Impact of Connection and Automation on Electrified Vehicle Energy Consumption

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Connected & Automated Vehicles

Multi-objective optimization of energy, mobility & safety

Automated Driving relies on a broad range of onboard sensors

Connected Driving Uses Communication with the infrastructure (V2I), other vehicles (V2V) and the cloud

CAVs: Connected & Automated Vehicles will use both automation and connectivity

Source: Praveen Chandrasekar, Frost&Sullivan, Leveraging ADAS to leapfrog in the Automated Driving space
Tomorrow’s Transportation Will Feature a Rich Combination of Technologies

- Various powertrains
- Various level of vehicle automation
- Various ITS technologies
- Various levels of communication

Diagram:
- Dynamic light sequencing
- Signal Broadcasting
- Eco-Approach
- Platooning
- Adaptive Cruise Control
- Variable Speed Limit
- Traffic Management Center
- HEV
- PHEV
- EV
- V2V
- V2I
Electric Drive Vehicles Could Benefit from CAVs Technologies from Connectivity and Automation

• Route Based Control would allow lower fuel consumption by optimizing electric consumption throughout a trip.
• Opportunity for optimal powertrain design and speed control
• Knowing location of charging stations, their status as well as the vehicles’ battery SOC would provide helpful information to drivers (i.e., when should they charge, where is the closest charging point...)
• Drivers could reserve charging stations in advance (i.e., shopping, restaurants...) or know when one becomes available as soon as a car is charged (i.e., work)
But Connectivity & Automation Could Also Lower the Energy Savings Potential of xEVs

- A lot of the CAVs technologies focus on improving traffic flow, leading to lower accelerations & decelerations (i.e. EcoSignal).
- This will improve the efficiency of conventional vehicles much more than that of xEVs that benefit from regenerative braking.
- Since xEVs benefit from deceleration events to recharge the battery, what will be the impact of having smoother a smaller number of deceleration events or even none of them?
Argonne has unique expertise and capabilities, of interest to DOT and DOE for differentiated research. Additional Lab expertise and resources could be leveraged:

- HPC, optimization, vehicle dynamometer testing, test procedure, sensors, cyber security, infrastructure resilience, grid, urban planning, buildings…

### Assumptions

**Market Penetration, Fleet distribution,**

### Mobility

**Polaris Transportation Simulation Model**

### Energy

**High Fidelity Vehicle Energy Consumption**

### National Impact

**National Impact (VISION)**

**Argonne Expertise**
Full Suite of Capabilities Required to Address CAVs Energy Impact

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

Evaluating energy impacts at the national level

Single Vehicle
- Eco-driving
- Eco-Routing
- Route-Based Control

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

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

National Level

POLARIS
At the Vehicle Level, Autonomie is Used to Model Advanced Vehicles

- Autonomie is a Plug&Play system simulation tool developed by Argonne & licensed by Siemens to more than 175 companies and universities worldwide.
- Autonomie has been developed in partnership with General Motors under funding from the US Department of Energy.
- One of the main application of the tool is focused on assessing the energy impact of advanced technologies with a particular focus on xEVs.
- The models and control algorithms have been validated using Argonne’s dynamometer test data.
- More than 50 turn-key vehicles and 120 powertrains are currently available.
Autonomie Vehicle Models Validated with Test Data

Test data from APRF (ANL)

-7
21
35

Control and Performance

- Engine operation target
- Heat capacity estimation
- Mode behaviors

Model Development (Autonomie)

- Engine power demand
- Engine on/off demand
- Engine speed demand
- Motor torque demand
- Battery power demand

Model Validation

- Engine speed (rad/s)
- Engine torque (Nm)
- Vehicle speed (m/s)
- Temperature (°C)
- Engine coolant loop
- Radiator
- Heatercore
- Fan
- Valve
- Teng_temperature
- Tamb_temperature
- Heatercore_temperature

Simulation data
Vehicle Model Validated within Test to Test Uncertainty

- Conv. Fuel consumption (kg)
- HEV Fuel consumption (kg)
- PHEV (CS) Fuel consumption (kg)
- EREV (CS) Fuel consumption (kg)
Vehicle Energy Impact Analysis for Various CAV Scenarios

- Database of recorded GPS traces
- Selection with Energy Criteria
- Speed transformation
- RWDC CAV2
- RWDC CAV1
- SSSpeed cycles
- 3 Midsize vehicles
  - Conventional
  - HEV
  - BEV

Results chart: Fuel Consumption (l/100km or l/100km equivalent) vs Speed (km/h)
Ideal CAVs Use Case -> Steady-State Cycles

- Fuel consumption results obtained with SSSpeed cycles simulations
  - Theoretical representation of the highest connectivity degree
    - No stops and constant speed
Energetic Criteria Used to Select RWDC
Source - Chicago Database

- Database of recorded GPS traces speed include different drivers, different cars...

- **Positive Kinetic Energy (PKE)** is a good driving style indicator:

  \[ PKE = \sum \frac{v(t+1)^2 - v(t)^2}{x} \text{ when } a(t) > 0 \]

  Where:
  - \( v(t) \): speed
  - \( v_m \): mean speed
  - \( a(t) \): acceleration

- Selection of RWDC with:
  - Distance between 2 and 7 km
  - 2 cycles with the same \( v_m \) per ten km/h
  - \( PKE \) close to the average database \( PKE_{avg} \)
    
    - \( 0.95 PKE_{avg}(v_m) < PKE < 1.05 PKE_{avg}(v_m) \)

- 18 RWDC Selected
Connectivity Potential is defined between RWDC and SS Speed Energy Consumptions

- Fuel consumption results obtained with selected RWDC simulations
Connectivity Representation with Stops Removed

- Modifications of the RWDC speed
  - Distance unchanged
  - Transformations:
    1. **Stops removal**
      \[ \Rightarrow \text{Every other stop removed} \]
Connectivity Representation with Speed Smoothing

- Modifications of the RWDC speed
  - Distance unchanged
  - Transformations:
    1. **Stops removal**
       ⇒ *Every other stop removed*
    2. **Traffic Smoothing**
       ⇒ *5s moving average*
Connectivity Representation with Acceleration Saturation

- Modifications of the RWDC speed
  - Distance unchanged
  - Transformations:
    1. **Stops removal**
       ⇒ *Every other stop removed*
    2. **Traffic Smoothing**
       ⇒ *5s moving average*
    3. **Acceleration saturation**
       ⇒ *by -1.5 and 1.5 m/s²*
Connectivity Representation with Speed Transformation

- Modifications of the RWDC speed
  - Distance unchanged
  - Transformations:
    1. **Stops removal**
       \( \Rightarrow \) *Every other stop removed*
    2. **Traffic Smoothing**
       \( \Rightarrow \) *5s moving average*
    3. **Acceleration saturation**
       \( \Rightarrow \) *by -1.5 and 1.5 m/s²*
    4. **Speed point by point transformation**
Two Sets of CAV RWDC Defined

- Modifications of the RWDC speed
  - Distance unchanged
  - Transformations:
    1. Stops removal
    2. Traffic Smoothing
    3. Acceleration saturation
    4. Speed point by point transformation

- 2 CAVs RWDC scenarios:
  - **CAVs RWDC 1** ⇒ Assumptions {1,2,3}
    - No speed point by point transformation
    - 10% PKE decrease
    - Same averaged speed
  - **CAVs RWDC 2** ⇒ Assumptions {1,2,3,4}
    - 12% PKE decrease
    - Average speed increased at low speed
Connectivity Decreases Fuel Consumption Especially at Low Vehicle Speed

- Fuel consumption results obtained with selected CAV RWDC simulations
35 to 50 % Potential Fuel Savings at Low Vehicle Speed

- Potential fuel consumption decrease results obtained with selected CAV RWDC simulations

- BEVs have biggest potential at low speed
Virtual Proving Grounds to Quickly Evaluate the Impact of V2V, V2I... on the Energy

Use cases examples:
- Eco-Approach & Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Route based control
- Impact on traffic flow...

Closed loop control critical for energy and speed optimization
Driving Environments and Vehicle Model

Traffic Environment
• UI provides many objects such as road, car, human, sensor, and signal

Simulink Model
• User needs to change if desired

Visualization & results
• No analysis tool provided

https://www.tassinternational.com/prescan
High fidelity vehicle models from Autonomie can replace PreScan vehicle model placeholders within Simulink.

Simulink Model
- User needs to change if desired.
Adaptive Cruise Control Impact for Multiple Powertrain Configurations

- Adaptive Cruise Control
  - Car1 follows Manhattan cycle
  - Car2, Car3, and Car4 follow the vehicle ahead of each one
  - Autonomie vehicles are applied. Conv(Car1), HEV(Car2 & Car3), and EV(Car4)
At the Fleet Level, Large Transportation System Models are Required to Evaluate CAVs Impact

Use cases examples:
- Eco-Lanes (dedicated freeway, variable speed limits, ECACC...)
- Wireless charging (bus lanes)
- Low Emissions Zones
- Platooning
- Smoother braking
- Mixed vehicle fleet (i.e. HEVs, BEVs + few CAVs)
- Increased VMT due to travel behavior changes
- Charging station location...

Fleet Definition

POL**RIS
Transportation Simulation

Powertrain Simulation

Energy consumption of the transportation network
Integrated Transportation Model (POLARIS)

- POLARIS is an agent-based transportation system model
- Decision making is decentralized. Each traveler has its own goals and behaviors. All aspects of activity and travel are represented in a single model
- Travelers are autonomous and can adopt to current conditions (congestion, mode availability, information available)
- Not restricted to a limited number of market segments (user groups)
- The agent based framework is flexible and can accommodate other types of agents (buildings, authorities, smart infrastructure)

NETWORK MODEL
- Physical laws that govern dynamics of traffic flow Newell’s model
- Managed Lanes
- Controlled intersections (traffic signals)
- Traveler information systems
- Traffic management
- Multimodal travel (Integrated corridor management)
Integrated Transportation System Model (POLARIS)
Individual Activity Travel Patterns Allow Accurate Drive Cycle Evaluation

In Chicago over 46% of time away from home is not at a work or school location.
Evaluating the Energy Impact of an Automation Scenario

3 Scenarios:
- UM: Unmanaged
- ML: Managed lane for heavy-duty trucks
- ML+ACC: Managed lane for trucks, and all trucks have adaptive cruise control (ACC)

Powertrain Technologies
- Each vehicle class has a conventional ICE version (CV) and a hybrid (HEV) version
- Each vehicle template has a unique combination of components and average mass

17,500 Vehicles
- 93.5% Light-Duty
- 7.5% Heavy-Duty

18 km Stretch of Highway in Chicago
25 on- and off- ramps

<table>
<thead>
<tr>
<th>Fleet Scenario</th>
<th>Light-Duty</th>
<th>Heavy-duty</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1 Baseline</td>
<td>3% HEV</td>
<td>0% HEV</td>
</tr>
<tr>
<td>FS2 HEV low</td>
<td>10% HEV</td>
<td>10% HEV</td>
</tr>
<tr>
<td>FS3 HEV high</td>
<td>10% HEV</td>
<td>20% HEV</td>
</tr>
</tbody>
</table>
Evaluating the Energy Impact of an Automation Scenario

- With managed lanes, the savings are lower, and non-existent when ACC is used. This is because braking, and its recuperation, is virtually eliminated.

- Overall fuel savings for trucks:
  - managed lanes (ML): 25%
  - managed lanes + ACC: 40%

- Class 8 hybridization ("mild" with ISG) saves approx. 15% in the unmanaged case; for class 6 ("full HEV"), savings are approx. 20%.

- With managed lanes, the savings are lower, and non-existent when ACC is used (No regen braking)
Conclusion

• A lot of good work has been performed, but since the focus has been for conventional vehicles at the individual level, additional in-depth analysis needs to be performed to assess the impact on energy.
• At the vehicle level using CAV-like RWDC, we showed that,
  – Connectivity decreases fuel consumption especially at low speed
  – 35 to 50 % connectivity potential fuel savings at low speed
    • BEVs have biggest potential at low speed
  – Connectivity doesn’t modify the hybridization potential
• System level analysis has to be performed including uncertainty using new set of tools.
• The potential increase in travel demand could reverse the recent significant gains.
• Advanced vehicle technologies such as electrified vehicles could minimize the impact of the demand effect through fuel energy diversification.
• CAVs could lead to an increase in advanced vehicles market penetration