Eligibility of vehicle automation and connectivity technologies for credits in fuel economy and GHG regulatory programs

Therese Langer, American Council for an Energy-Efficient Economy

AVS 2017
The American Council for an Energy-Efficient Economy is a nonprofit 501(c)(3) founded in 1980. We act as a catalyst to advance energy efficiency policies, programs, technologies, investments, & behaviors.

Our research explores economic impacts, financing options, behavior changes, program design, and utility planning, as well as US national, state, & local policy.

Our work is made possible by foundation funding, contracts, government grants, and conference revenue.
Compliance credits for automated and connected vehicle technologies

• Idea: Offer manufacturers credits toward compliance with fuel economy/GHG standards based (in theory) on fuel savings through, e.g.:
  • Smoother driving (adaptive cruise control)
  • Reduced congestion (crash avoidance technology)
  • Facilitation of electrification and sharing (autonomous driving)

• But not necessarily a good idea!
Example: crash avoidance technology

• Daimler proposal: Calculate average gallons wasted per vehicle mile in delay due to accidents preventable by a given technology
  • Congestion due to accidents results in extra 6 grams of carbon dioxide per mile on average;
  • Credit crash avoidance tech proportionately—e.g. forward collision warning + adaptive brake assist = 1.0 gpm.

• Draft House bill granting off-cycle credits
  • At least 3 grams per mile for 3 “advanced vehicle” (safety) technologies and 6 gpm for connected vehicle technologies
  • No demonstration of effectiveness offered/required
Average credits granted to date toward compliance with light-duty GHG standard

NB: Bottom of stack is required fleet-average value
Principles for granting off-cycle credits

- Technology must be new and innovative
- Demonstration of emissions reduction/fuel savings must be rigorous and fully documented
- Fuel savings must accrue to vehicle carrying the technology
Additionality of technologies’ energy/emissions benefits

• Test: Would technologies materialize without off-cycle credits?

• Example--automatic emergency braking: Ten major vehicle manufacturers had already committed to making this a standard feature

• Technologies that save fuel on-cycle don’t need to pass this test. Does this make sense? (Yes)
Alternative to off-cycle credits

- Mersky and Samaras (2016)* noted off-cycle credits not suitable for AV technology
- For adaptive cruise control, mimicked following another vehicle on the existing test cycles
- Found -3% to +10% change in average fuel economy, depending on following algorithm; adding appropriate test cycle would incentivize optimization

Real-world testing

• Rather than change test cycles, consider moving to real-world testing
• Technology-neutral, improves program across the board
• Recognizes AV technologies that move individual vehicles toward optimal driving
Fully autonomous vehicles

• Introduce multiple additional possibilities to reduce or increase fuel use
• Policy choices will help determine energy impacts
• But for miles traveled, vehicle occupancy--can fuel economy standards be the right tool? (Unlikely)
• Think bigger!
Recommendations

• Preserve integrity/effectiveness of existing standards
• Ensure changes deliver real-world benefits
• Avoid technology-specific fixes
Recommendations (autonomous vehicles)

• Consider what mobility and land use scenarios we want and consider how autonomous vehicles can help get us there.

• Treat autonomous vehicles like travel behavior change, not fuel economy technology.
Truck CACC Fuel Economy Testing:
Initial Test Track Results

Xiao-Yun Lu and Steven E. Shladover, PATH, U. C. Berkeley
Brian McAuliffe, National Research Council of Canada
Barry Pekilis, Transport Canada
Stefan Bergquist and Aravind Kailas
Matt Hanson, Caltrans
Osman Altan, FHWA

July 11, 2017
Outline

• Background
• CACC Control System Design
• Test Scenarios
• Test Procedures
• Test Results (Weighing Fuel Tanks)
• Alternate Analysis (without Weighing Tanks)
• Conclusions
Project Background

• Cooperative Truck Platooning
  – The prototype system tested is based on Cooperative Adaptive Cruise Control (CACC) technology
  – Multiple vehicles using 5.9 GHz DSRC based V2V communications and forward sensors to help maintain a constant Time-Gap between vehicles
  – Level 1 automation: driver steering

• Potential Benefits
  – Improved fuel economy
  – Reduced emissions
  – Improved road-use efficiency
  – Reduce driver workload
CACC Control System

Dual Antenna

DSRC radio

Ethernet

PAT H
Linux Laptop

Ethernet

Fused sensor data

Volvo XPC: sensor data processing

J-Bus interface

J-Bus

Engine/engine control commands

Tablet DVI

Video recording computer

PC-104
QNX RTOS

Fused sensor data
Truck CACC Test Scenarios

- Fuel consumption measurements based on SAE J1321
  - Time Gap (T-Gap):
    • 1.5s, 1.2s, 0.9s, 0.6s
  - Standard trailer vs. aerodynamic trailer
    • Boat tails & Side skirts
  - With/without ballast (rolling resistance)
    • 65,000lbs & 29,000 lbs
  - Maximum speed:
    • 65mph vs. 55mph
Test Procedures

- Synchronized operation of 3 trucks using CACC
- A control truck at the same speed followed 2 miles behind (as baseline for variations in ambient conditions)
- Single truck constant speed reference runs, 4 trucks drove 1 mile apart
- Weighed auxiliary fuel tanks of all trucks after each run (64 miles)
- Each condition repeated at least 3 times to produce average fuel consumption estimates
Aerodynamics of Cooperative Truck Platooning

- As vehicles approach, they influence the flow-field around each other

Low-speed air-wake of lead vehicle influences trailing vehicle (lower airspeed = lower drag)

High-pressure zone in front of trailing vehicle influences lead vehicle (pushes on the front vehicle)
Aerodynamics of Cooperative Truck Platooning

• As vehicles approach, they influence the flow-field around each other

Magnitude of each effect is dependent on separation distance!

…what happens for a 3-vehicle platoon?

Trailing Vehicle

Middle Vehicle

Separation Distance

Lead Vehicle
Test Track, Trailer Modification, Fuel Tank Removal/Mounting, and Weighing
CACC 0.6s Gap @ 65 mph
Fuel Savings for Individual Trucks (ref. standard truck)

- Lead truck
- 2nd truck
- 3rd truck
Alternate Analysis – without Weighing Tanks

• Data used:
  – Trailers with side skirts and rear end flaps
  – Only in reasonably good weather conditions

• Based on vehicle measurement
  – Cumulative distance from J-1939 Bus speed
  – Cumulative fuel consumption of fuel rate from J-1939 Bus
  – Average Fuel Rate:

\[
\text{Ave Fuel Rate} = \frac{\text{Cumulative fuel Consumption}}{\text{Cumulative Distance}}
\]
Alternate Analysis (65 mph + 65,000 lbs)

- What’s happening at 1.2s might be due to weather (e.g. windy), which we will work on further.
Conclusions

• Collaboration among multiple project partners conserved resources, close cooperation promoted mutual learning

• Truck CACC showed significant energy savings for followers, but not for leader, for selected range of gaps

• Consistent with findings from other research projects

• Test drivers were professionals and enthusiastic about use of the system

• Additional experiments needed for other conditions to show wider range of trends including shorter distance
Travel and environmental impacts of unoccupied VMT in RoboTaxi fleet based on GPS trajectory data

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2 Department of Civil & Environmental Engineering
University of Michigan, Ann Arbor

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Background and Research Question

- Taxi fleets are integral part of public transportation system.
- VMT = vehicle miles travelled
- Occupied VMT → passenger on board (inevitable)
- Unoccupied VMT → empty cruising (undesirable)

Minimizing unoccupied VMT in the operation of Robotaxis

Challenge

Potential Remedy

Energy and environmental impacts?

✓ Fuel Consumption
✓ Well-To-Wheel (WTW) Life Cycle GHG Emissions
Methodology

- Data Driven Approach: GPS Trajectory: Beijing’s taxi fleet
- A sample of 12,400 taxis for three days
  - 569,115 passenger trips
  - 3.023 million occupied VMT (69%)
  - 1.334 million unoccupied VMT (31%)

Objective: Minimize Unoccupied VMT
Decision variable: Number of Depots

1. Depot Siting
   - Use k-means clustering of Origin/Destination (OD) locations

2. Vehicle Assignment Strategy
   - Trip chaining with respect to vehicle range
Trip Chaining - Intuition

- **Heuristic method:** Greedy Search Algorithm
- Combine multiple passenger trips that are *chainable spatiotemporally* in a vehicle trip

Vehicle Trip
(limited by vehicle range)

- Logic similar to Fagnant & Kockleman (2014)

Unoccupied VMT

Occupied VMT (taxi route)

Origin

Destination
Results

- More depots = less unoccupied VMT
- Insignificant reduction after 100 depots
- More than 20% reduction in WTW emissions of operation

Vehicle range=400 miles
search time=5 min
Results – Electric Robotaxi

- 2016 MB Smart for two
  Battery size = 76 miles

- 2017 Nissan Leaf
  Battery size = 110 miles

- 2017 Tesla Model S P100D
  Battery size = 310 miles

- Unoccupied VMT is sensitive to vehicle range in low number of charging stations but after 100 charging stations sensitivity decreases.
- Larger battery is not meaningfully justifiable
E-Robotaxi – Environmental Impacts

- **Automation + Electrification:** ~40% reduction in WTW GHG emissions, equivalent to 0.7 MMT CO$_2$-eq annually
- Grid mix consists of **96% coal-based** electricity generation!
Conclusions

- Robotaxis can significantly reduce unoccupied VMT if replaced by regular taxis even with a simple dispatch strategy.
- Synergy of vehicle automaton and electrification brings high levels of environmental benefits in decarbonizing the public transportation even if grid is highly carbon intensive.

Reduction in unoccupied VMT could counteract with surplus VMT from induced travel demand or replacing private cars.
A Green Routing Fuel Saving Opportunity Study on Large-Scale Real-World Travel Data

AVS 2017

Lei Zhu, Jacob Holden, Jeffrey Gonder, Eric Wood

National Renewable Energy Laboratory

July 11
Background and Problem Statement

Background

• One particular interest of Automated Vehicle is to choose fuel-efficient routes—“green routing.”

Problem Statement

• The green routing fuel-saving potentials for large-scale real-world travel data have not been discussed.

• Prerequisites
  o Pre-trip fuel consumption estimation method
  o Pathfinding services requires accurate traffic and network data
Background and Problem Statement

• The proposed green routing fuel-saving evaluation framework uses a routing API (i.e. Google Directions API) and an enhanced pre-trip fuel consumption rate estimation method and applies them to a large-scale, real-world travel data set in California.
Methodology

- The green routing fuel-saving opportunity evaluation framework
Methodology

• Enhanced pre-trip fuel consumption estimation method
  o Microscopic FASTSim model -estimated fuel economy for each actual route as ground truth
  o Training a model to estimate fuel consumption rate by average speed, functional class, and road grade
Methodology

Fuel Economy vs. Link Average Speed (by Functional Class)

Fuel Consumption Rate Adjustments vs. Road Grade (by Speed)
Methodology

- Google Directions API provide quality route information for alternative route options.
  - Polyline
  - “Duration in Traffic” – assign a future departure time
  - Distance
  - ...

- USGS Digital Elevation Model (DEM)- elevation and road grade information

- TomTom MultiNet road network- functional class feature.
Experiment and Results Discussion

• Data description
  o 44,805 O/D pairs

• An average of 2.2 API route options per O/D pair
  (For all O/D pairs, a total of 100,031 Google API-procured routes)
Experiment and Results Discussion

• Overall Actual Route Ratio Distribution
  o Potential fuel saving routes- 31% (blue)
  o If an actual route matches one of API routes, the actual route is more likely to be a green route. (No fuel savings versus fuel savings potential (58% vs. 20%).)

Ratio Distribution of Actual Routes

- API greenest route: 58%
- API potential fuel saving route: 11%
- Actual potential fuel saving route: 11%
- Actual outperform route: 20%
**Experiment and Results Discussion**

- **Fuel Consumption and Fuel Savings**
  - Potential fuel saving - 476 gallons
  - 12% of fuel consumption from potential fuel saving actual routes
  - equals 4.5% of the total

![Cumulative fuel consumption chart](chart.png)

- **Cumulative fuel consumption**
  - Actual: 6,718 gallons
  - Green (potential saving): 3,896 gallons
  - Potential saving: 3,420 gallons
  - 12% savings from potential fuel saving actual routes
The green routes sometimes provide time penalties and sometimes offer time savings

- **Time difference** = actual route duration - greenest route duration
  - +: time saving
  - -: time cost

- **Most desirable routes**: Both time and fuel savings (49% of potential routes; 66% of total fuel savings in gallons)

- **Least desirable routes**: require large time penalties to achieve little fuel savings
Experiment and Results Discussion

- The green routes sometimes provide time penalties and sometimes offer time savings
  - **Time difference** = actual route duration - greenest route duration
    - +: time saving
    - -: time cost
  - **Most desirable routes**: Both time and fuel savings (49% of potential routes; 66% of total fuel savings in gallons)
  - **Least desirable routes**: require large time penalties to achieve little fuel savings
Experiment and Results Discussion

• For the least desirable routes
  o (assuming $2.50/gallon)
  o Fuel saving and time cost decrease as value of time increases.
Conclusions

• The framework provides a feasible way to assess potential fuel savings for a large-scale, real-world travel data set.
  o 12% fuel savings estimate for potential routes (or, 4.5% for the entire set of actual routes)
  o 2/3 of fuel savings come from the routes to save both time and fuel

• The framework is transferable and can be developed as an application tool for any locations having real-world travel data.
Thank you!
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Holistic Assessment of the Co-Benefits and Tradeoffs between Safety, Mobility and the Environment for Automated and Connected Vehicles

Matthew J. Barth, Guoyuan Wu, Danyang Tian

July 11th, 2017
Connected and Automated Vehicle Synergies and Tradeoffs of Safety, Mobility, and Environment

Safety & Mobility:
- Collision avoidance
- Increased spacings

Safety & Energy:
- Electronic Brake Lights
- Conservative automated maneuvers

Mobility & Energy:
- CACC
- Higher speeds
Worldwide CAV Applications/Projects

- Smart city Challenge, U.S. DOT, USA, 2016
- ecoDriver, FP7 European project, IFSITAR-COSYS-LIVIC, France, 2015
- Robot Taxi Inc., The Olympics of the future, Japan
- Eco-routing navigation system, 2012: AERIS, 2015, UC, Riverside, CA, USA
- Eco-Cooperative Adaptive Cruise Control (CACC)-Q, Lamar University, TX, USA, 2016
- Advanced Forward Collision Warning, Virginia Polytechnic Institute & State University (Virginia Tech), USA, 2012
- SOCIONICAL, 2007; AUTOPIA, 2011; MINECO/FEDER Project, 2013; Spain
- Cooperative Adaptive Cruise Control, Integrated Vehicle Safety Department, TNO, Netherlands, 2016
- REM 2030, 2016; Online Path Planning, 2016; DLR, Germany

Lane-change warning system, Tsinghua University, China, 2016
Hybrid collision warning systems, Korea Advanced Institute of Science and Technology, Republic of Korea, 2016
Broad Classification of CAV Applications

• **Vehicle-centric:**
  - Distributed/decentralized maneuvers
  - Equipped vehicles that interacting with their surroundings, or vehicles’ ego states

• **Infrastructure-centric:**
  - Centralized surveillance
  - Intelligent Traffic Management Centers (TMC)
  - Roadway infrastructure, e.g., inductive loop detectors, communication-capable roadside units

• **Traveler-centric:**
  - Pedestrians
  - Bicycles
  - Two-wheel wheelchairs

(Photos: Mohamed Zaki, 2014)
A Measure of Effectiveness Performance Oriented Taxonomy

Key MOEs Framework

Safety
- Direct Impact
  - Indicators library:
    - Spacing;
    - Speed difference;
    - Time-to-collision;
    - Queue length;
    - Number of congestion occurrences;
    - Number of detected critical and non-critical conflicts, etc.

Efficiency
- Reliability
- Mobility

Environmental Impacts
- Non-Electric Vehicles
- Electric Vehicles

Social Inclusion & Land Use
- Total Covered Area
- Accessibility
- Special Groups

User Experience
- Driving Comfort

Figure: Overview of the performance measure framework (measures in red are focused in this study)
The survey includes but not limit to:

- Forward collision warning
- Lane-change warning
- Curve warning system
- Emergency Electric Brake Light warning
- Adaptive Cruise Control
- Cooperative Adaptive Cruise Control
- Eco-routing navigation system
- Urban parking management
- Lane speed monitoring
- Queue-end warning
- Local danger warning
- Pedestrian protection system
### Category Summary

**Table:** Category summary in terms of Measures of Effectiveness (MOEs)

<table>
<thead>
<tr>
<th>Category</th>
<th>Safety focused (25)</th>
<th>Mobility focused (18)</th>
<th>Environmental impacts focused (15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S: Safety; M: Mobility; E: Environmental impacts; ↑: Improvement; ?: Unknown, Neutral or Deteriorated</td>
<td>15 out of 25 (60%)</td>
<td>7 out of 18 (39%)</td>
<td>7 out of 15 (47%)</td>
</tr>
<tr>
<td></td>
<td>6 out of 25 (24%)</td>
<td>6 out of 18 (33%)</td>
<td>3 out of 15 (20%)</td>
</tr>
<tr>
<td></td>
<td>3 out of 25 (12%)</td>
<td>4 out of 18 (22%)</td>
<td>4 out of 15 (27%)</td>
</tr>
<tr>
<td></td>
<td>1 out of 25 (4%)</td>
<td>1 out of 18 (6%)</td>
<td>1 out of 15 (7%)</td>
</tr>
</tbody>
</table>
This category summary is based on the most recent literature samples in 2015 and 2016;

Safety is the most important issue among all the connected vehicle applications;

Synergistic effects (in terms of other MOEs) of the single-MOE-focused applications were rarely analyzed;

A trend exists that a portion of connected vehicle applications are being designed to improve more than one MOE (usually two);

Very few application improves all the three MOEs (safety, mobility and environmental impacts) simultaneously;

A combination of different-MOE-focused applications was used to achieve improvement of several aspects of MOEs, instead of fine tuning system parameters of the single application.
Parameters Tuning

Positive synergistic effects can be achieved, in terms of improvement of other MOEs, by fine tuning the system parameters of a single application.
Vehicle-Centric Applications Examples (1)

Forward collision warning with brake assist [16]
- Emergency Electronic Brake Light [17]
- Safe lane-change recommendation [18]
- Lane change warning system [19]
- Chain collision avoidance application [27]
- Lane-departure avoidance [28]
- A cooperative collision avoidance algorithm [29]
- Motorway accident warning [13]
- Cooperative Adaptive Cruise Control [14] [15]
- Lane speed monitoring [26]
- Variable speed limit/speed harmonization [25]

<table>
<thead>
<tr>
<th>Application</th>
<th>Safety Improvement</th>
<th>Mobility Improvement</th>
<th>Environment Impacts Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A lane closure alert</td>
<td>Potential rear-end reduction</td>
<td>Relief of bottlenecks congestion</td>
<td>Unknown</td>
</tr>
<tr>
<td>Cooperative Adaptive Cruise Control (CACC)</td>
<td>Harmonizing the speed of platoons in a safe manner</td>
<td>Increasing the traffic capacity under high penetration rates</td>
<td></td>
</tr>
</tbody>
</table>
Vehicle-Centric Applications Examples (2)

### Applications and Improvements

<table>
<thead>
<tr>
<th>Application</th>
<th>Safety Improvement</th>
<th>Mobility Improvement</th>
<th>Environment Impacts Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-collision system</td>
<td>Time-to-Collision as surrogate collision risk evaluation</td>
<td>Increased stop-and-go behaviors</td>
<td>Safety enhancement probably achieved at the cost of larger GHG emissions</td>
</tr>
<tr>
<td>Emergency Electronics Brake Light (EEBL)</td>
<td>Collision number reduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lane change warning system</td>
<td>Real-time minimum safe distance</td>
<td></td>
<td>Unknown</td>
</tr>
</tbody>
</table>

### Notes
- Forward collision warning with brake assist [16]
- Emergency Electronic Brake Light [17]
- Safe lane-change recommendation [18]
- Lane change warning system [19]
- Chain collision avoidance application [27]
- Lane-departure avoidance [28]
- A cooperative collision avoidance algorithm [29]
- Motorway accident warning [13]
- Cooperative Adaptive Cruise Control [14] [15]
- Lane speed monitoring [26]
- Variable speed limit/speed harmonization [25]
- Eco-driving assistance system [20]
- Adaptive cruise control integrated with hybrid powertrain [21]
- Eco-routing navigation system [22]
- Urban parking allocation [23]
- Online path planning for electric vehicles [24]
Vehicle-Centric Applications Examples (3)

<table>
<thead>
<tr>
<th>Application</th>
<th>Safety Improvement</th>
<th>Mobility Improvement</th>
<th>Environment Impacts Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-Driving application</td>
<td>Integration of various information sources (not validate)</td>
<td>Steady-speed, smooth-deceleration traffic but with longer travel time</td>
<td>Eco-friendly speed</td>
</tr>
<tr>
<td>Intelligent Environment-Friendly Vehicles</td>
<td>Adaptive Cruise Control (ACC)</td>
<td>Unknown</td>
<td>Hybrid powertrain</td>
</tr>
</tbody>
</table>
Case Study: Lane Speed Monitoring (1)

- Simulation network:
  - California SR-91E

- Simulation scenario:
  - 10%, 20%, 50%, 80% are selected as penetration rates of application-equipped vehicles

- MOEs indicators:
  - Average conflict number (safety)
    Surrogate Safety Assessment Model (SSAM)
  - Average speed/average travel time (mobility)
    PARAllel MICroscopic Simulator (PARAMICS)
  - Average fuel consumption (environmental impacts)
    PARAllel MICroscopic Simulator (PARAMICS) + USEPA MOtor Vehicle Emission Simulator (MOVES) model
Case Study: Lane Speed Monitoring (2)

- Radar plots:

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Figure: Radar plots of three normalized MOEs for LSM

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Conclusions

• 10% penetration rate: 8% travel time decrease versus 3% more fuel and higher potential conflict risks;
• 20% penetration rate: similar to 10% penetration rate case;
• 50% penetration rate: barely reduce travel time;
• 80% penetration rate: all MOEs deteriorate

Future directions

• More related future research direction can be inspired by the drawbacks of current applications, e.g., the combination of several applications to overcome disadvantages of a single application;
• Many factors could affect the performance, e.g., penetration rate of application-equipped especially when there is growing trend toward mixed traffic within the next decade.
Road Test of CAV Eco-ACC on Rolling Terrain

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Research Associate, Office of Operations R&D
Federal Highway Administration

Jiaqi Ma, Ph.D.
Research Scientist / Project Manager
Leidos, Inc
This vehicle controller optimizes fuel consumption by giving speed and powertrain commend to CAVs.
Eco-drive Control Breakdown

- Transmission
- Battery Usage
- Power Request Optimization: 8-20% Savings
- Power Efficiency Optimization: 15-25% Savings

Components:
- Powertrain
- Cruise Control
Formulation (Regular Vehicle)

- Cost Function is defined as:

\[ J = \psi(x_{tf}) + \int_{t_0}^{t_f} L(x,F) \, dt \]

- where \( \psi(x_v(T)) \) is the terminal cost and \( L(x_v,u_1) \) is the running cost

\[ \psi(x_{tf}) = \gamma_1 (x_1(t_f) - v_l(t_f-t_0))^2 + \gamma_2 (x_2(t_f) - v_l)^2 \]

\[ L(x,F) = w_1 \frac{\dot{m}_{fuel}}{Cost_{fuel}} + w_2 \frac{(x_2(t) - v_l)^2}{Cost_{mobility}} + w_3 \frac{(F - F_{res})^2}{Cost_{comfort}} \]

\[ \dot{m}_{fuel}(T_e,n,x_2) = \beta_0 T_e n x_2 + \beta_1 T_e + \beta_2 n x_2 + \beta_3 + \beta_4 (n x_2)^2 \]
Formulation (Relaxed PMP Solution)

\[ L = (1 - g_2) \{ (1 - g_1) [(1 - g_0) L_{00}(x, u) + g_0 L_{01}(x, u)] + g_1 [(1 - g_0) L_{10}(x, u) + g_0 L_{11}(x, u)] \} + g_2 L_b(x, F_b) \]

\[ H = g_0 g_1 g_2 G_1 + g_0 g_1 G_2 + g_0 g_2 G_3 + g_1 g_2 G_4 + g_0 G_5 + g_1 G_6 + g_2 G_7 + G_8 \]

where

\[ G_1 = -\{(L_{00} - L_{01} + L_{11} - L_{10}) + \lambda^T (f_{00} - f_{01} + f_{11} - f_{10})\} \]

\[ G_2 = (L_{00} - L_{01} + L_{11} - L_{10}) + \lambda^T (f_{00} - f_{01} + f_{11} - f_{10}) \]

\[ G_3 = -\{(L_{01} - L_{00}) + \lambda^T (f_{01} - f_{00})\} \]

\[ G_4 = -\{(L_{10} - L_{00}) + \lambda^T (f_{10} - f_{00})\} \]

\[ G_5 = (L_{01} - L_{00}) + \lambda^T (f_{01} - f_{00}) \]

\[ G_6 = (L_{10} - L_{00}) + \lambda^T (f_{10} - f_{00}) \]

\[ G_7 = (L_b - L_{00}) + \lambda^T (f_b - f_{00}) \]

\[ G_8 = L_{00} + \lambda^T f_{00} \]

• Control law:

\[ u(t) = (-m \cdot n \cdot \lambda_2(t) - w_1 \cdot m^2 [\beta_0 \cdot n \cdot x_2(t) + \beta_1] + 2 \cdot n \cdot w_3 F_{res}) / (2n^2 \cdot w_3) \]
Eco-ACC on Rolling Terrain Results

![Graph showing fuel consumption and improvement percentages for different road types and optimization methods.]

- Proposed Controller
- Baseline
- Vehicle Dynamics Optimization Only
- Integrated Optimization
- Gear Optimization

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Fuel Consumption (g)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Arterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Arterial (Long)</td>
<td>19.76</td>
<td>45.16</td>
</tr>
<tr>
<td>Collector Road</td>
<td>24.65</td>
<td>19.81</td>
</tr>
<tr>
<td>Collector Road (Long)</td>
<td>26.08</td>
<td>15.32</td>
</tr>
<tr>
<td></td>
<td>45.91</td>
<td>10.72</td>
</tr>
<tr>
<td></td>
<td>51.19</td>
<td>51.42</td>
</tr>
<tr>
<td></td>
<td>49.59</td>
<td>53.74</td>
</tr>
<tr>
<td></td>
<td>66.90</td>
<td></td>
</tr>
</tbody>
</table>

Note: The graphs and data suggest significant improvements in fuel consumption and optimization through proposed controller and integrated optimization methods.
Eco-drive Tests

Field Test

Hardware in the Loop Simulation

2016.12-2017.10

2017.4-2018.4
Connected Automation Platform

Features

Rugged development platform to support connected vehicle and automation research
Data Collection Flow Chart

PC

ETHERNET

PINPOINT GPS

IMU

FLOWMETER

MICRO-AUTOBOX

FUEL RATE

MASS AIR FLOW

CAN LOGGER

ODOMETER

SPEED
Control Implementation

- P = 10
- I = 0.01
- D = 0.1
- Upper Sat = 100%
- Lower Sat = -5%
1. George Washington Pkwy between I-495 and Memorial Bridge (8*2=16mi)
2. River Road: town of Potomac – end (6.5*2=13 mi)
3. Georgetown Pike – test sites (2*2=4 mi)
4. Georgetown Pike (between VA-7 and VA-123) Beltway - Great Falls (4.5 *2=9 mi)
5. US-17 between I-66 and Warrenton (8*2)
## Field Test Results: Georgetown Pike

**WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10S45I1**

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_028*</td>
<td>0.193</td>
<td>200.7</td>
<td>14.09</td>
<td>59.8</td>
<td>0.160</td>
<td>21.2%</td>
<td>163.0</td>
</tr>
<tr>
<td>exp1_029</td>
<td>0.193</td>
<td>206.3</td>
<td>1.203</td>
<td>59.6</td>
<td>0.160</td>
<td>21.2%</td>
<td>163.3</td>
</tr>
<tr>
<td>exp1_030</td>
<td>0.228</td>
<td>357.3</td>
<td>1.003</td>
<td>68.7</td>
<td>0.175</td>
<td>13.8%</td>
<td>163.6</td>
</tr>
</tbody>
</table>

*Braking eliminated from this run

**WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10**

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_031</td>
<td>0.211</td>
<td>200.7</td>
<td>1.937</td>
<td>65.5</td>
<td>0.175</td>
<td>13.8%</td>
<td>163.3</td>
</tr>
<tr>
<td>exp1_032</td>
<td>0.214</td>
<td>222.0</td>
<td>2.115</td>
<td>66.3</td>
<td>0.177</td>
<td>12.8%</td>
<td>162.7</td>
</tr>
</tbody>
</table>

**WESTBOUND WRENCH EFFORT, PID=10,0.01,0.1, PROFILE A10S45**

<table>
<thead>
<tr>
<th>Filename</th>
<th>Total (l)</th>
<th>Max (ml/min)</th>
<th>Min (ml/min)</th>
<th>Average (ml/min)</th>
<th>Total (cut) (l)</th>
<th>Savings</th>
<th>Run Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp1_036</td>
<td>0.215</td>
<td>225.4</td>
<td>1.988</td>
<td>66.9</td>
<td>0.177</td>
<td>12.8%</td>
<td>162.5</td>
</tr>
<tr>
<td>exp1_037</td>
<td>0.217</td>
<td>225.4</td>
<td>1.296</td>
<td>67.3</td>
<td>0.180</td>
<td>11.3%</td>
<td>162.6</td>
</tr>
</tbody>
</table>

Road segment surrounding stoplight was cut from all datasets
Speed Profile: Georgetown Pike

River Rd Northbound Speeds for exp1_056 (2017-04-09)

River Rd Northbound Speeds for exp1_054 (2017-04-09)
More Data for Statistical Analysis
Contact

- Email: jh8dn@virginia.edu

- ResearchGate Link
  - https://www.researchgate.net/profile/Jia_Hu15
  - All my related papers are available through the link
Estimating Energy Efficiency of Connected and Autonomous Vehicles in a Mixed Fleet

Liang Hu, Chaoru Lu, Jing Dong, and Jie Yang

7/11/2017

AVS 2017, San Francisco, CA
Lead vehicle

Car-following models

On-road fuel/energy economy data

Fuel/Energy consumption models

Velocity & Acceleration

Energy efficiency
Lead vehicle follows a driving cycle

- Urban Dynamometer Driving Schedule (UDDS)
  - city test
  - distance: 12 km
  - length: 1369 sec
  - average speed: 31.5 km/h
## Car-following models

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Manual vehicle</th>
<th>CAV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDM(^1)</td>
<td>IDM_CAV(^1)</td>
</tr>
<tr>
<td>Desired velocity (v_0)</td>
<td></td>
<td>33.3 m/s</td>
</tr>
<tr>
<td>Free acceleration exponent (d)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Desired time gap (T)</td>
<td></td>
<td>1.5 sec</td>
</tr>
<tr>
<td>Standstill distance (s_0)</td>
<td></td>
<td>2 m</td>
</tr>
<tr>
<td>Acceleration range (a)</td>
<td></td>
<td>-6 ~ 1.4 m/s(^2)</td>
</tr>
<tr>
<td>Desired deceleration (b)</td>
<td>2 m/s(^2)</td>
<td>2 m/s(^2)</td>
</tr>
<tr>
<td>Coolness factor (c)</td>
<td>—</td>
<td>0.99</td>
</tr>
</tbody>
</table>

\(^1\)Kesting et al., 2010. \(^2\)Shladover et al., 2012.
The proposed car-following model

\[ a_{CAV} = a - \frac{a + \frac{V_n^2 - V_{n-1}^2}{2\Delta x}}{\exp\left(\frac{\Delta x}{s_0 + V_n \times T} - 1 - \alpha \times \frac{V_n}{V_{max}} \times \frac{V_{max} - V_n}{V_{max}}\right)} \]

\[ \alpha = \begin{cases} 
\frac{1}{\ln(position \ of \ the \ target \ CAV)} + 1, & if \ lead \ vehicle \ is \ manual \\
1, & else
\end{cases} \]
Fuel consumption model of GVs

- The VT-Micro fuel consumption model

\[
\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} L_{i,j} v^i a^j \quad \text{for } a \geq 0
\]

\[
\ln FC = \sum_{i=0}^{3} \sum_{j=0}^{3} M_{i,j} v^i a^j \quad \text{for } a < 0
\]

*FC*: instantaneous fuel consumption, mL/s;
*v*: vehicle velocity, m/s;
*a*: vehicle acceleration, m/s²;
*L_{i,j}*: regression coefficients;
*M_{i,j}*: regression coefficients.
Fuel consumption model of GVs

- Calibrated and validated model using OBD-II data

<table>
<thead>
<tr>
<th></th>
<th>$\alpha \geq 0$</th>
<th>$\alpha &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted $R^2$</td>
<td>0.8245</td>
<td>0.6616</td>
</tr>
</tbody>
</table>

### Table

<table>
<thead>
<tr>
<th></th>
<th>$\alpha \geq 0$</th>
<th>$\alpha &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Constant</td>
<td>$v^1$</td>
</tr>
<tr>
<td>Constant</td>
<td>-1.23E+00</td>
<td>6.05E-02</td>
</tr>
<tr>
<td>$\alpha^1$</td>
<td>4.69E-01</td>
<td>3.39E-01</td>
</tr>
<tr>
<td>$\alpha^2$</td>
<td>-4.54E-02</td>
<td>-1.33E-01</td>
</tr>
<tr>
<td>$\alpha^3$</td>
<td>1.34E-02</td>
<td>2.08E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\alpha &lt; 0$</th>
<th>$\alpha^1$</th>
<th>$\alpha^2$</th>
<th>$\alpha^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Constant</td>
<td>$v^1$</td>
<td>$v^2$</td>
<td>$v^3$</td>
</tr>
<tr>
<td>Constant</td>
<td>-7.89E-01</td>
<td>-2.14E-02</td>
<td>5.61E-03</td>
<td>-9.16E-05</td>
</tr>
<tr>
<td>$\alpha^1$</td>
<td>2.83E-01</td>
<td>-1.02E-01</td>
<td>2.01E-02</td>
<td>-4.43E-04</td>
</tr>
<tr>
<td>$\alpha^2$</td>
<td>1.39E-01</td>
<td>-7.45E-02</td>
<td>1.40E-02</td>
<td>-3.44E-04</td>
</tr>
<tr>
<td>$\alpha^3$</td>
<td>9.13E-03</td>
<td>-9.58E-03</td>
<td>2.16E-03</td>
<td>-5.77E-05</td>
</tr>
</tbody>
</table>
Energy consumption model of EVs

- Power-based model considering regenerative braking

\[ EC = b_0 + b_1 VSP + b_2 P_{aux} \]

\[ VSP = v(1.1a + C_{rr}) + C_{aero}v^3 \]

\[ \ln P_{aux} = c_0 + c_1 T \]

- \( EC \): instantaneous energy consumption (+/-), W;
- \( VSP \): vehicle specific power, W/kg;
- \( P_{aux} \): vehicle auxiliary load, W;
- \( v \): vehicle velocity, m/s;
- \( a \): vehicle acceleration, m/s²;
- \( C_{rr} \): rolling resistance coefficient, N/kg;
- \( C_{aero} \): aerodynamics drag coefficient, N s²/m² kg;
- \( T \): ambient temperature, °C;
- \( b, c \): regression coefficients.
Energy consumption model of EVs

- Calibrated and validated model using OBD-II data.

![Graph showing the relationship between estimated and actual trip energy consumption (kWh).]

<table>
<thead>
<tr>
<th>VSP</th>
<th>v</th>
<th>b₀</th>
<th>b₁</th>
<th>b₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0</td>
<td>&lt;12.5</td>
<td>3.22E+03</td>
<td>1.16E+03</td>
<td>2.15E+00</td>
</tr>
<tr>
<td></td>
<td>≥12.5</td>
<td>8.43E+03</td>
<td>7.57E+02</td>
<td>2.60E+00</td>
</tr>
<tr>
<td>=0</td>
<td>&lt;12.5</td>
<td>6.10E+02</td>
<td>-</td>
<td>1.19E+00</td>
</tr>
<tr>
<td></td>
<td>≥12.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>&lt;0</td>
<td>&lt;12.5</td>
<td>7.20E+02</td>
<td>5.58E+02</td>
<td>2.10E+00</td>
</tr>
<tr>
<td></td>
<td>≥12.5</td>
<td>8.12E+03</td>
<td>5.94E+02</td>
<td>2.57E+00</td>
</tr>
</tbody>
</table>
All gasoline-CAVs in the fleet

![Graph showing CAV fuel consumption (L) vs Position of CAVs]

- **Manual**
- **CAV_IDM**
- **CAV_Nissan**
- **CAV_Proposed**

**CAV fuel consumption (L)**

- **Position of CAVs**: 1 to 15
- **CAV_IDM**: -1.6%
- **CAV_Nissan**: -4.0%
- **CAV_Proposed**: -9.0%
One CAV at different position

Fleet fuel consumption change

Position of the CAV

CAV_IDM    CAV_Nissan    CAV_Proposed

Fleet fuel consumption change

Position of the CAV
Different market penetration of CAVs

![Graph showing fleet fuel consumption change vs. market penetration of CAVs for three different models: CAV_IDM, CAV_Nissan, and CAV_Proposed. The graph illustrates how fleet fuel consumption changes with increasing market penetration.]
All electric-CAVs in the fleet

CAV energy consumption (kWh)

Position of CAVs

CAV_IDM  CAV_Nissan  CAV_Proposed

1.9%  2.8%  -2.8%

CAV_IDM  CAV_Nissan  CAV_Proposed

Introduction  Methods  Results  Summary
Summary

- **Gasoline vehicles, UDDS**
  - a CAV fleet consumes less fuel than a manual vehicle fleet;
  - 1 CAV at the front of a mixed fleet has larger impacts on the fleet fuel efficiency;
  - higher % of CAV leads to more fuel savings, but the marginal benefit diminishes after about 30%.

- **Electric vehicles, UDDS**
  - CAV did not show energy saving benefit under urban driving conditions.
Thank you

Corresponding author:
Dr. Jing Dong
jingdong@iastate.edu
Leveraging Shared Autonomous Electric Vehicles as First/Last-Mile Connections for Transit

Farhan Javed, PhD
Tony Zhang
T. Donna Chen, PE, PhD
Cul-de-sac design

People with disability

Lack of pedestrian infrastructure

Bad weather
Data requirements

• Transit Ridership Data
• P&R License Plate Data
• Network Characteristics
• Mode of First/Last Mile Connection

Legend

- Tukwila_Station_Access_Origins
- Tukwila_Station_Access_Dest
- Tukwila_Station_Egress_Origins
- Tukwila_Station_Egress_Dest
- License Plate Data

Access Mode

- Bicycled
- Bus
- P&R
- Walked
- Dropped-off

Sources: ESRI, HERE, Geochart, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, @OpenStreetMap contributors, and the GIS User Community.
Network Mapping/Simulation Visualization
Simulation Environment

- Real time update of vehicle status
- Edge Weighted Digraph for the use of the Dijkstra's Algorithm
- Vehicle capacity constraint (4 seats)
- Service constraint (10 min window)
Results

Fleet Size 200

Number of Vehicles in Use

Time (hours)

Percentage of Trips Served

Average: 92.43%
Results

Average VMT: 181 mi