Energy Impact of CAV—Reducing Estimation Uncertainty with Disaggregate Consumer Choice Modeling

Zhenhong Lin, ORNL
Automated Vehicle Symposium
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We face large uncertainty in CAV energy impact estimates

- 60% to +300% change in fuel use, estimated by the 3-lab joint report (2016)
  - Consumer heterogeneity is largely ignored. Alt fuel is ignored.

- Reducing estimation uncertainty, but why?

![Figure ES-2. Estimated bounds on total U.S. LDV fuel use per year under the base (Conventional) and three CAV scenarios, based on the study’s synthesis approach from CAV feature impact ranges reported in existing literature.](image.png)

Imagine “petroleum-based VMT x 2”

- Induced travel demand from smart mobility can worsen energy & emissions, unless efficiency and clean fuels are promoted
  - CA SB 802, zero-emission requirement for self-driving cars removed just before committee votes on 4/18/2017. Is the requirement necessary or over-sensitive?

- Important to understand market dynamics of fuel and mobility technologies

Market penetration race: “efficiency/clean fuel” vs. “smart mobility”

Figure 10. Influence of each demand and vehicle efficiency effect on total fuel use, for the “Full-With Rideshare-UB” case shown as percentages of total baseline fuel use

Quantify assumption-impact linkages with systems dynamics models

- MA3T-MC modeling goal—to analyze market dynamics/transition of fuel and mobility and the resulting energy impact
- Competition and synergy between electrification, automation and sharing
- Consumer heterogeneity: who will choose what and why?
- R&D planning: what are the near-term bottlenecks and long-term priorities?
- Policy intervention: when and where needed, and how?

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**Scenarios**

- What if shared mobility eliminates first/last-mile inconvenience?
- What if automation increases travel demand?
- What if battery costs $100/kWh by 2030?
- What if fast-charging is strategically offered and level-1 charging is everywhere?
- What if PEV incentives are removed or increased?

**MA3T-Mobility Choice**

**Impact**

- Mobility
- Consumer
- Technology
- Infrastructure
- Policies

**Market Acceptance**

- Sales & Inventory

**Environment**

**Energy**

**Economy**
MA3T-MC choice structure echoes with EEMS future state narratives framework and covers almost all DOE VTO R&D activities

**DOE R&D portfolio**
- advanced batteries and electric drive systems
- lightweight materials
- advanced combustion engines
- alternative fuels
- energy efficient mobility systems


**Figure 4: Future state narratives framework**
- Personal-Automated
- Shared-Automated
- Incremental Change
- Shared-Mobility

**Vehicle Ownership**
- Personal
- Increasing vehicle sharing
- Shared

**Vehicle Control**
- Driver
- Increasing automation

**Increasing vehicle sharing**
- Driver
- Vehicle Ownership
- Shared
Consumer surveys, stakeholder engagement and existing models

• Consumer surveys
  – Advanced PEV Travel and Charging Behavior survey
  – Beijing Household Travel Survey
  – National Household Travel Survey
  – Seattle GPS travel data
  – Northern California Multi-tasking Travel Survey
  – Mobility services cost-benefit calculator (potentially used for survey)
  – WholeTraveler survey

• Industry stakeholder interests
  – “Insurance” value of vehicle features
  – Consumer valuation of efficiency
  – Automation and electrification

• Existing models and capabilities
  – TEDB, Autonomie, GREET, VISION, SERA, the EV Project, Polaris
Heterogenous consumers described by correlated and mobility-relevant attributes

- 1080 consumer segments (being expanded)
  - Area type (rural, urban), income level, household vehicle ownership, home charging availability, lifestyle (e.g. young children, retired, elderly), driving intensity (e.g. frequent drivers with short commute), risk attitude (e.g. innovator vs. late majority),

- Consumer attributes
  - Household annual PMT, VPMT, VMT, shared PMT, trip number, per-trip time, vehicle occupancy, transit access time, transit wait time, commute distance

![Graph showing rural vs. urban in PMT and transit access time](image)

![Graph showing percentage of households owning hybrid or alternative fuel vehicles](image)
Automated vehicles likely more expensive and more efficient

- Key assumption (for model testing purpose only) on fully-automated vehicles
  - 2030: cost x 1.5, fuel rate x 1
  - 2050: cost x 1, fuel rate x 0.5

![CAV efficiency](image)

![CAV incremental cost](image)

MA3T-MC: synergy between vehicle automation and electrification

- Preliminary observation: range-limited BEVs benefit more from automation than efficient technologies (PHEVs and HEVs)
  - Same efficiency gain (assumption) leads to larger energy cost savings for conventional ICE vehicles than for already-efficient PHEV and HEV
  - But for range-limited BEVs, the automation-enabled efficiency gain leads to valuable range extension
Automation improves efficiency, extends electric range and eliminates range anxiety

If automation reduces kWh/mile by 50%, e-range is doubled and range-feasible days increases from 87% to 99%, a $2200/year value based on $50 per infeasible day.

Shown driver example: 21208 mile/year, 35 round-trip commute distance, based on NHTS 2009
Automation value is greater on range extension than on energy cost savings

- Graphs show automation effect on consumer utility by fuel type, for an example driver
- Efficiency improvement from automation leads to energy cost savings and range extension
- Energy savings greater for conventional ICE than for PHEV
- Range anxiety of short-range BEVs can be eliminated
- The above conclusions are subject to driving patterns. Consumer heterogeneity should be considered
Value of automation-enabled range extension worth differs significantly for different driving patterns.
Summary

- MA3T-MC is developed to support scenario analysis of EEMS future narratives framework.
- Preliminary results show that under certain circumstances, automation can OVERALL accelerate BEV acceptance and slow down PHEV/HEV.
- However, the above statement is not valid for all consumer segments, because the value of automation-enabled range extension can be as big as >$2000/year for some consumers and as little as $0 for others due to different driving patterns.
- Consideration of consumer heterogeneity may remove uncertainty factors and thus can potentially reduce energy impact estimation uncertainty (to be tested).
Truck CACC Fuel Economy Testing: Initial Test Track Results

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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
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?
Test Track, Trailer Modification, Fuel Tank Removal/Mounting, and Weighing
CACC 0.6s Gap @ 65 mph
**Test Results** - **NRC Canada Fuel Saving Estimates** (65 mph + 65,000 lbs)

**Fuel Savings for Individual Trucks**
(ref. standard truck)

- 3rd truck
- 2nd truck
- lead 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.

Following Distance [m] or Time Gap [s]
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
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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 day
  - 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)
Results

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

Trip Chaining via Greedy Search Algorithm

Mean of Unoccupied VMT

Vehicle range = 400 miles
Search time = 5 min

Environmental Impacts

% Change in total VMT, GHG emissions, and fuel consumption
Results – Electric Robotaxi

- 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

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

Trip Chaining via Greedy Search Algorithm (Electric Robotaxis)

- Regular Taxis
- Range= 76 miles
- Range= 110 miles
- Range= 310 miles

Mean of Unoccupied VMT x 100000 vs Number of Charging Stations
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 automation 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

• 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

Initialization → API query → Map matching → Fuel consumption estimation → Similarity assessment → Fuel saving analysis
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**
  - 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
  - Potential fuel saving routes - 31% (blue)
  - 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%).)
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)
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

- The green routes sometimes provide time penalties and sometimes offer time savings
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  - **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, IFSTTAR-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
- Hybrid collision warning systems, Korea Advanced Institute of Science and Technology, Republic of Korea, 2016
- Lane-change warning system, Tsinghua University, China, 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
A Measure of Effectiveness Performance Oriented Taxonomy

Key MOEs Framework

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

Efficiency
- Reliability
- Mobility
  - Flow;
  - Queue length;
  - Average travel time;
  - Average parking search time;
  - Average/total speeds;
  - Vehicle-miles-traveled;
  - Vehicle-hours-traveled;
  - Delay;
  - Number of stops;
  - On-time performance;
  - Level of service;
  - Volume to capacity ratio, etc.

Environmental Impacts
- Non Electric Vehicles
- Electric Vehicles
  - Fuel consumption;
  - Energy consumption;
  - Pollutant emissions;
  - Number of stops;
  - Average speed, etc.

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

User Experience
- Driving Comfort

Figure: Overview of the performance measure framework (measures in red are focused in this study)
Survey Taxonomy

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 focus</th>
<th>Safety focused (25)</th>
<th>Mobility focused (18)</th>
<th>Environmental impacts focused (15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety focused</td>
<td><img src="image" alt="Safety Improvement" /> ?</td>
<td><img src="image" alt="Safety Improvement" /> ?</td>
<td><img src="image" alt="Safety Improvement" /> ?</td>
</tr>
<tr>
<td>Mobility focused</td>
<td><img src="image" alt="Mobility Improvement" /> ?</td>
<td><img src="image" alt="Mobility Improvement" /> ?</td>
<td><img src="image" alt="Mobility Improvement" /> ?</td>
</tr>
<tr>
<td>Environmental impacts focused</td>
<td><img src="image" alt="Environmental Improvement" /> ?</td>
<td><img src="image" alt="Environmental Improvement" /> ?</td>
<td><img src="image" alt="Environmental Improvement" /> ?</td>
</tr>
<tr>
<td>Safety focused count</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>Mobility focused count</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>Environmental impacts focused count</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>Safety focused rating</td>
<td>(60%)</td>
<td>(33%)</td>
<td>(47%)</td>
</tr>
<tr>
<td>Mobility focused rating</td>
<td>(24%)</td>
<td>(33%)</td>
<td>(20%)</td>
</tr>
<tr>
<td>Environmental impacts focused rating</td>
<td>(12%)</td>
<td>(22%)</td>
<td>(27%)</td>
</tr>
</tbody>
</table>

S: Safety; M: Mobility; E: Environmental impacts; ↑: Improvement; ?: Unknown, Neutral or Deteriorated
Category Summary Conclusions

- 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.
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]

Safety

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]

Mobility

Safety Improvement

Potential rear-end reduction
Relief of bottlenecks congestion

Mobility Improvement

Harmonizing the speed of platoons in a safe manner
Increasing the traffic capacity under high penetration rates

Environment Impacts Improvement

Unknown

<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)

<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>
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>

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- Emergency Electronic Brake Light [17]
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- 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]
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)
    PARAmeter MICroscopic Simulator (PARAMICS)
  - Average fuel consumption (environmental impacts)
    PARAmeter MICroscopic Simulator (PARAMICS) + USEPA MOtor Vehicle Emission Simulator (MOVES) model
Case Study: Lane Speed Monitoring (2)

- Radar plots:

Figure: Radar plots of three normalized MOEs for LSM
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.