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

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Automated Vehicle Symposium

July 3rd, 2017

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?

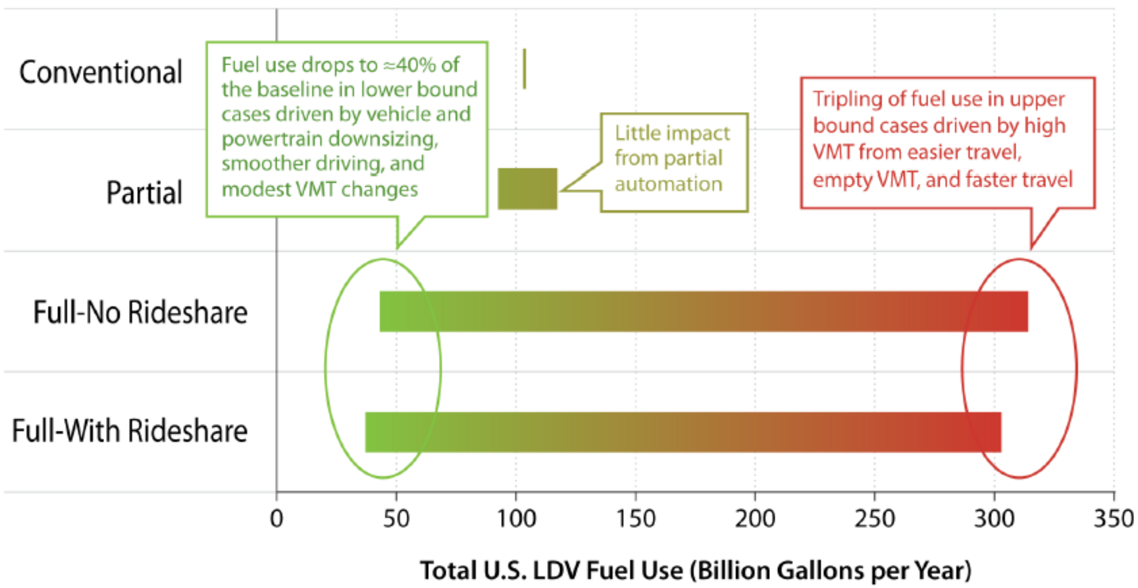


Figure ES-2. Estimated bounds on total U.S. LDV fuel use per year under the base (Conventional) and three CAV scenarios, based on the study's synthesis approach from CAV feature impact ranges reported in existing literature

Source: T. Stephens, et. al. 2016. "Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles". NREL/TP-5400-67216

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

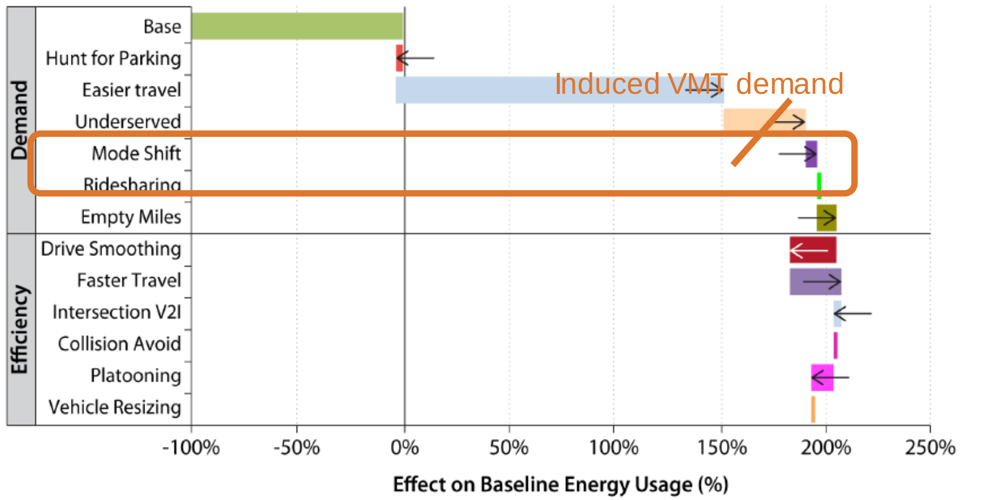
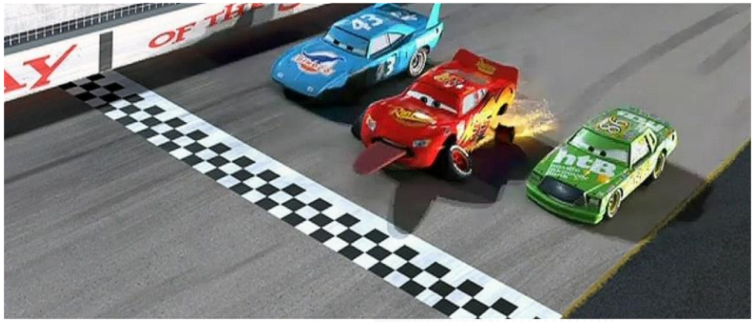


Figure 10. Influence of each demand and vehicle efficiency effect on total fuel use, for the "Full-With Rideshare-UB" case shown as percentages of total baseline fuel use

Source: T. Stephens, et. al. 2016. "Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles". NREL/TP-5400-67216

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



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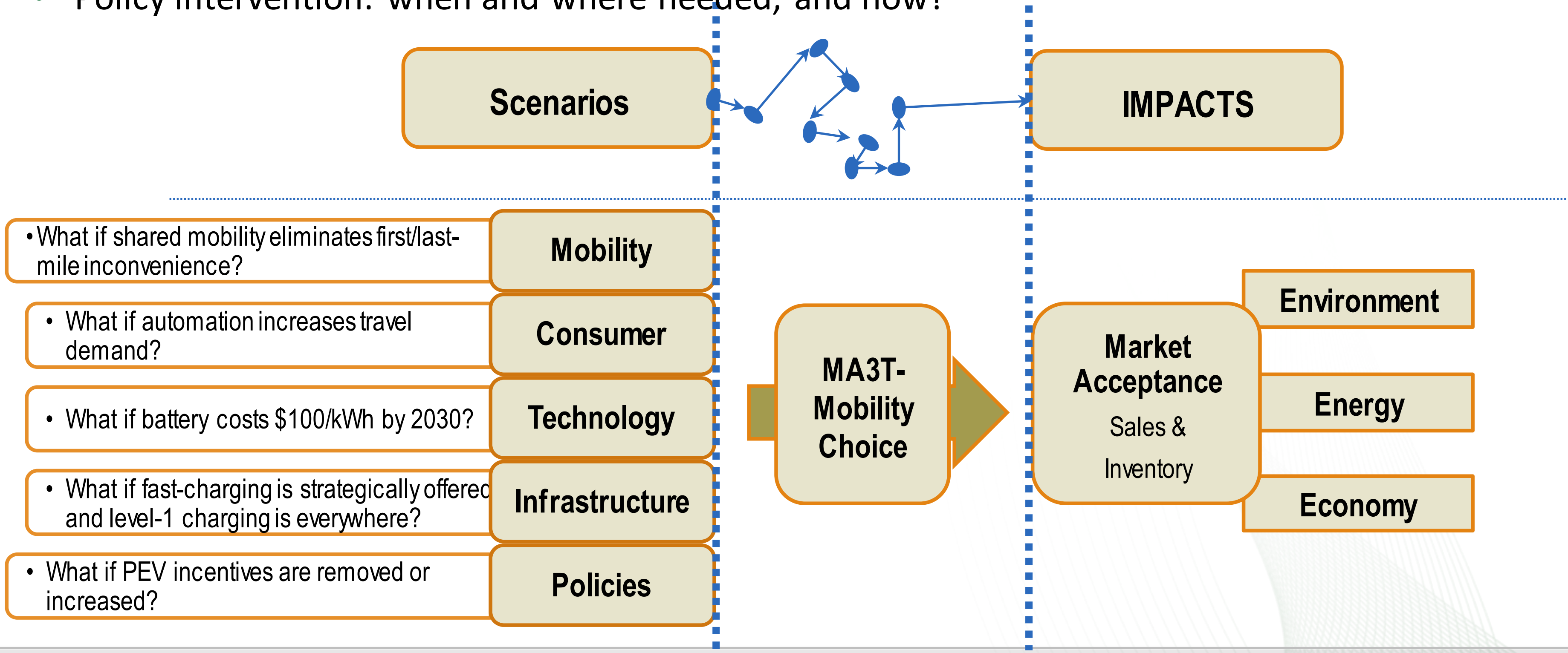
Quantify assumption-impact linkages with systems dynamics models

- 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?



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

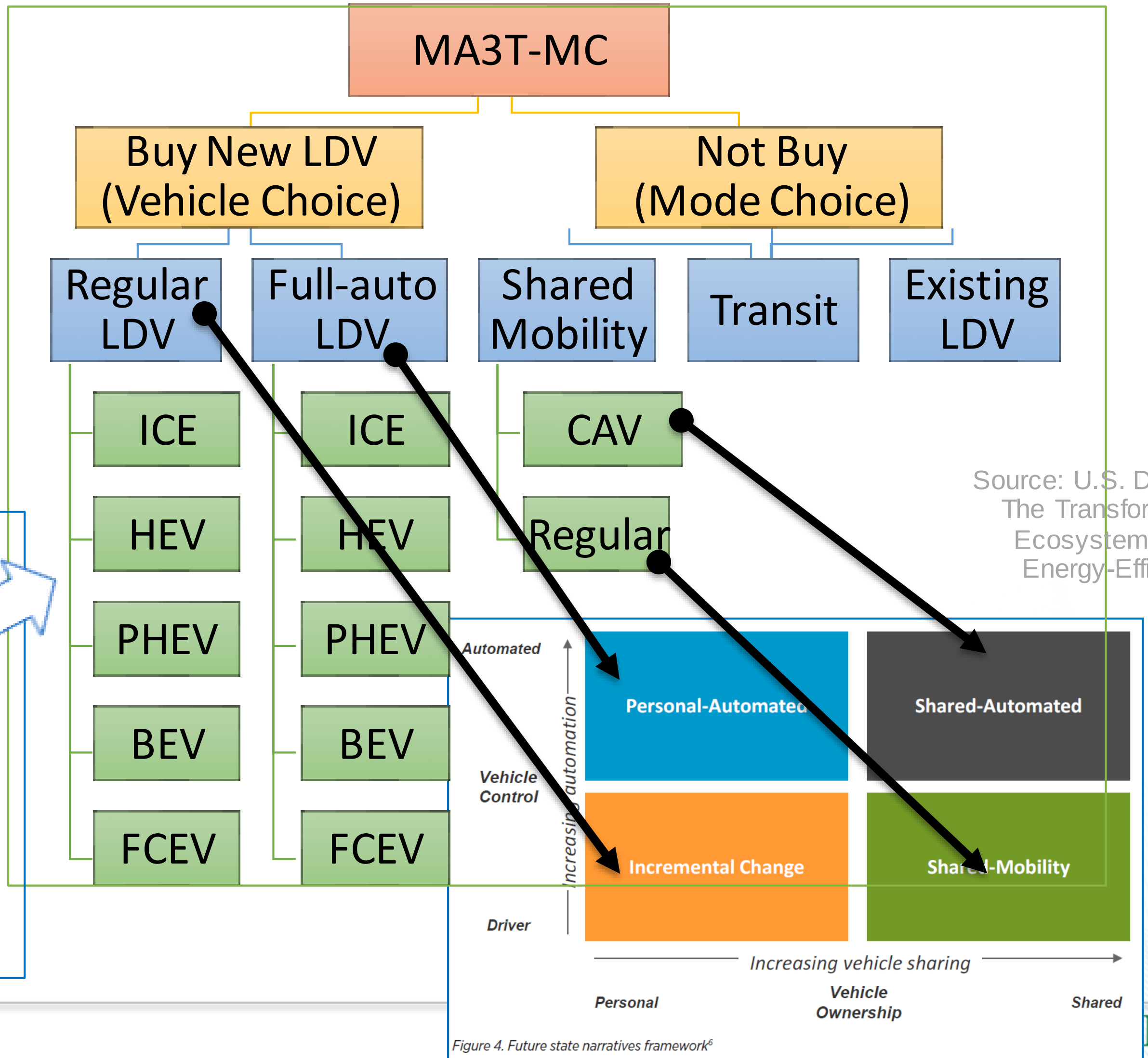


Figure 4. Future state narratives framework[6]

Source: U.S. DOE/EERE 2017. The Transforming Mobility Ecosystem: Enabling an Energy-Efficient Future

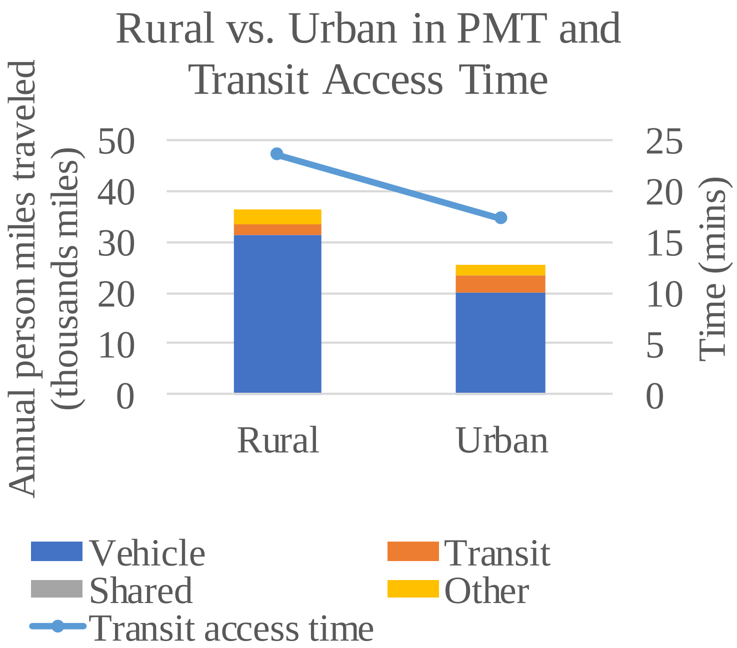
DOE R&D portfolio
- advanced batteries and electric drive systems
- lightweight materials
- advanced combustion engines
- alternative fuels
- energy efficient mobility systems

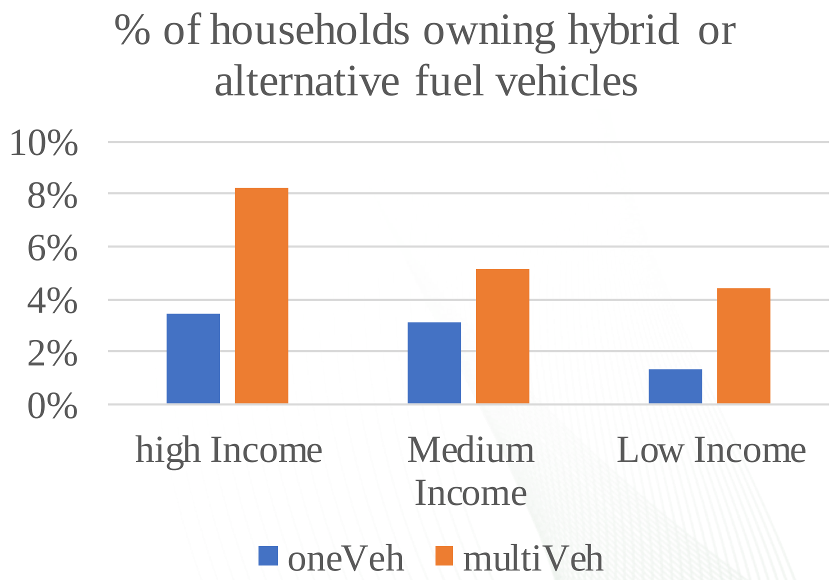
Consumer surveys, stakeholder engagement and existing models

- 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





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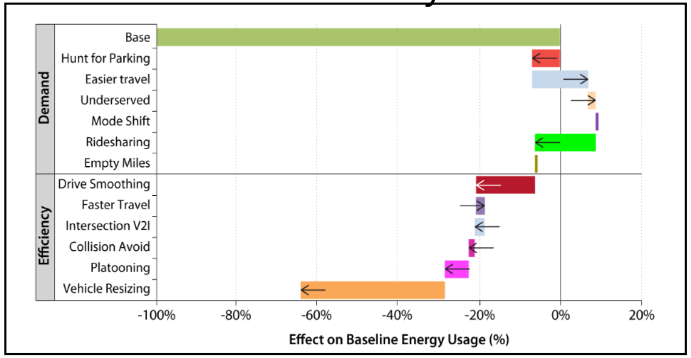
Automated vehicles likely more expensive and more efficient

- 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



CAV incremental cost

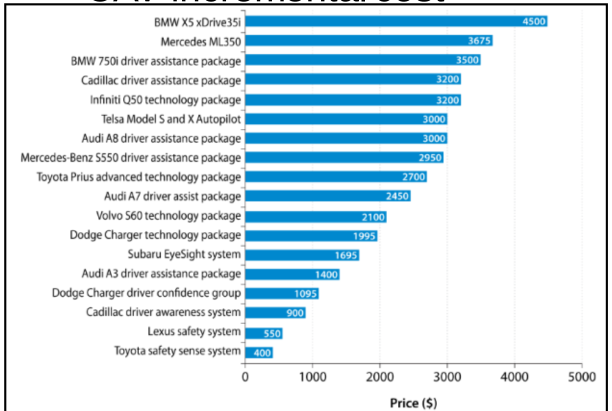
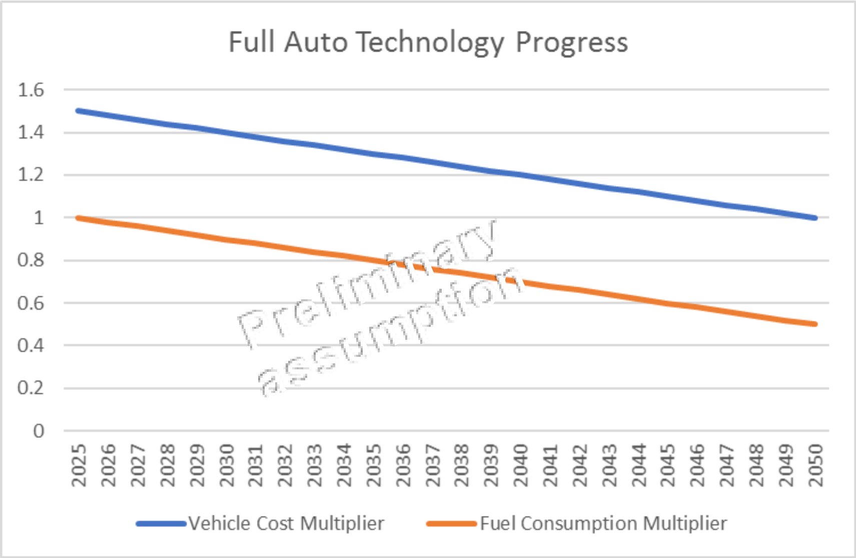


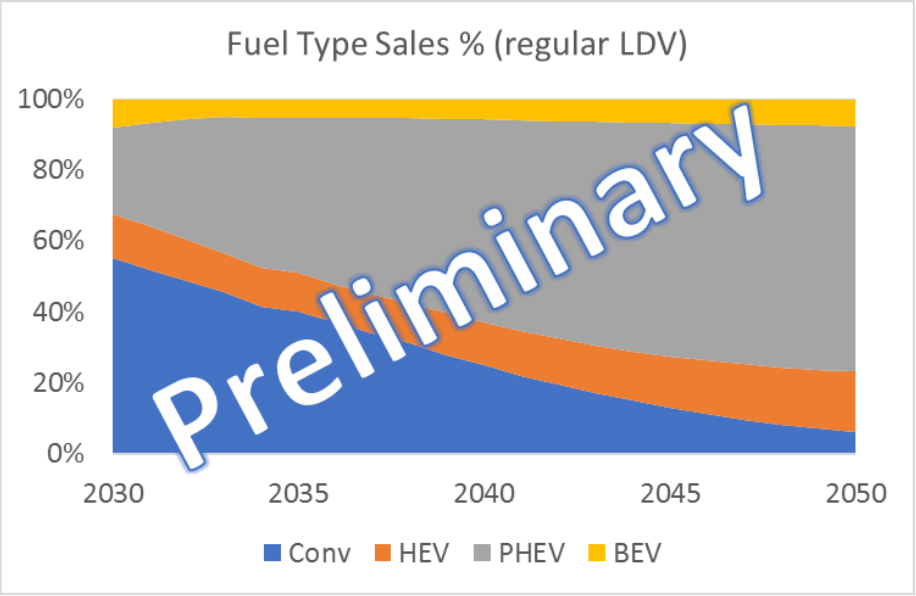
Figure 9. OEM pricing of different driver assistance packages

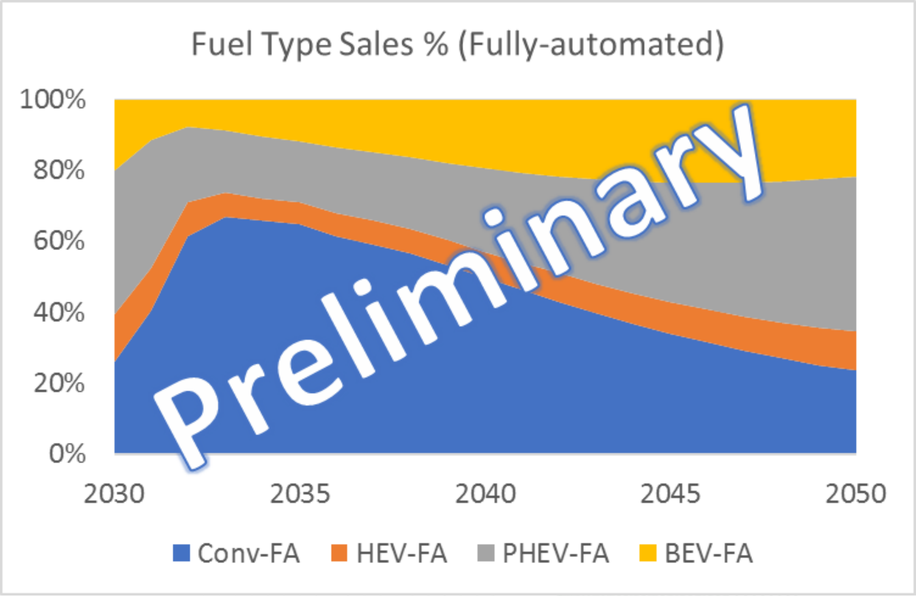


Source: T. Stephens, et. al. 2016. “Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles”. NREL/TP-5400-67216

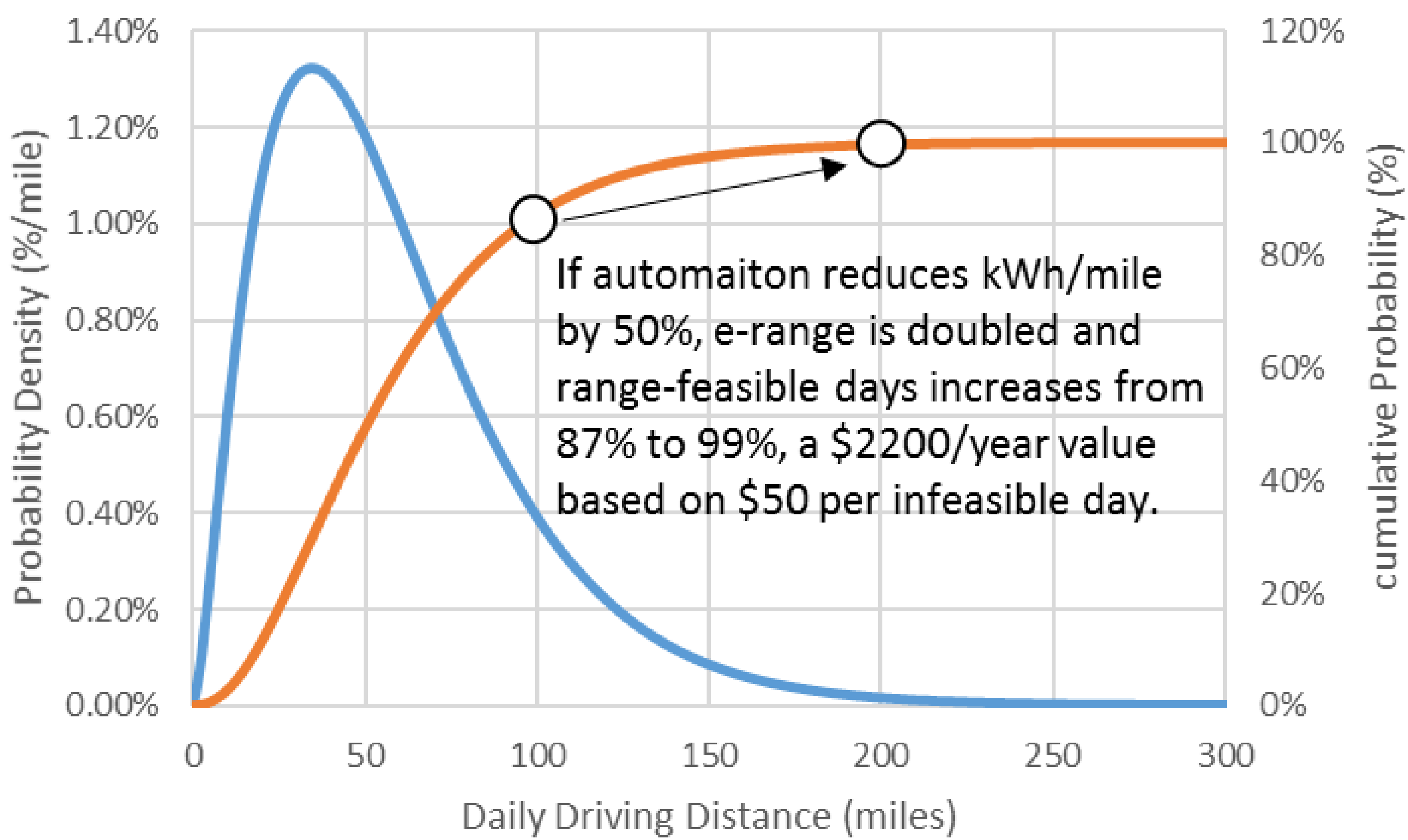
MA3T-MC: synergy between vehicle automation and electrification

- 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



Shown driver example: 21208 mile/year, 35 round-trip commute distance, based on NHTS 2009

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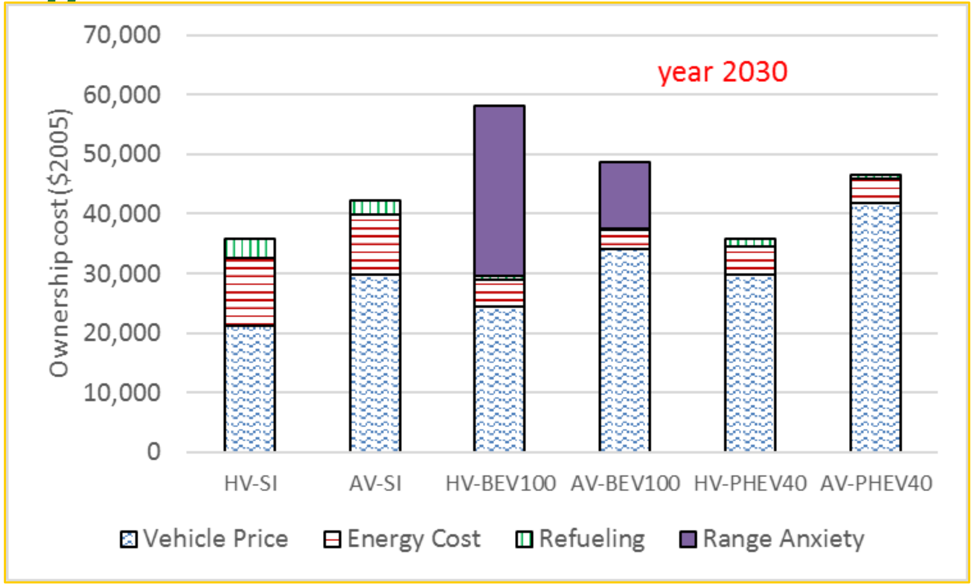
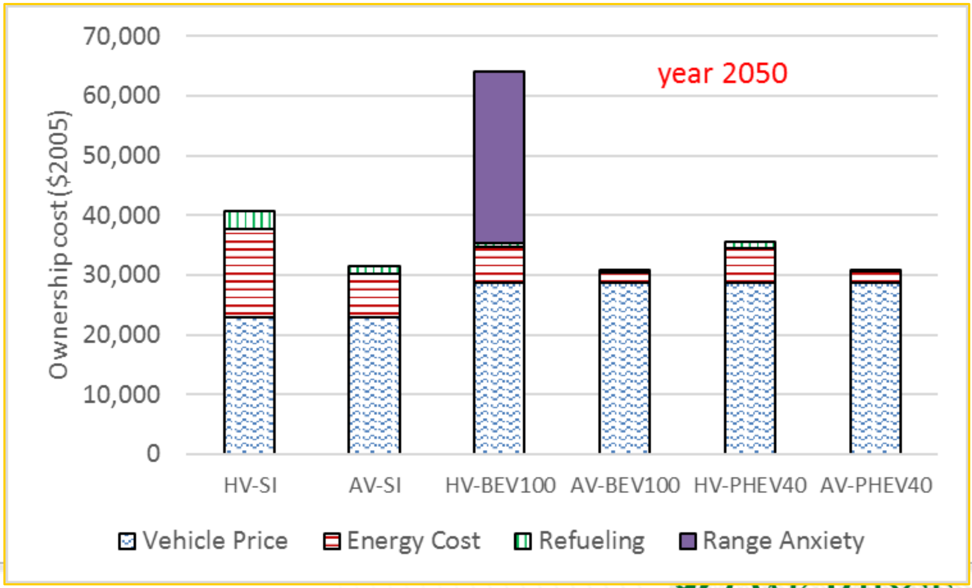
Automation value is greater on range extension than on energy cost savings

- 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





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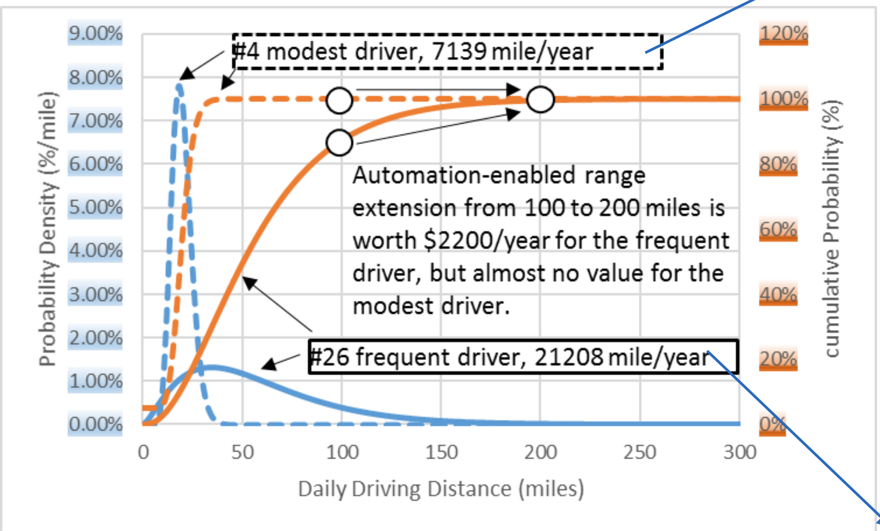
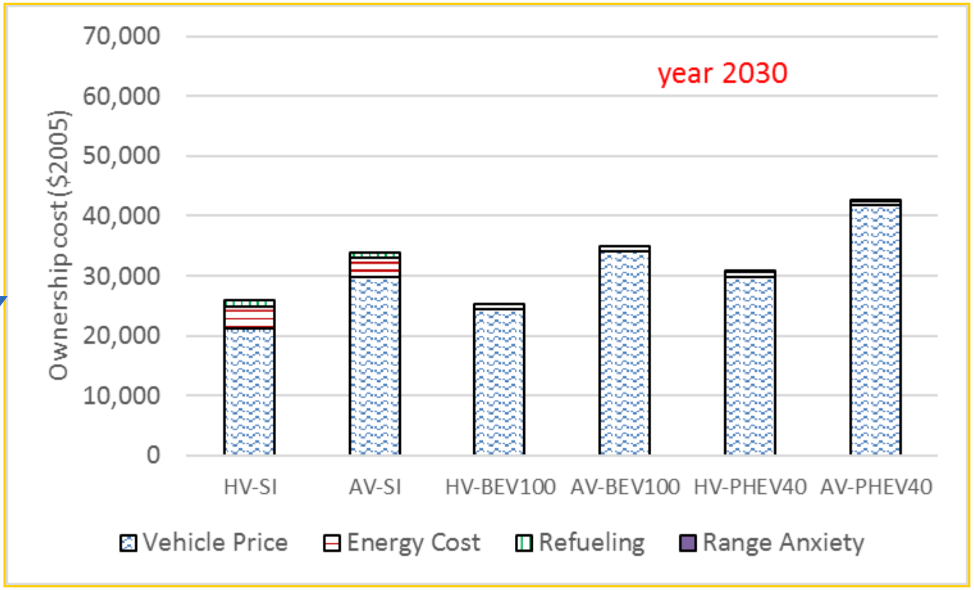
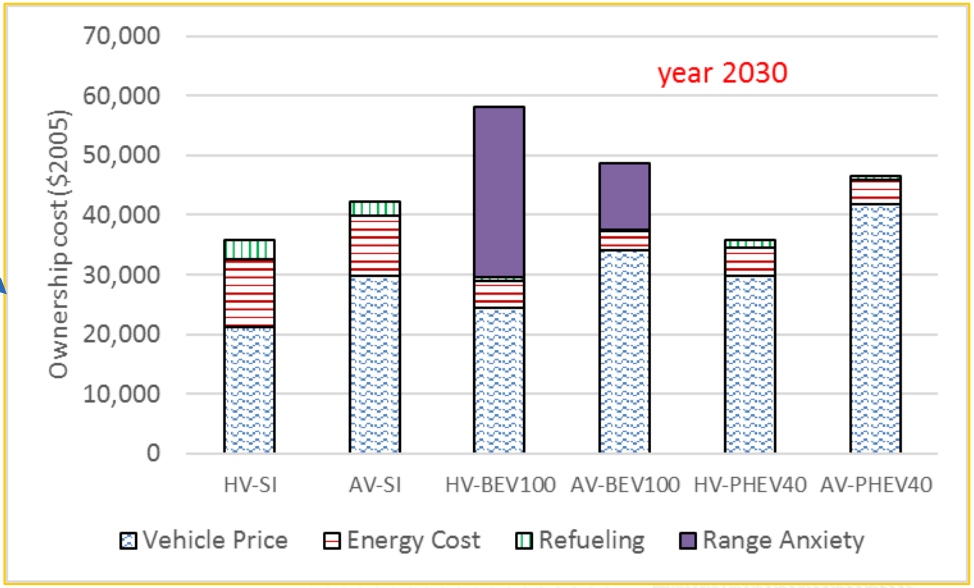
Value of automation-enabled range extension worth differs significantly for different driving patterns







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).

BREAKOUT SESSION

AUTOMATED VEHICLES SYMPOSIUM 2017

USERS. VEHICLES. INFRASTRUCTURE.

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

Transport Canada

Stefan Bergquist and Aravind Kailas

VOLVO

Matt Hanson, Caltrans

Caltrans

Osman Altan, FHWA

July 11, 2017

CALIFORNIA PATH

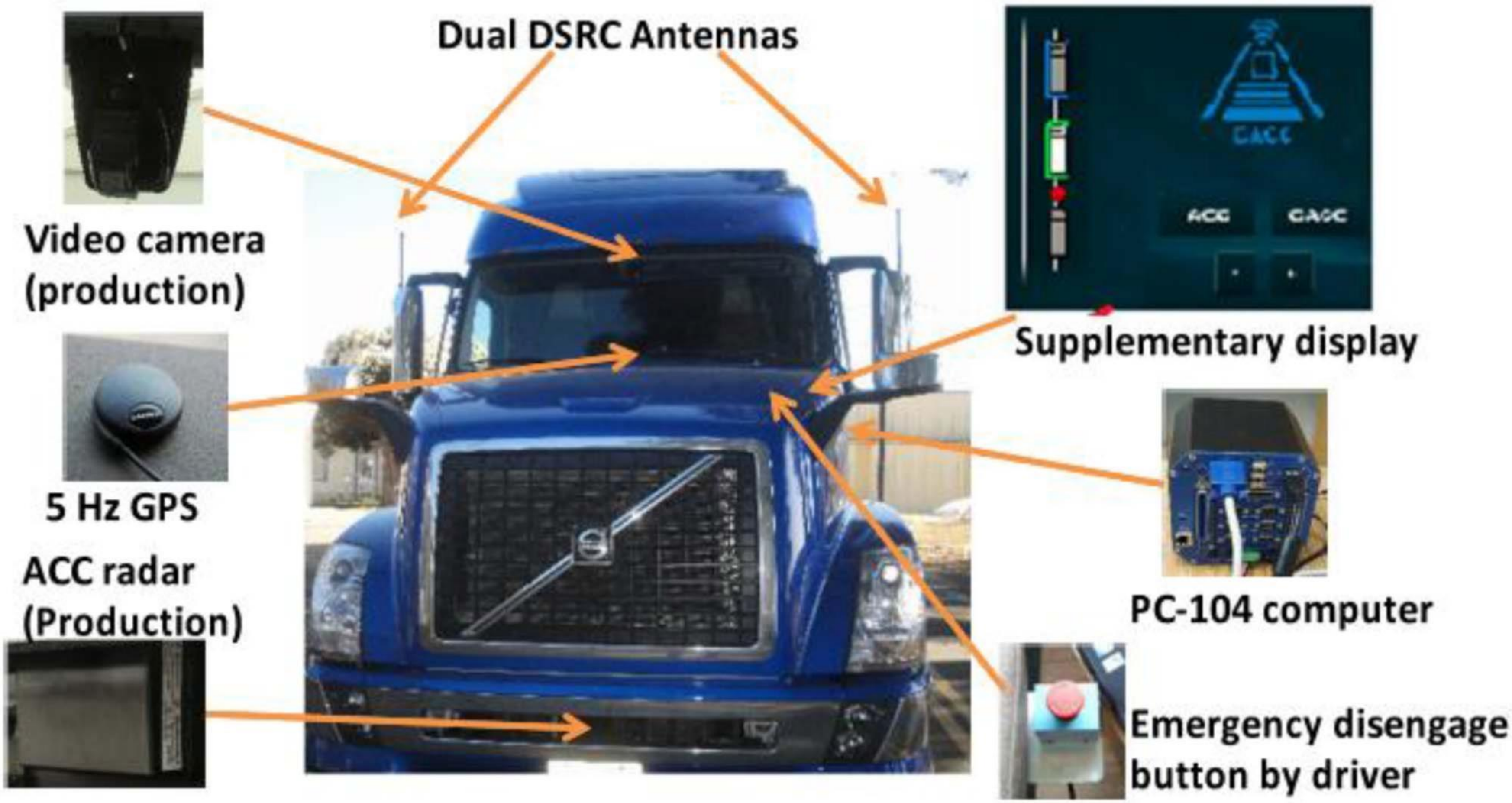
Outline

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

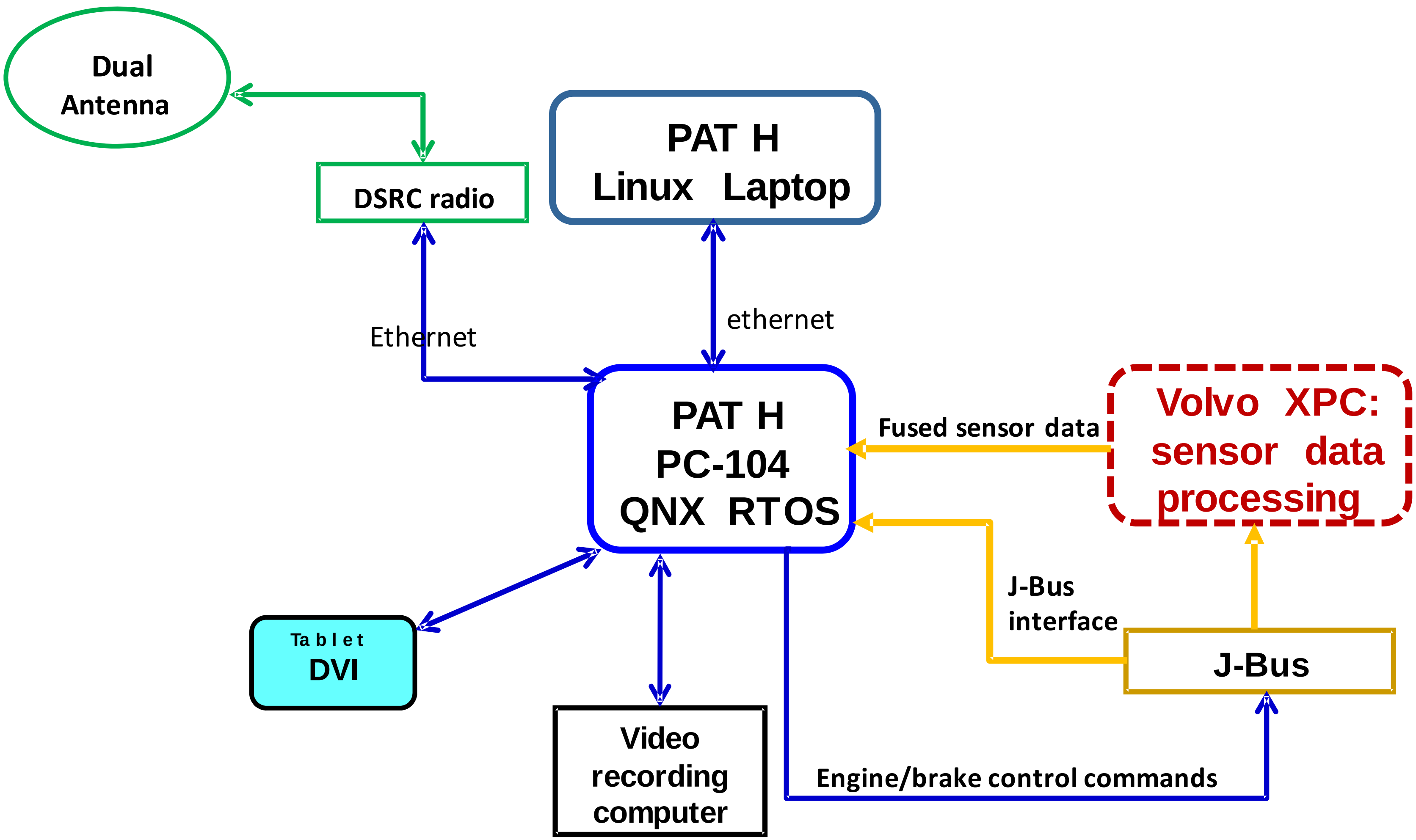
Project Background

- 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 System Design – Structure



CACC Control System



Truck CACC Test Scenarios

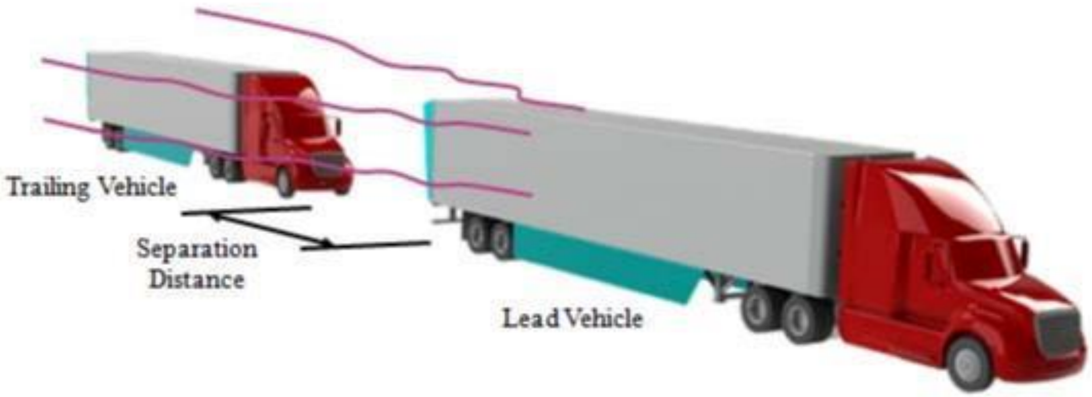
- Fuel consumption measurements based on SAE J1321
  - Time Gap (T-Gap):
    - 1.5s, 1.2s, 0.9s, 0.6s
  - Standard trailer vs. aerodynamic trailer
    - Boat tails & Side skirts
  - With/without ballast (rolling resistance)
    - 65,000lbs & 29,000 lbs
  - Maximum speed:
    - 65mph vs. 55mph

Test Procedures

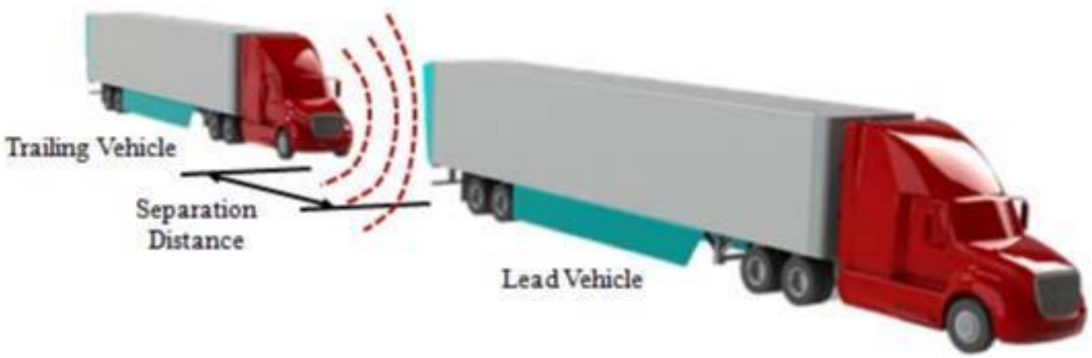
- **Synchronized operation of 3 trucks using CACC**
- **A control truck at the same speed followed 2 miles behind (as baseline for variations in ambient conditions)**
- **Single truck constant speed reference runs, 4 trucks drove 1 mile apart**
- **Weighed auxiliary fuel tanks of all trucks after each 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)



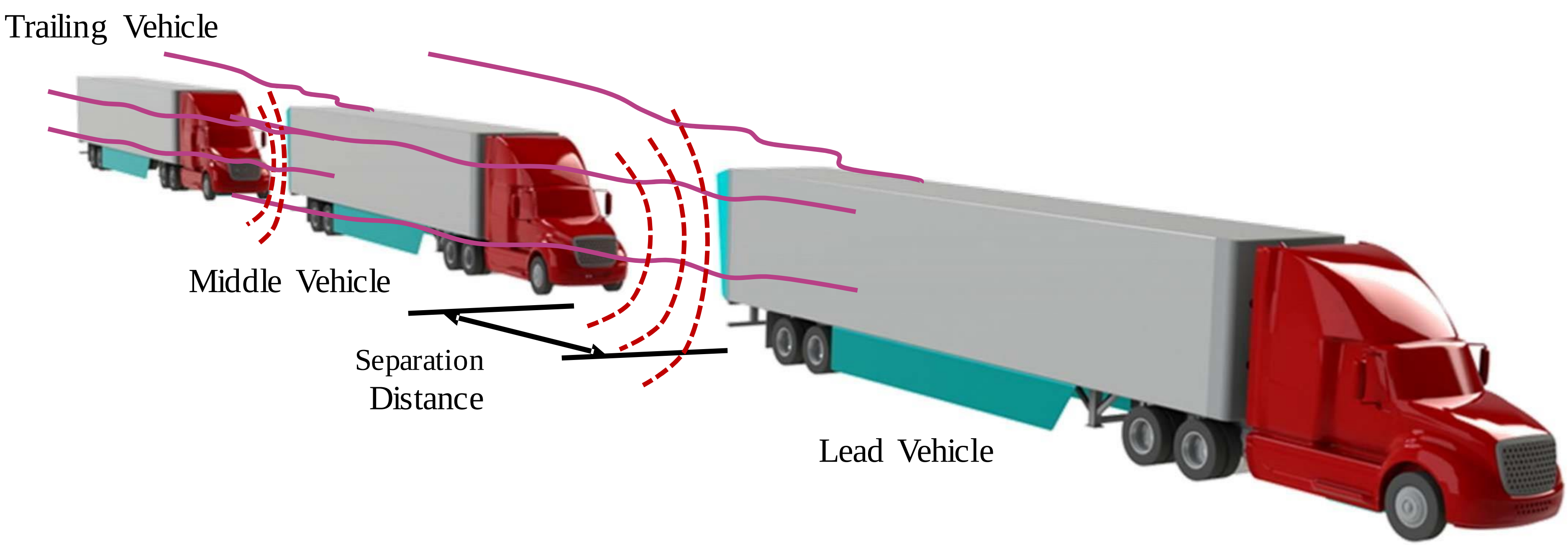
High-pressure zone in front of trailing vehicle influences lead vehicle
(pushes on the front vehicle)

Aerodynamics of Cooperative Truck Platooning

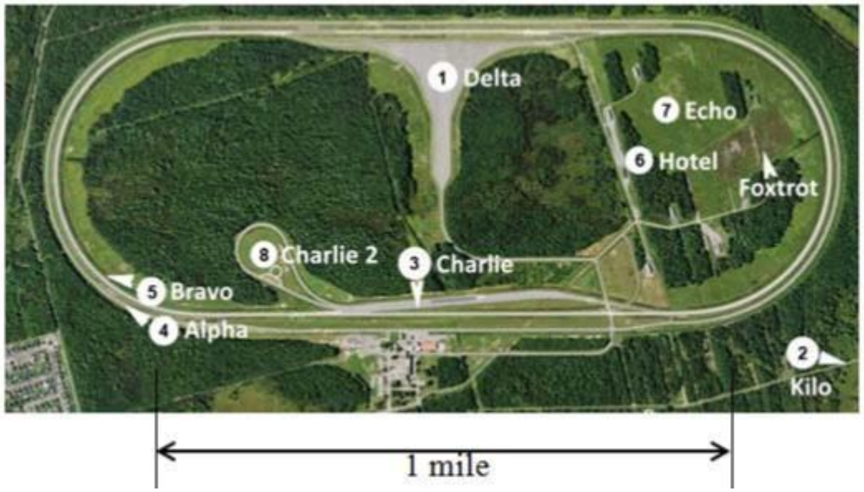
- **As vehicles approach, they influence the flow-field around each other**

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

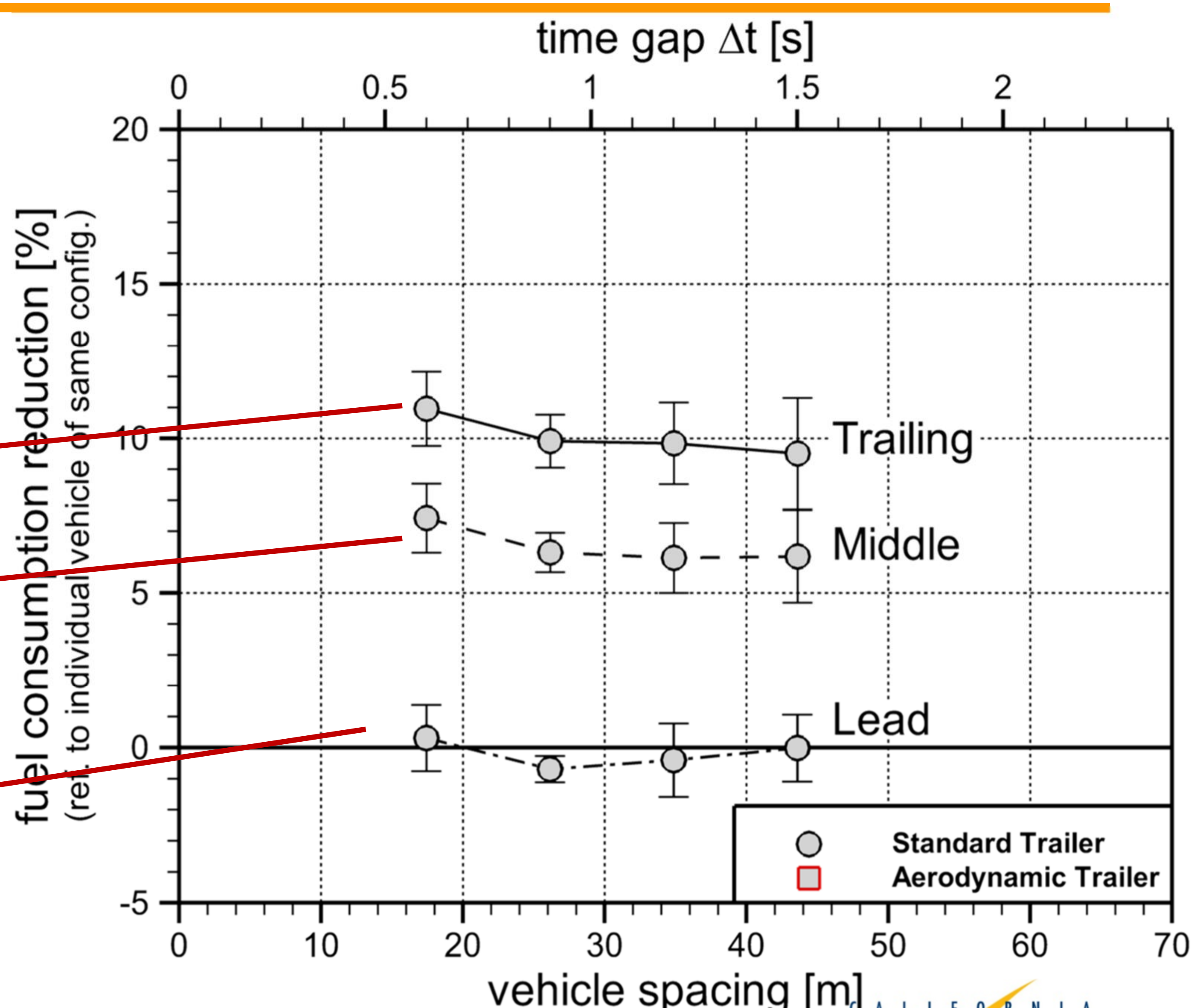
Test Results - NRC Canada Fuel Saving Estimates (65 mph + 65,000 lbs)

Fuel Savings for Individual Trucks
(ref. standard truck)

3rd truck

2nd truck

lead truck



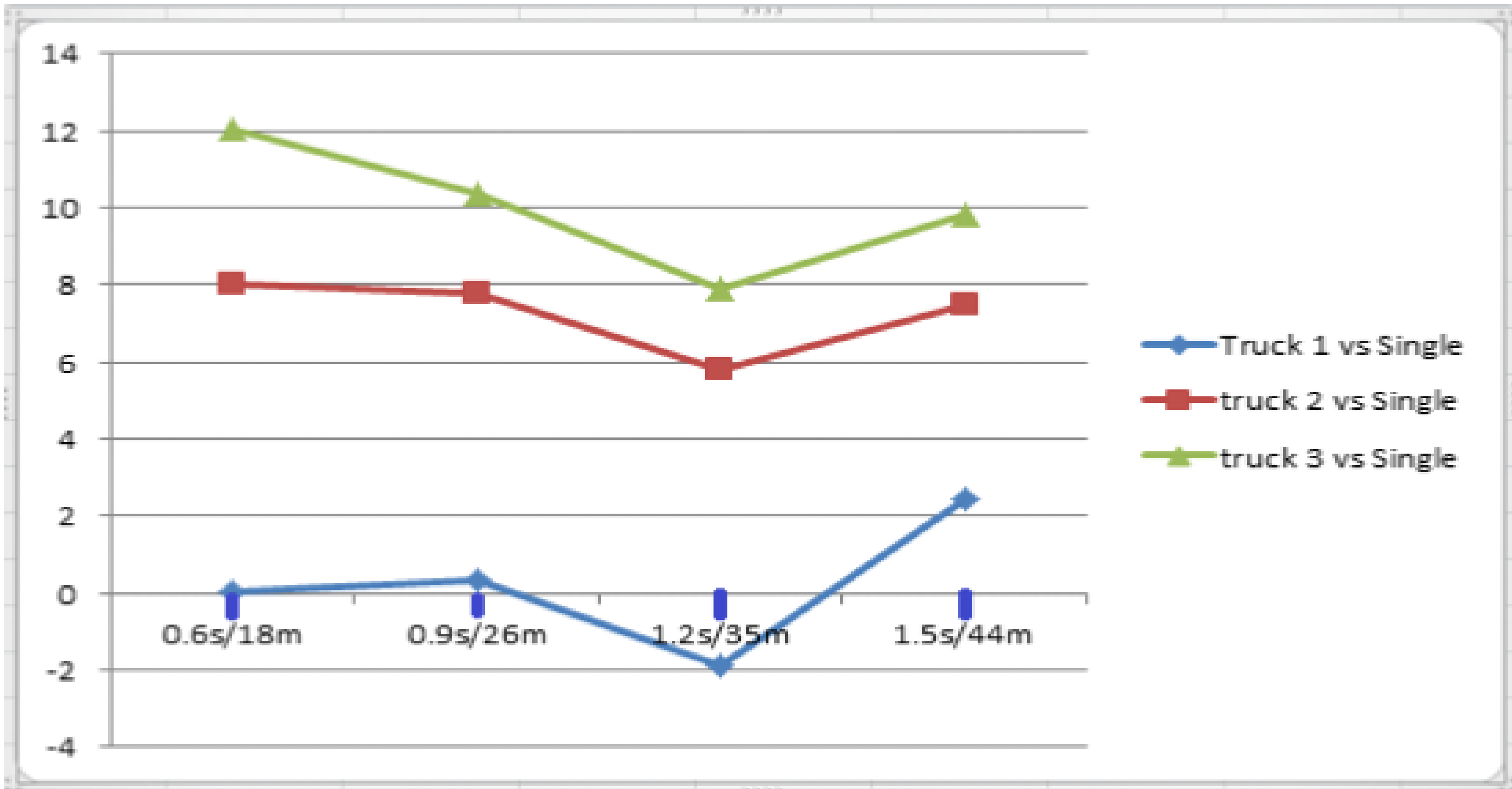
Alternate Analysis – without Weighing Tanks

- **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**

Travel and environmental impacts of unoccupied VMT in Robotaxi fleet based on GPS trajectory data

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Neda Masoud[2], **Henry Liu**[2] and **Ming Xu**[1,2]

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SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY UNIVERSITY OF MICHIGAN

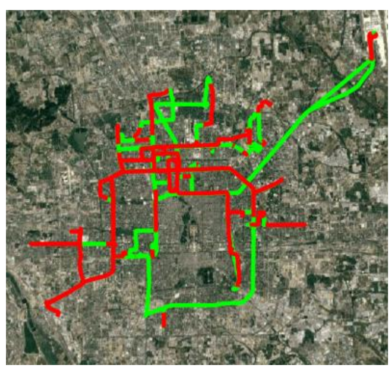
COLLEGE OF ENGINEERING CIVIL & ENVIRONMENTAL ENGINEERING UNIVERSITY OF MICHIGAN

Background and Research Question

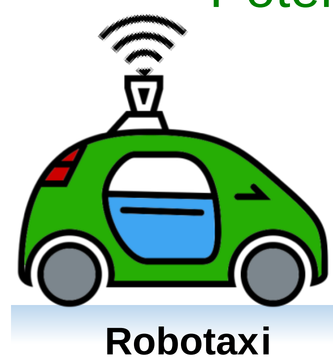
- Taxi fleets are integral part of public transportation system.
- VMT = vehicle miles travelled
- Occupied VMT → passenger on board (inevitable)
- Unoccupied VMT → empty cruising (undesirable)

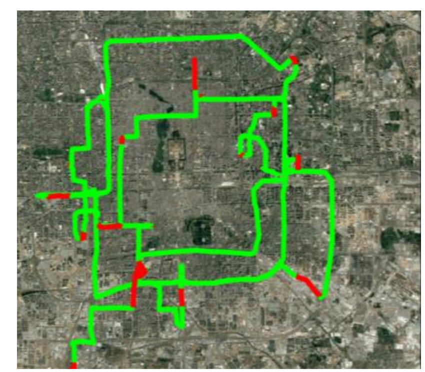
Minimizing unoccupied VMT in the operation of Robotaxis

Challenge



Potential Remedy





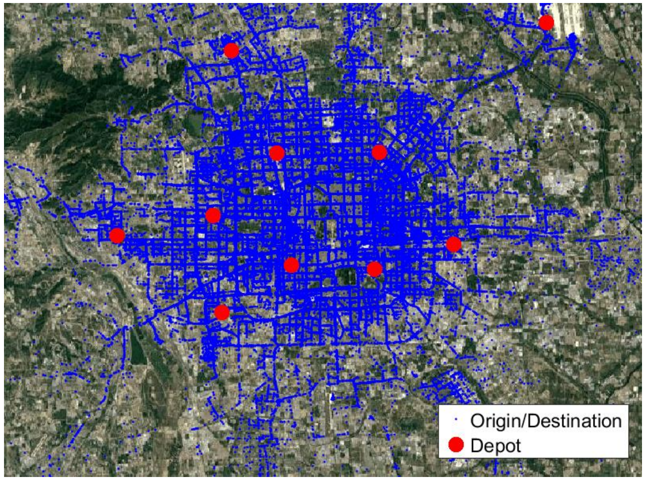
Energy and environmental impacts?
- ✓ Fuel Consumption
- ✓ Well-To-Wheel (WTW) Life Cycle GHG Emissions

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

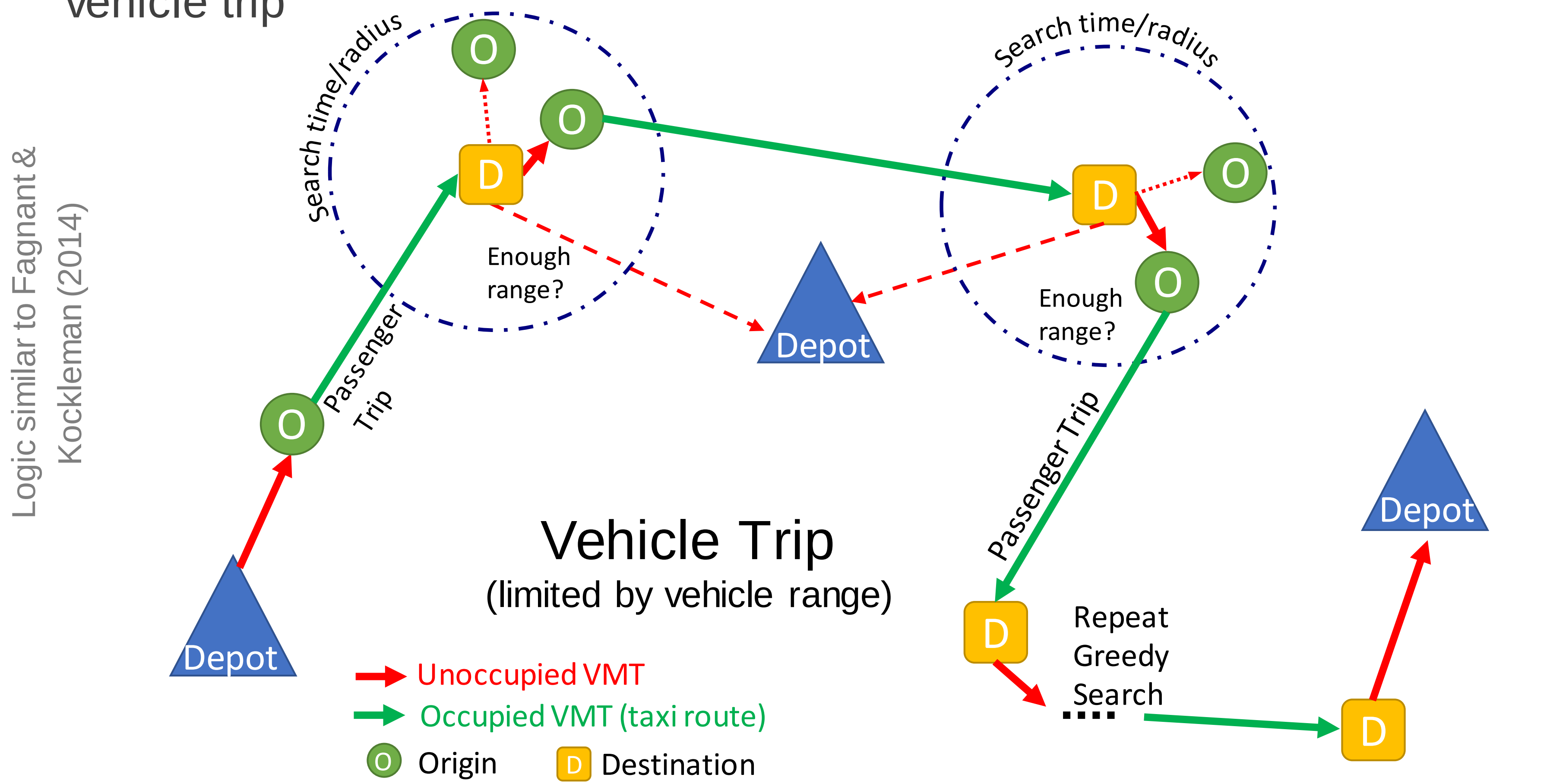
1. Depot Siting
   - Use k-means clustering of Origin/Destination (OD) locations



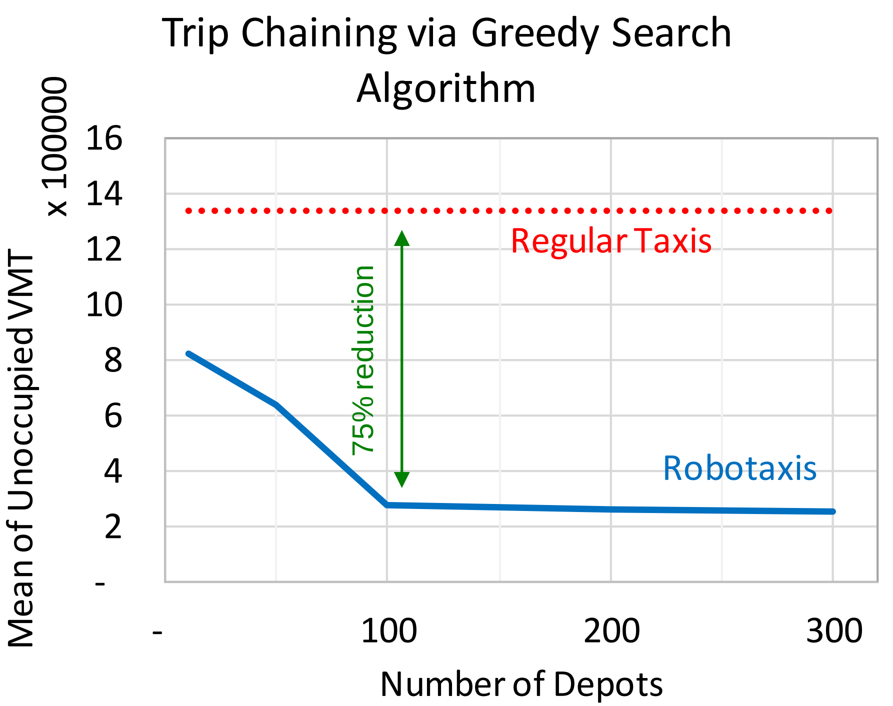
2. Vehicle Assignment Strategy
   - Trip chaining with respect to vehicle range

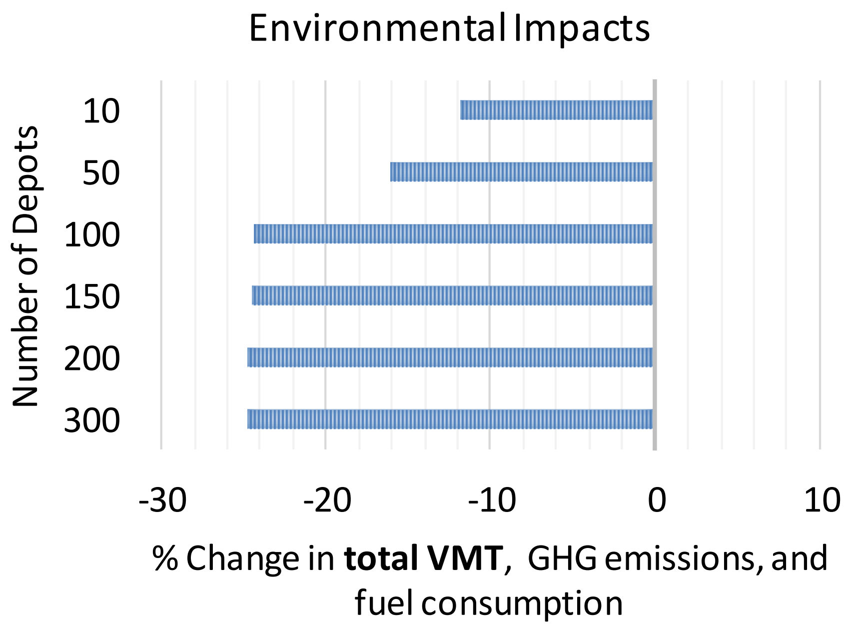
Trip Chaining - Intuition

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



Results





Vehicle range=400 miles
search time=5 min

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

Results – Electric Robotaxi

2016 MB Smart for two

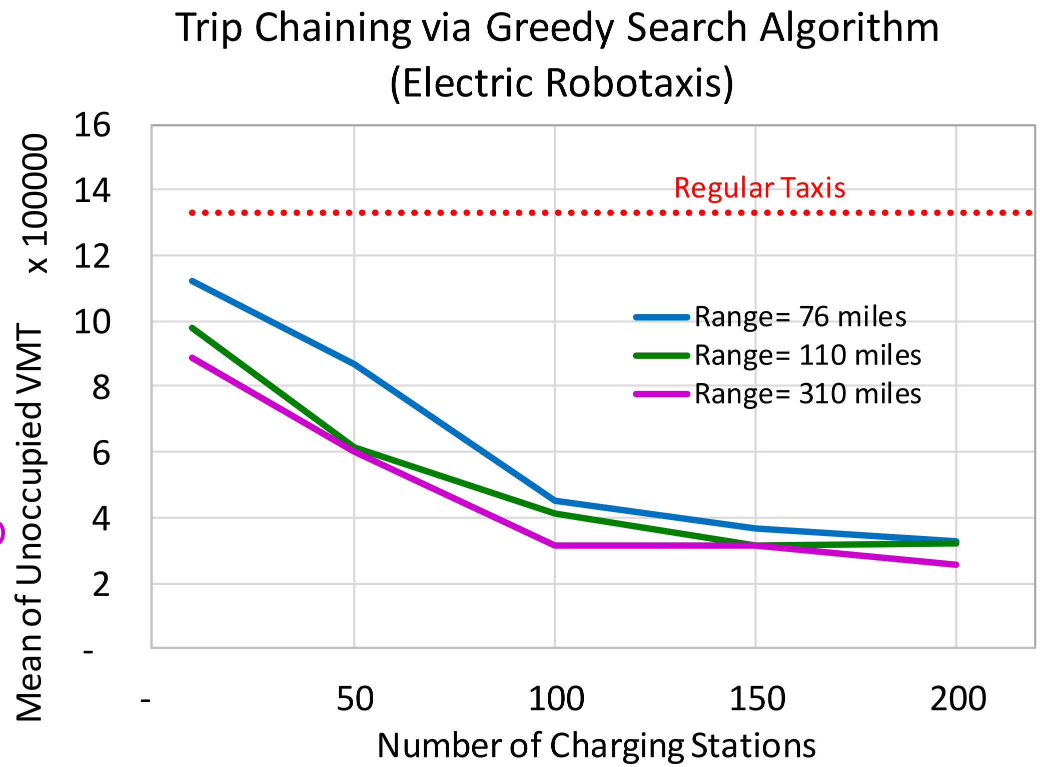
Battery size = 76 miles

2017 Nissan Leaf

Battery size = 110 miles

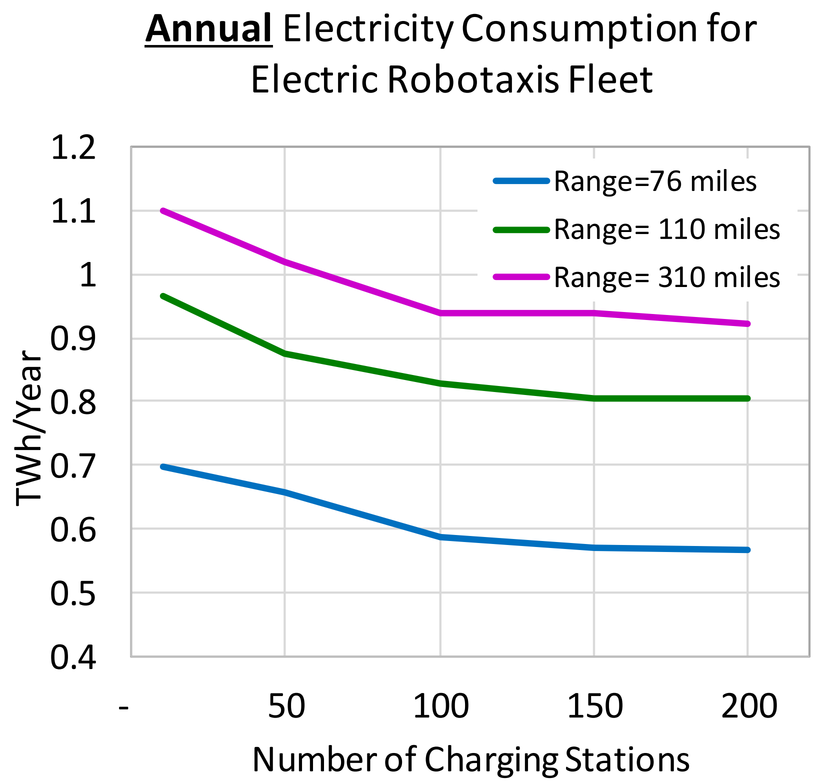
2017 Tesla Model S P100D

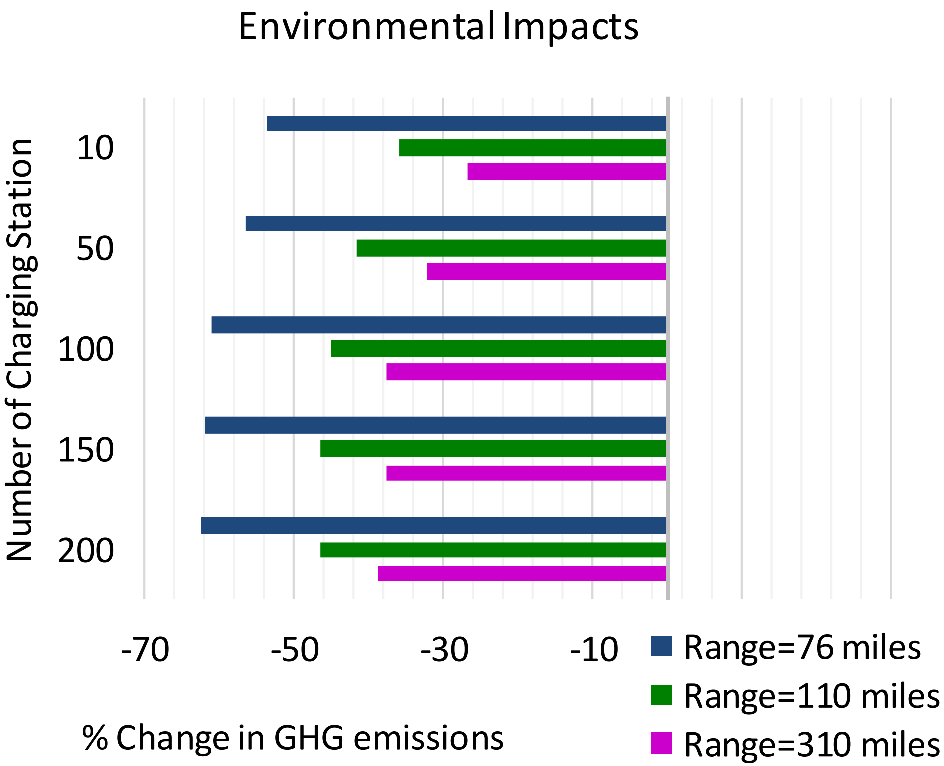
Battery size = 310 miles



- 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 $CO_{2\text{-eq}}$ 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.

Question?

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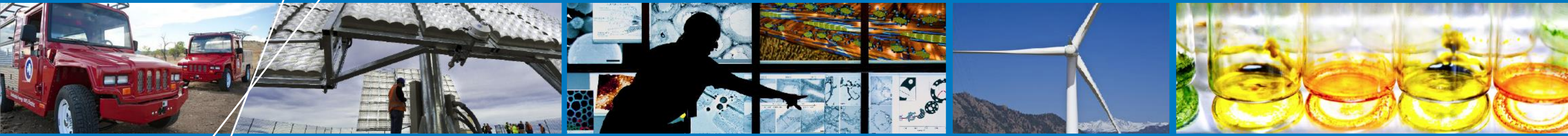
A Green Routing Fuel Saving Opportunity Study on Large-Scale Real-World Travel Data



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

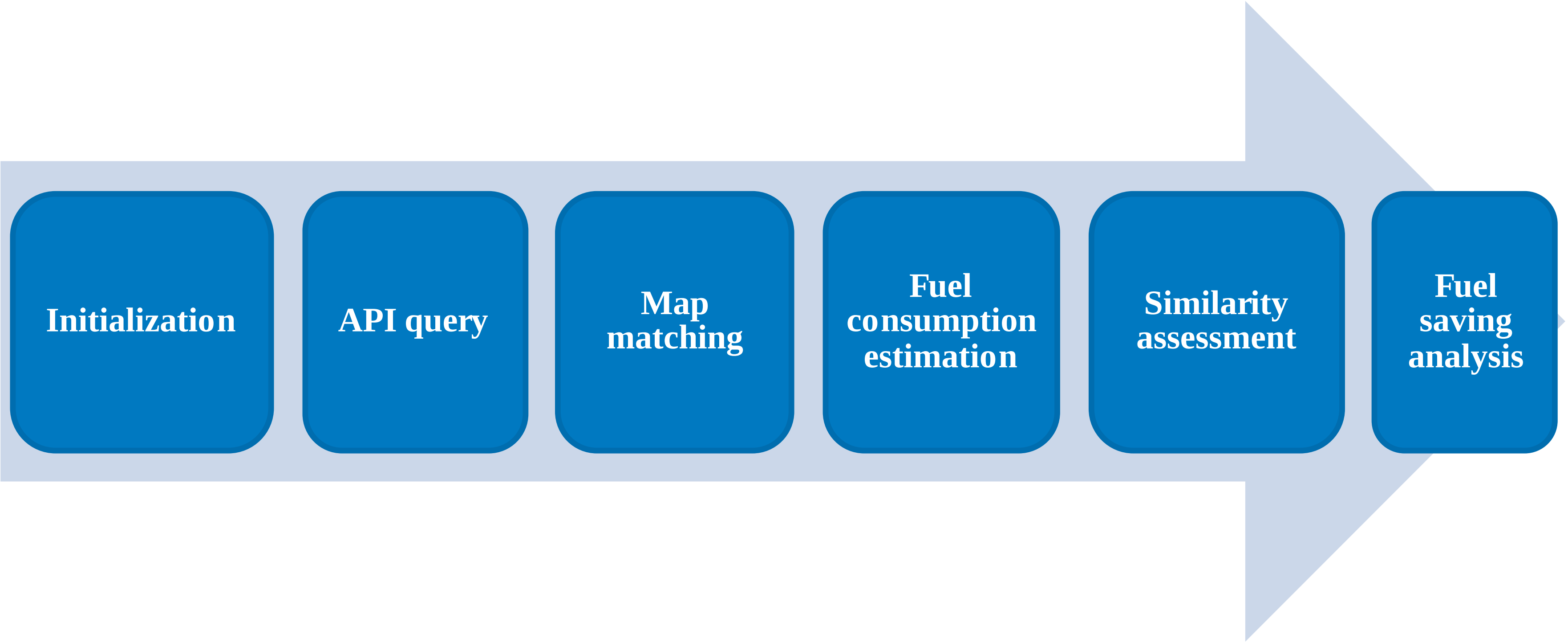
- The green routing fuel-saving potentials for **large-scale real-world** travel data have not been discussed.
- Prerequisites
  - Pre-trip fuel consumption estimation method
  - Pathfinding services requires accurate traffic and network data

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

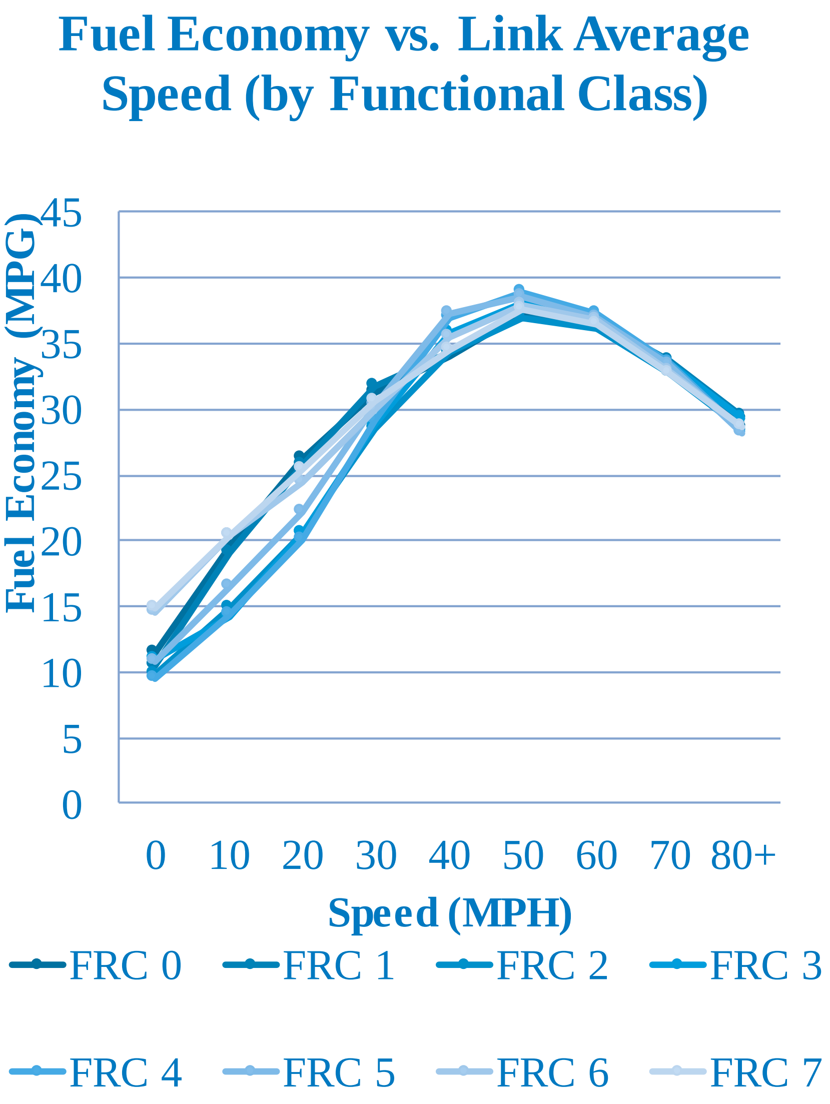
- **The green routing fuel-saving opportunity evaluation framework**

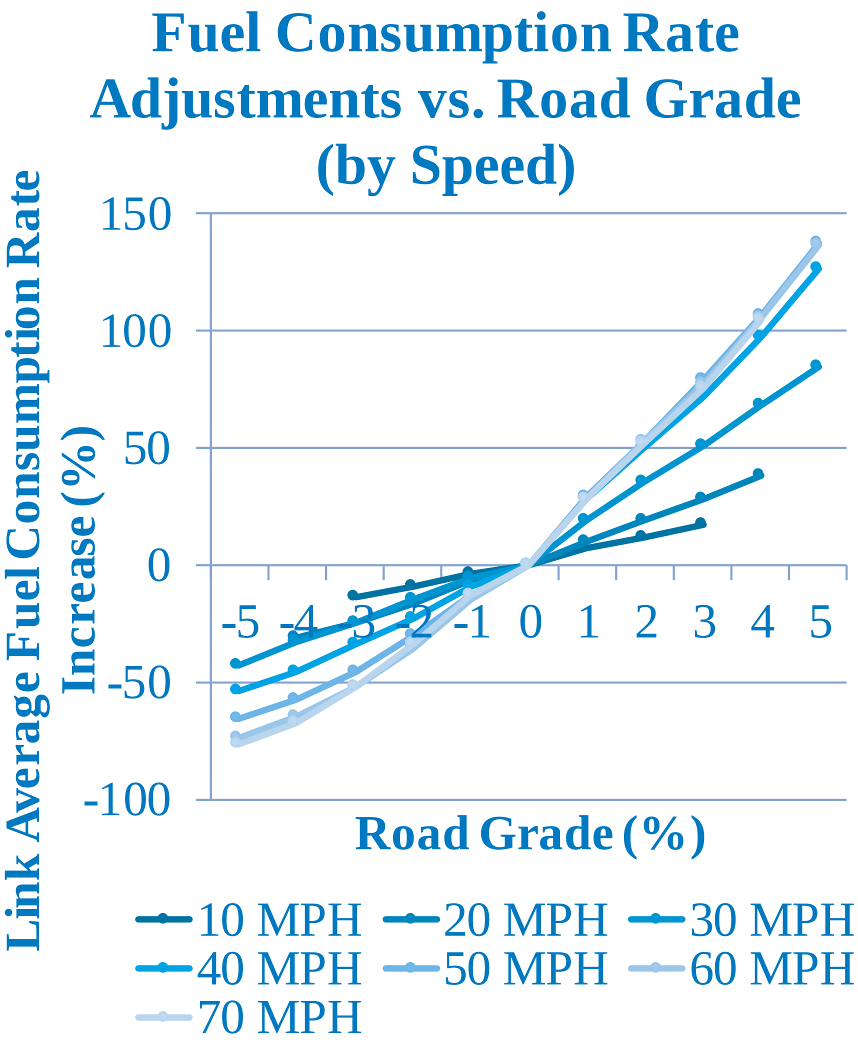


Methodology

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

Methodology





Methodology

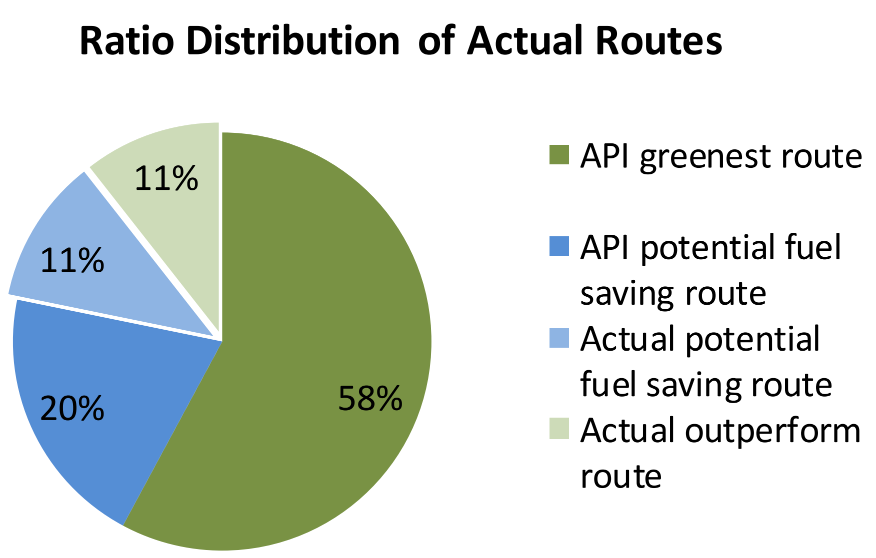
- Google Directions API provide quality route information for **alternative route** options.
  - Polyline
  - “Duration in Traffic” –assign a future departure time
  - Distance
  - …
- USGS Digital Elevation Model (DEM)- elevation and **road grade** information
- TomTom MultiNet road network- **functional 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)**

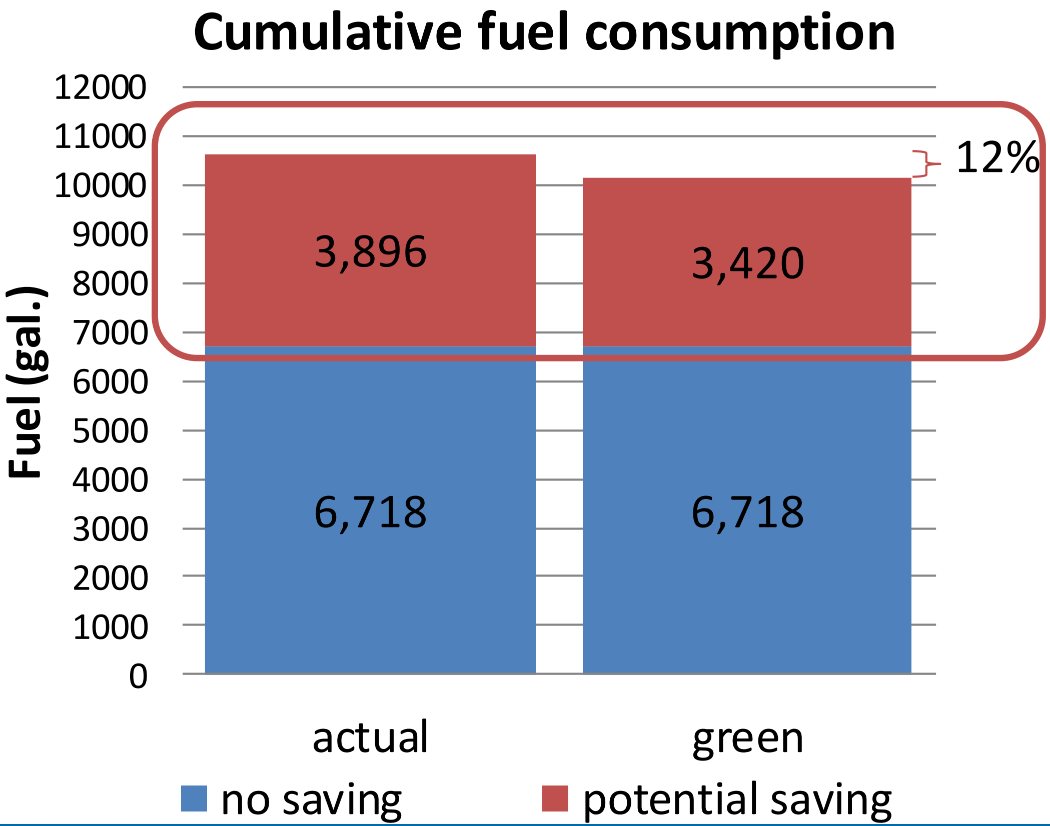
Experiment and Results Discussion

- **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%).)



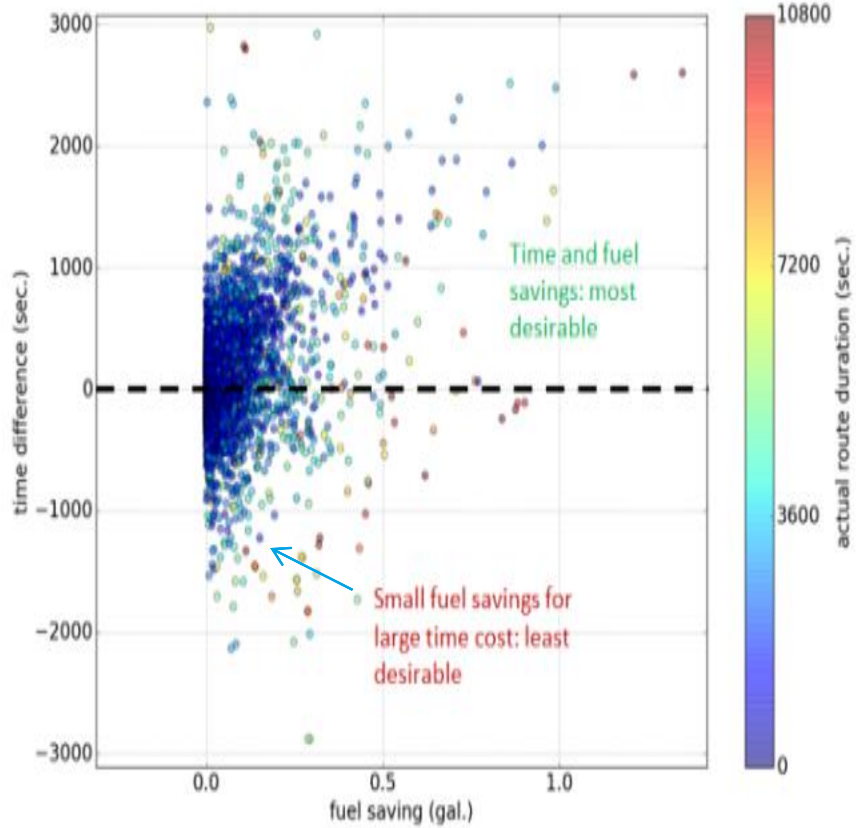
Experiment and Results Discussion

- **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



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



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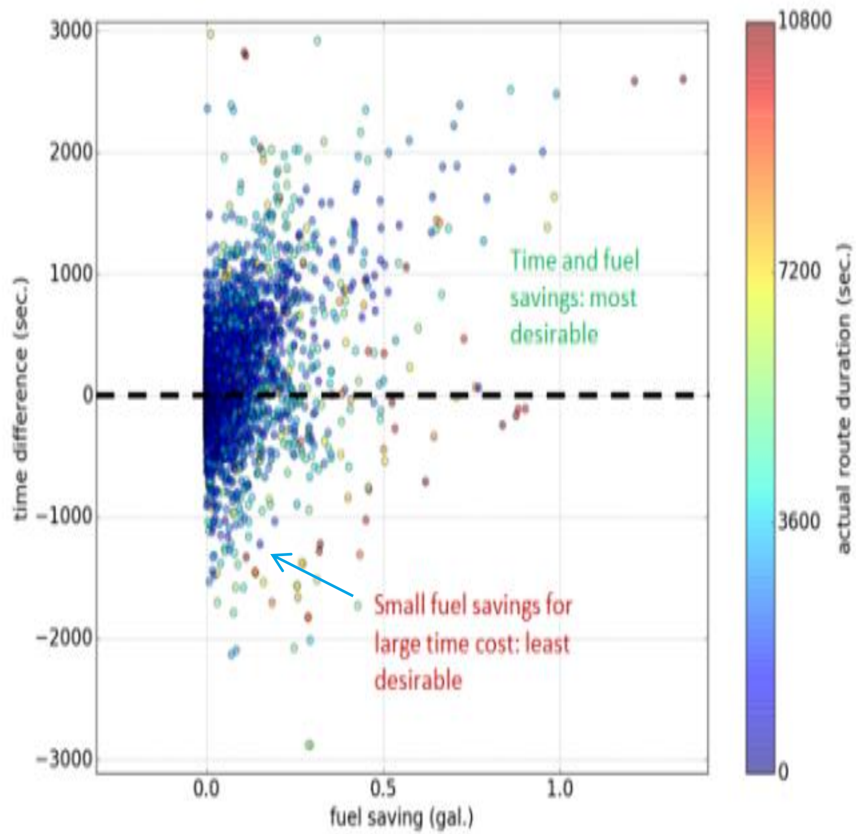
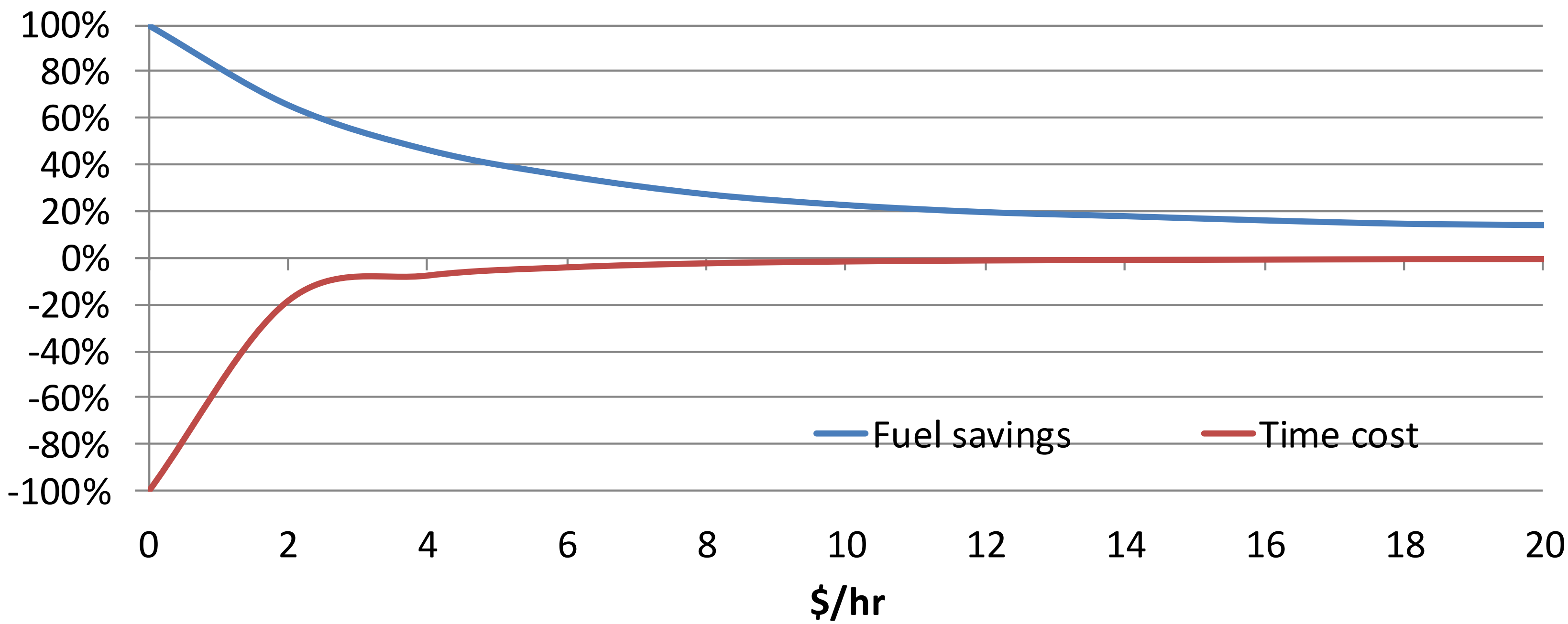


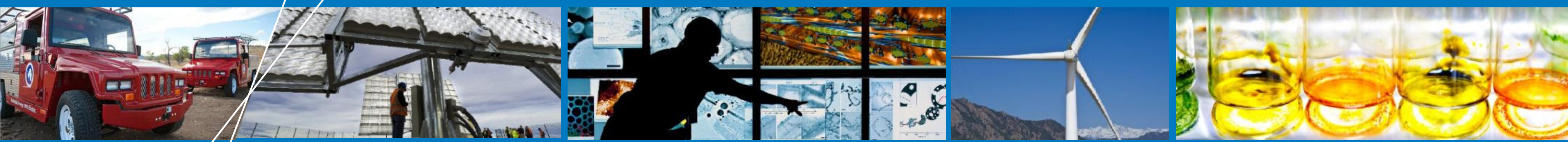
Experiment and Results Discussion

- **For the *least desirable routes***
  - (assuming $2.50/gallon)
  - 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.**
  - 12% fuel savings estimate for potential routes (or, 4.5% for the entire set of actual routes)
  - 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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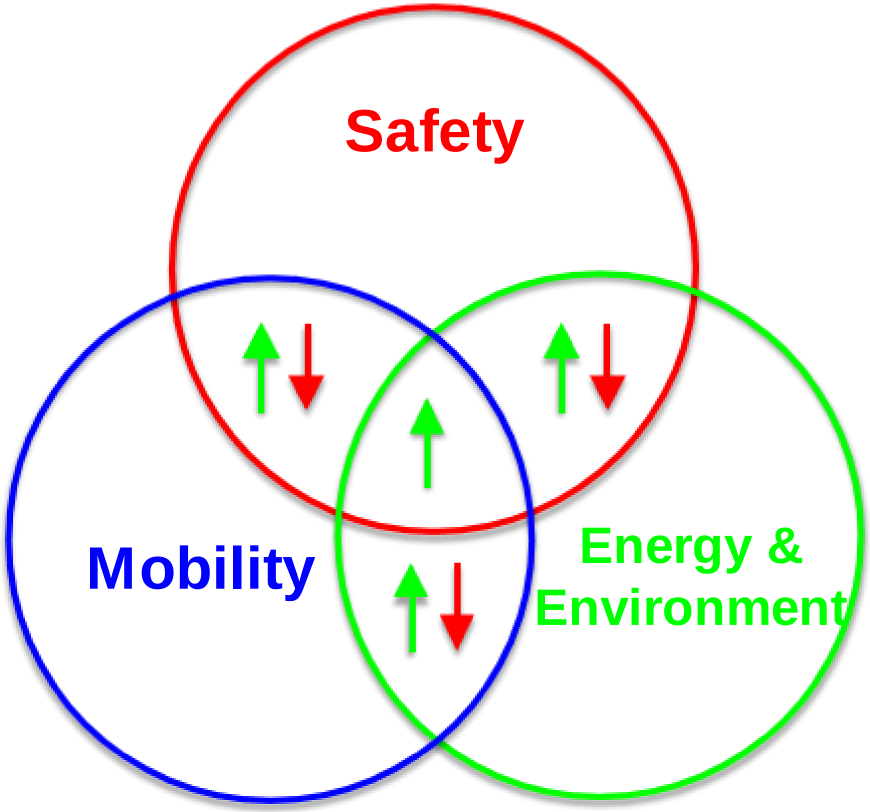
Holistic Assessment of the Co-Benefits and Tradeoffs between Safety, Mobility and the Environment for Automated and Connected Vehicles

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

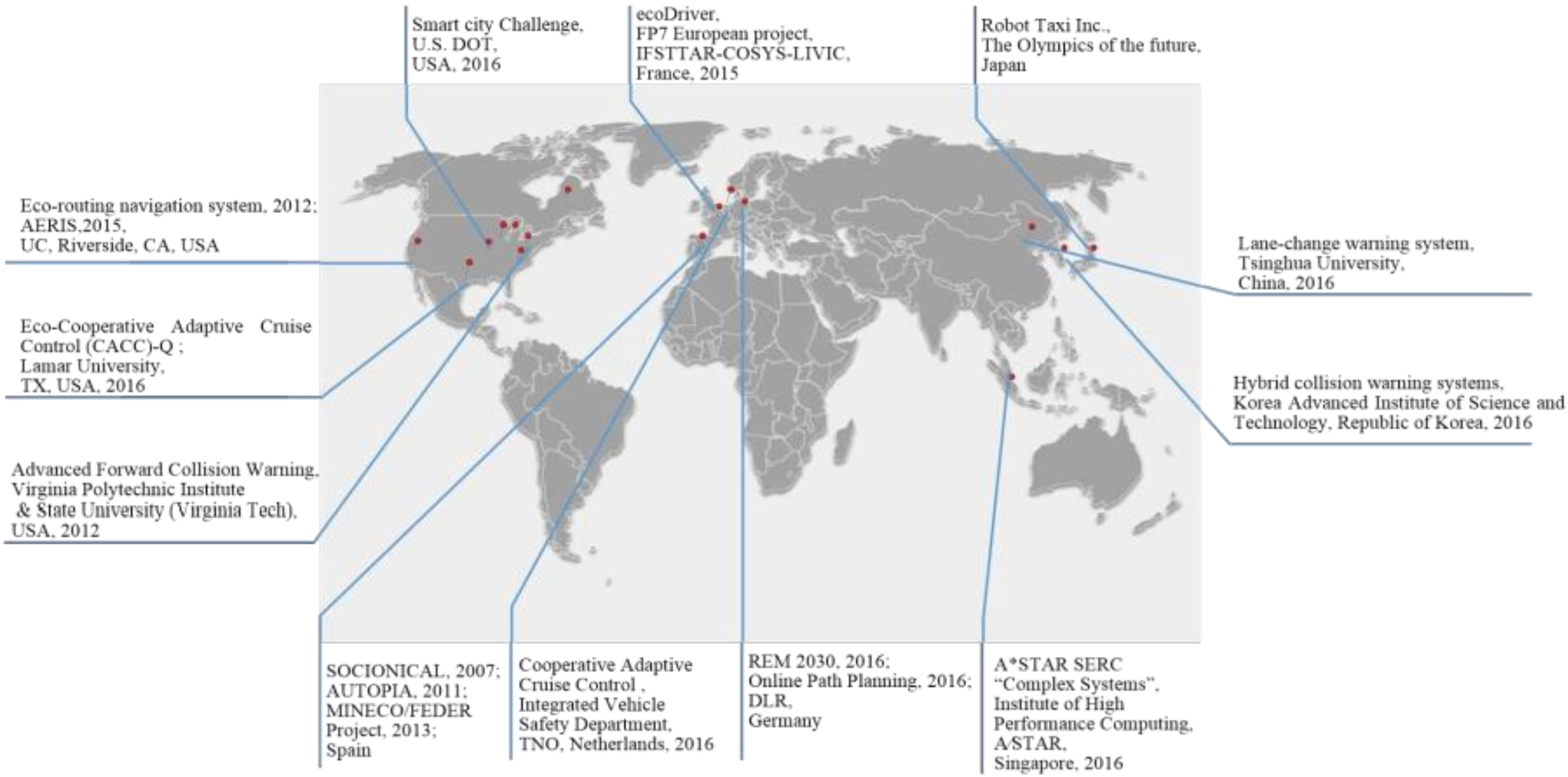
Safety & Energy:

- Electronic Brake Lights
- Conservative automated maneuvers

Mobi l i ty & Energy:

- CACC
- Higher speeds

Worldwide CAV Applications/Projects



Broad Classification of CAV Applications

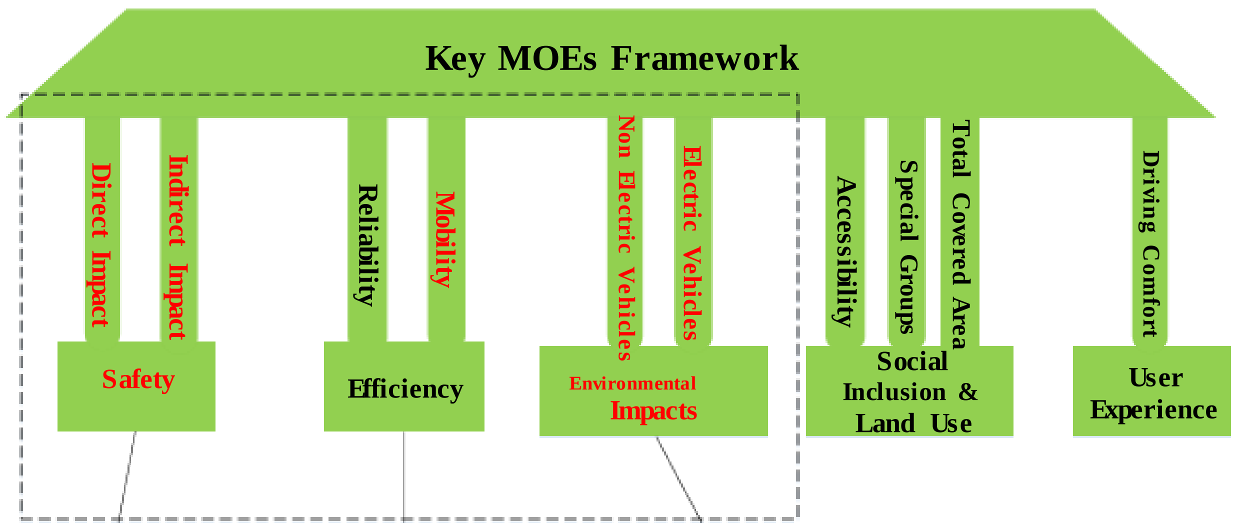
(Photos: Mohamed Zaki, 2014)

- ***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



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

Indicators library:
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.

Indicators library:
Fuel consumption;
Energy consumption;
Pollutant emissions;
Number of stops;
Average speed, etc.

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

Survey Taxonomy

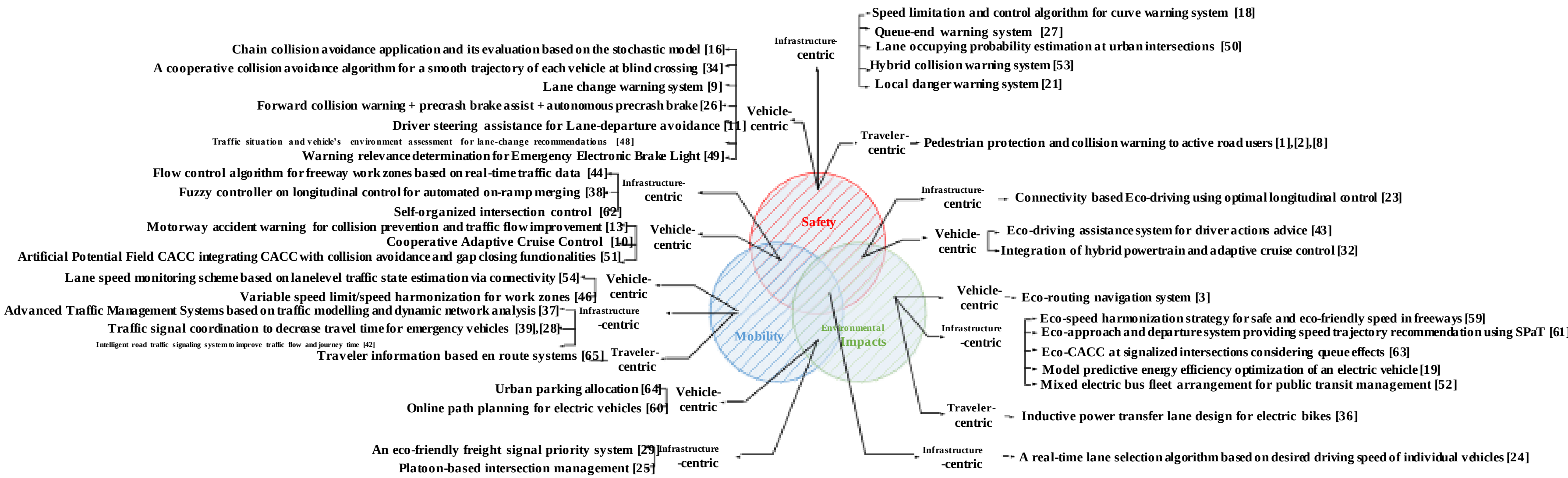


Figure: **Survey taxonomy in terms of Measures of Effectiveness (MOEs)**

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)**

Safety focused (25)	S M E ↑ ? ?	S M E ↑ ↑ ?	S M E ↑ ? ↑	S M E ↑ ↑ ↑
	15 out of 25 (60%)	6 out of 25 (24%)	3 out of 25 (12%)	1 out of 25 (4%)
Mobility focused (18)	S M E ? ↑ ?	S M E ↑ ↑ ?	S M E ? ↑ ↑	S M E ↑ ↑ ↑
	7 out of 18 (39%)	6 out of 18 (33%)	4 out of 18 (22%)	1 out of 18 (6%)
Environmental impacts focused (15)	S M E ? ? ↑	S M E ↑ ? ↑	S M E ? ↑ ↑	S M E ↑ ↑ ↑
	7 out of 15 (47%)	3 out of 15 (20%)	4 out of 15 (27%)	1 out of 15 (7%)

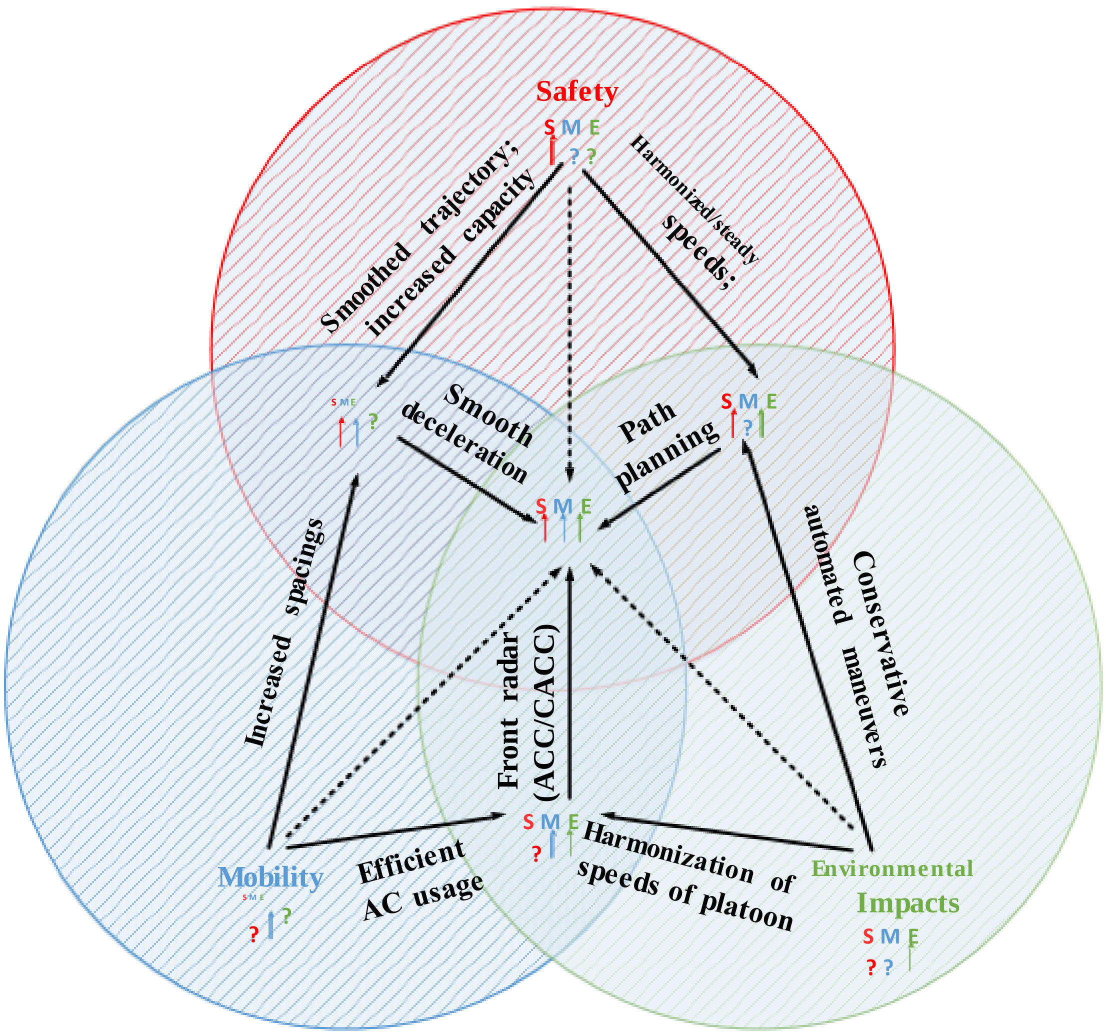
S: Safety; M: Mobility; E: Environmental impacts; ↑ : Improvement; ?: Unknown, Neutral or Deteriorated

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.

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.



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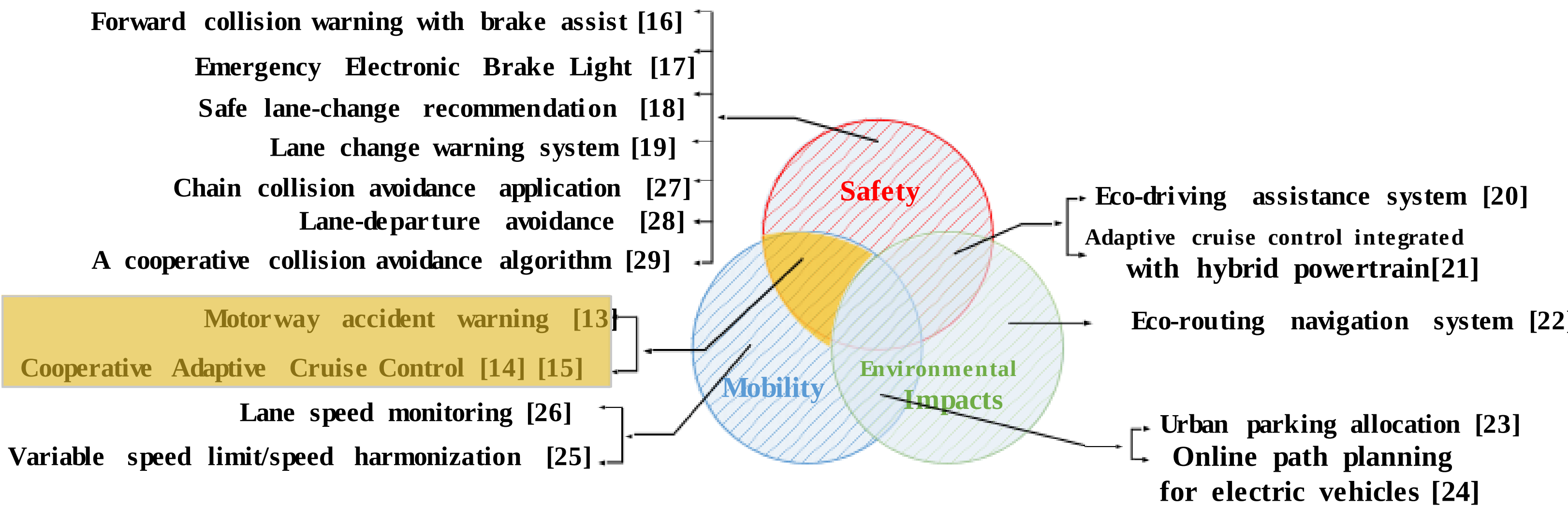
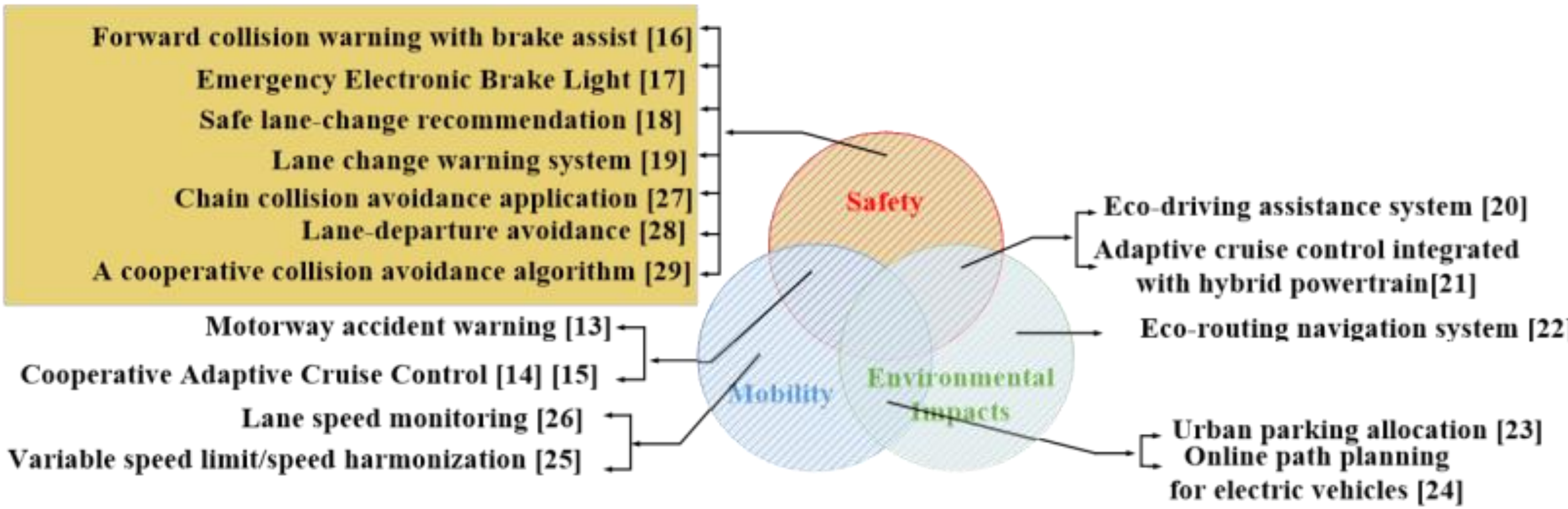
Vehicle-Centric Applications Examples (1)



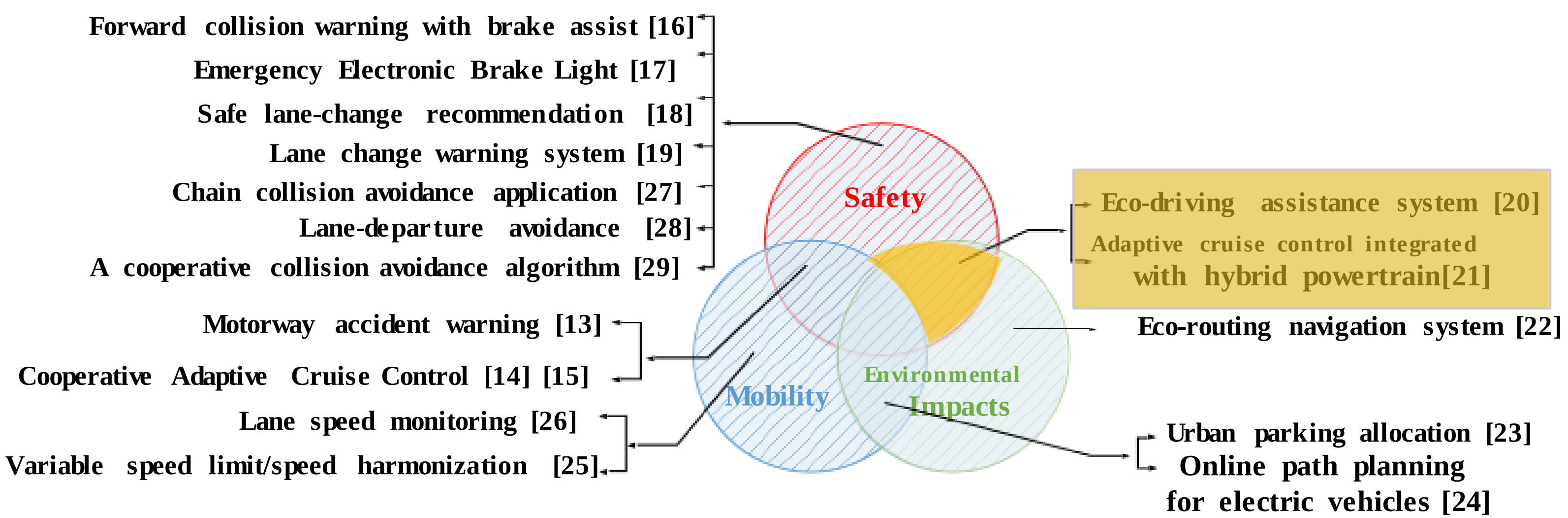
Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
A lane closure alert	Potential rear-end reduction	Relief of bottlenecks congestion	Unknown
Cooperative Adaptive Cruise Control (CACC)	Harmonizing the speed of platoons in a safe manner	Increasing the traffic capacity under high penetration rates	

Vehicle-Centric Applications Examples (2)



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

Vehicle-Centric Applications Examples (3)



Application	Safety Improvement	Mobility Improvement	Environment Impacts Improvement
Eco-Driving application	Integration of various information sources (not validate)	Steady-speed, smooth-deceleration traffic but with longer travel time	Eco-friendly speed
Intelligent Environment-Friendly Vehicles	Adaptive Cruise Control (ACC)	Unknown	Hybrid powertrain

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:

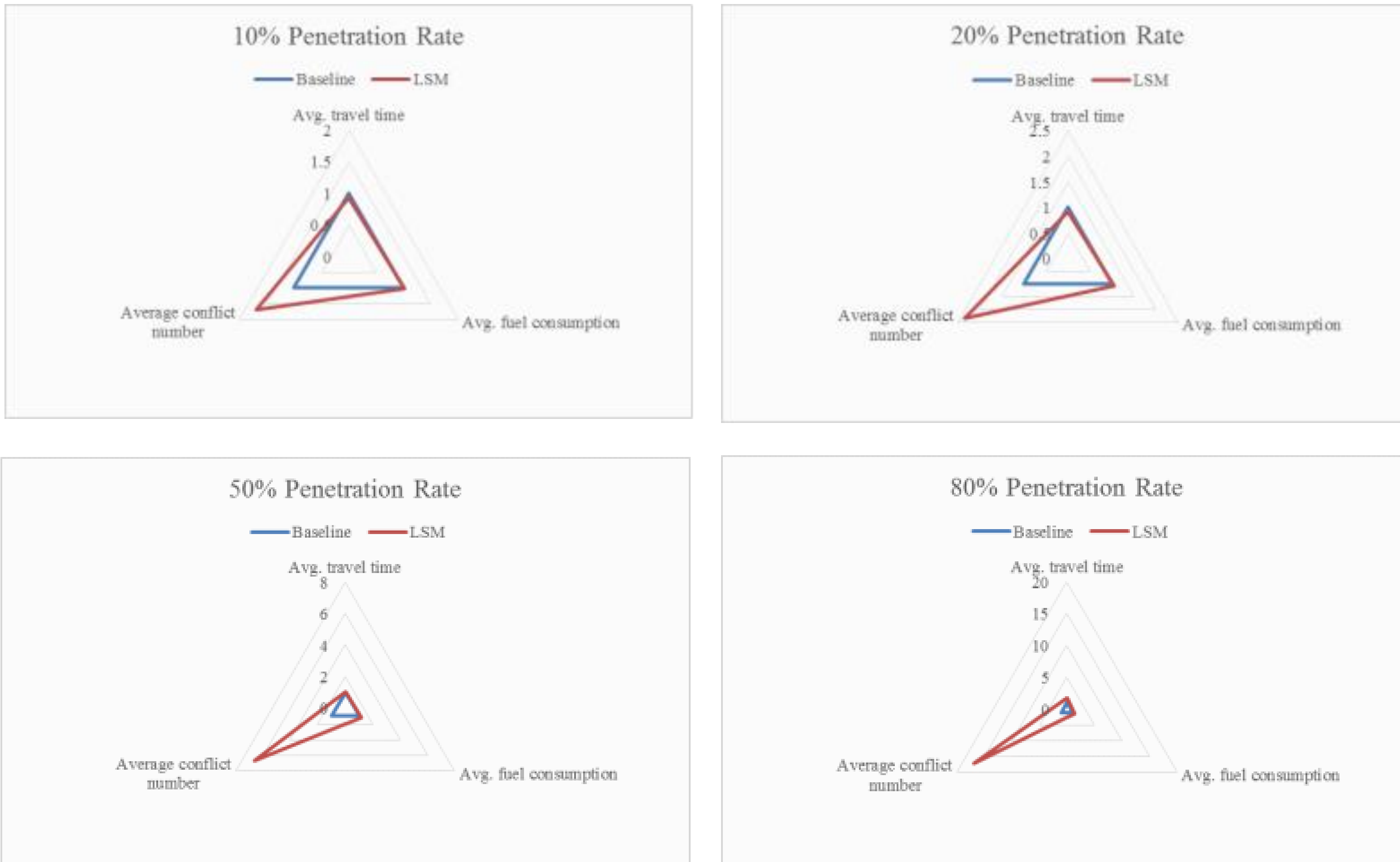


Figure: **Radar plots of three normalized MOEs for LSM**

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.