Potential Energy and Emissions Benefits of Vehicle Automation and Connectivity

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Tools and GIS Session

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Framework for Automated Vehicle Benefits

- “Big picture” of automated vehicle impacts
- Short-term direct impacts
- Longer-term indirect impacts

- Focus on the relationship between the vehicle operations and energy/emissions
- Connected a traffic microsimulation software (PTV Vissim) with EPA’s emission inventory model for highway vehicles (MOVES)
Three-Layered Modeling Framework

Automated Vehicle Technologies in Driving Behavior Models

<table>
<thead>
<tr>
<th>Adaptive Cruise Control (ACC)</th>
<th>Cooperative Adaptive Cruise Control (CACC)</th>
<th>Speed Harmonization</th>
<th>Platooning</th>
</tr>
</thead>
</table>

Microscopic Traffic Simulation Models

i.e. PTV Vissim, Aimsun, INTEGRATION

Modal Vehicle Emissions Models

<table>
<thead>
<tr>
<th>MOVES</th>
<th>CMEM</th>
<th>VT-Micro</th>
</tr>
</thead>
</table>
# SAE J3016 Levels of Automation

<table>
<thead>
<tr>
<th>SAE level</th>
<th>Name</th>
<th>Narrative Definition</th>
<th>Execution of Steering and Acceleration/Deceleration</th>
<th>Monitoring of Driving Environment</th>
<th>Fallback Performance of Dynamic Driving Task</th>
<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Human driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>Human driver and system</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
<td>System</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>All driving modes</td>
</tr>
</tbody>
</table>

https://www.sae.org/misc/pdfs/automated_driving.pdf
Modeling Approach

- Produce 15 random Vissim seeds from speed distribution
- Process Vissim output to create operating mode distributions
- Apply Vissim modeled roadway network in MOVES
- Run MOVES model and analyze emission results
Scenario Development

- Modeled passenger cars on Interstate 91 northbound near Springfield, MA
  - Speeds and traffic volumes from MassDOT
- Modified CACC Driver Model DLL from Turner-Fairbank Highway Research Center (FHWA)
  - Does not include platooning, lane change, or designated lane
- Ran three different microsimulation scenarios in Vissim:
  1) Baseline with default Wiedemann 99 car-following algorithm
  2) All vehicles using CACC driver model
  3) Default Wiedemann 99 algorithm with traffic oscillations set to zero
- MOVES project-level energy and emissions calculated on a per vehicle basis for each scenario
Weidemann Car Following

- A closer following headway
- The reduction of oscillations in driver car following behavior

Capri (2012), International Journal of Traffic and Transportation Engineering
Map of I-91 Network
Input I-91 Traffic Speeds and Volumes

Cumulative Distribution Function of Speeds on I-91 Northbound in April 2017

- Input Cumulative Distribution
- Normal Cumulative Distribution

Input Volumes for I-91 Northbound Network:

1. Locale_ID: 26_NB
   Volume: 2,562

2. Locale_ID: 252152
   Volume: 714

3. Locale_ID: S14-061-281-24
   Volume: 700

4. Locale_ID: R15509
   Volume: 351

5. Locale_ID: R15510
   Volume: 92

6. Locale_ID: 236286_NB
   Volume: 1,045
Network Performance

- Box plots of speeds for each link
  - 25th percentile, median, 75th percentile, mean (red dot)
MOVES Operating Modes

- Vehicle-specific power (VSP) and emissions are well correlated
- VSP is derived from instantaneous speed and acceleration along with other constants such as vehicle mass and aerodynamic drag
  - Microsimulations run at 10 Hz
- MOVES operating modes assigned according to VSP and speed bins
  - Separate op modes for braking (opModeID 0) and idling (opModeID 1)

Beardsley (2011), MOVES Workshop
Vehicle-Specific Power (VSP)

\[ P_{V,t} = \frac{A v_t + B v_t^2 + C v_t^3 + m v_t a_t}{m} \]

In this form, VSP \((P_{V,t}, \text{kW/Mg})\) is estimated in terms of vehicles’:

- speed at time \(t\) \((v_t, \text{m/sec})\),
- acceleration \(a_t\), defined as \(v_t - v_{t-1}\), \((\text{m/sec}^2)\),
- mass \(m\) \((\text{Mg})\) (usually referred to as “weight”),
- track-road load coefficients \(A\), \(B\) and \(C\), representing rolling resistance, rotational resistance and aerodynamic drag, in units of kW-sec/m, kW-sec\(^2\)/m\(^2\) and kW-sec\(^3\)/m\(^3\), respectively.\(^3\)
Operating Mode Distributions

I-91 Springfield Link 101
Link-Level Emission and Energy Impacts

Energy/CO$_2$

PM2.5

Scenario
Baseline
CACC
Wiedemann

Energy Rate (MMBTU/veh/hr)

PM2.5 Emission Rate (g/veh/hr)
Network Emissions and Energy Impacts

**Energy/CO₂**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy Rate (MMBTU/veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
</tr>
<tr>
<td>CACC</td>
<td></td>
</tr>
<tr>
<td>Wiedemann</td>
<td></td>
</tr>
</tbody>
</table>

**PM2.5**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>PM 2.5 Emission Rate (g/veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
</tr>
<tr>
<td>CACC</td>
<td></td>
</tr>
<tr>
<td>Wiedemann</td>
<td></td>
</tr>
</tbody>
</table>
### Minimum/Maximum Impacts

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>CACC from Baseline</th>
<th>Wiedemann from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>THC</td>
<td>-2.2%</td>
<td>22.1%</td>
</tr>
<tr>
<td>CO</td>
<td>2.5%</td>
<td>33.9%</td>
</tr>
<tr>
<td>NOx</td>
<td>-5.6%</td>
<td>10.4%</td>
</tr>
<tr>
<td>VOC</td>
<td>-2.2%</td>
<td>21.2%</td>
</tr>
<tr>
<td>Energy/CO₂</td>
<td>-4.7%</td>
<td>4.7%</td>
</tr>
<tr>
<td>PM2.5</td>
<td>6.8%</td>
<td>39.2%</td>
</tr>
</tbody>
</table>

- **CACC scenario shows mostly benefits from baseline**
  - CO and PM2.5 only have reductions
- **Wiedemann scenario without oscillations often has disbenefits**
  - Possible benefits and disbenefits are approximately equal for NOx, VOC, and Energy/CO₂
Conclusions and Future Work

- **Results**
  - Automated vehicles generally show **less braking**, leave **less headway**, and have **less fluctuations in speed and acceleration** than baseline
  - CACC has less of an effect on energy and emissions in freely flowing traffic
  - Wiedemann oscillation smoothing does not produce much benefit
  - DLL needs to be thoroughly tested and validated

- **Next Steps**
  - **Vary traffic volumes** to simulate more heavily congested scenarios
  - Experiment with **different penetrations of CACC**-enabled vehicles
  - Investigate lane changing capabilities to accommodate merging
Discussion

- **Modeling Recommendations**
  - Update tools to reflect connected and automated vehicle (CAV) technologies
    - Integrate CAV technologies into MOVES driving behavior
    - Add custom operating mode distributions for regulatory analysis

- **Broader Issues**
  - Travel behavior
    - Shared vehicles
    - Shared trips
    - Effect on VMT
    - Parking
  - Vehicle operations
    - Drivetrain technologies (fossil fuel vs. electric)
    - Emission sources (mobile vs. stationary)
For More Information

http://www.dot.gov/

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