Household-level variables
  – HH size
  – HH income
  – No. adults, workers, vehicles
  – HH members by race/ethnicity
  – HH members by educ. level
  – HH members by occupation type
Travel patterns can be transferred to households with similar characteristics

• Derive transferable variables such as total trip rates, commute distance, trip rates by various modes and with different purposes
• Cluster individuals into several homogeneous groups representing various lifestyles, utilizing rule-based Exhaustive Chi-squared Automatic Interaction Detector decision tree for each transferable variable
  – This is a flexible approach to define clusters that makes efficient use of information without requiring too many clusters
• Fitting the best statistical distribution to each one of the final decision tree clusters
• Transferring cluster membership to the national level to map travel patterns to appropriate households nationwide
Response to Reviewer Comments

• This project is a new start
Collaborations

• Close collaboration with the related VTO project VAN022 (ANL, NREL, ORNL)
  – Defining scenarios and assumptions for case studies
  – Will take results and roll up to national level

• Informal collaborations with wider research community through TRB subcommittee and Automated Vehicle Symposium
Remaining Challenges and Barriers

• Further develop expansion aggregation methods and apply these to simulation results
  – Transferability of travel patterns
  – Mapping CAV efficiency to routes throughout U.S.

• Estimating potential adoption of CAVs technologies by different population segments

• Assessing CAVs impacts in other transportation sectors (heavy-duty vehicles)
Proposed Future Work

• Expand transferability modeling to additional travel characteristics
• Estimate possible utilization of CAVs by different user groups
• Analyze potential platoon formation by long-haul trucks
• Analyze results of CAVs scenario simulations and roll up to national level
  – Connected vehicles in urban environment (traffic smoothing)
  – Connected vehicles on highways (CACC, platooning)
  – Automated vehicles in urban environment (driverless taxis, with/without ridesharing)
Summary

• The future of CAVs is very uncertain; key unknowns include impacts on
  – Travel demand
  – Vehicle use/ownership, CAVs adoption
  – Coevolution of vehicles with automation and connectivity
• Simulation and analyses of well-defined scenarios need to be
  synthesized into consistent, national-level assessments of potential
  impacts
• Important data gaps have been identified to help define scenarios and
  case studies to analyze next
• Synthesis approaches are being developed
  – Consumer value/adoption
  – Disaggregation by road type
  – Transfer of region-specific results to national scale
• Costs and values of CAV technologies to consumers are being used to
  assess potential adoption by different consumer segments
• These will connect projected outcomes to policy and technology
  drivers