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# Operation Strategy of the Near-term Deployment of Cooperative Adaptive Cruise Control Technology

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# Presentation Outline

- Introduction
- Near-term deployment of CAV
- Case Study for Manage Lane
- Future Research

# INTRODUCTION

# Background

- Safety
  - 35 thousand highway deaths & 3.6 million crashes in 2015 *
  - The leading cause of death for ages 1-44**
- Mobility***
  - 6.9 billion hours of travel delay
  - $160 billion congestion cost
- Environment***
  - 3.1 billion gallons of fuel wasted
  - 60 billion pounds of additional CO2


*** Traffic Safety Facts, National Highway Traffic Safety Administration (August 2016)**
****Ten Leading Causes of Death by Age Group, United States –2014, Centers for Disease Control and Prevention**
*****2015 Urban Mobility Scorecard, Texas A&M Transportation Institute and INRIX (August 2015)**

# Connected and Automated Vehicles

## Level of Automation


Level 1: driver assistance

Level 2: partial automation

Here Today

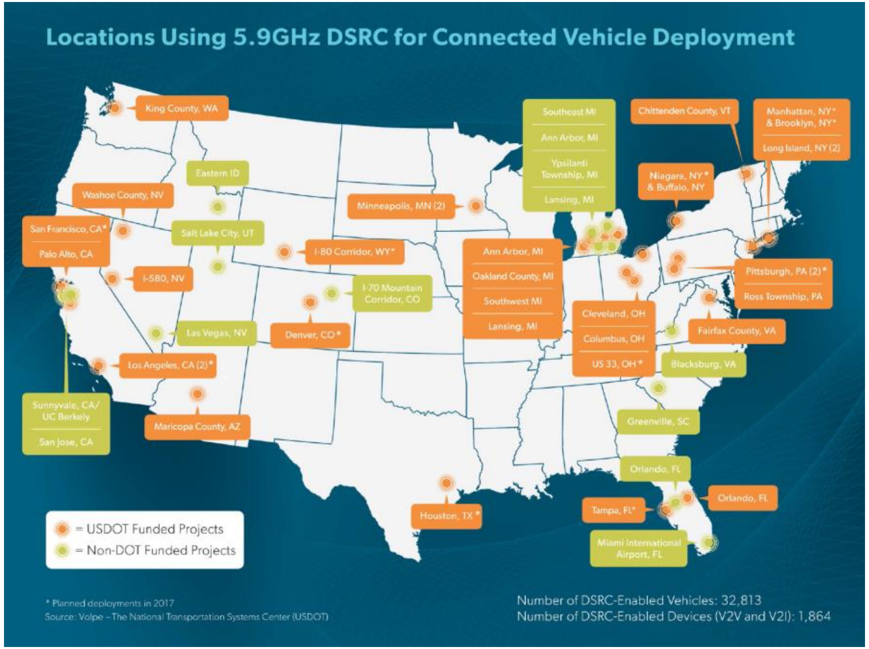
Level 3: conditional automation

Level 4: high automation

In Testing

Level 5: full automation

Someday (?)




- 72,000 vehicles and 65,000 C2X device have been equipped with V2X technology thorough the United States

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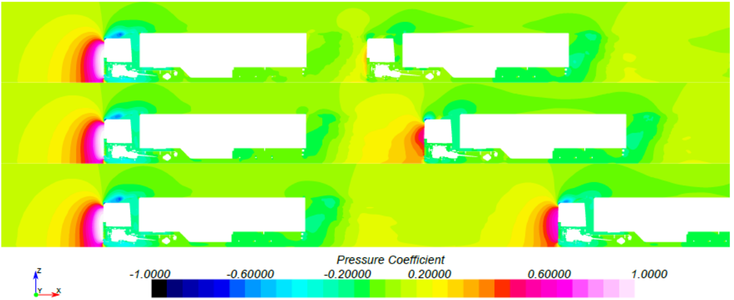
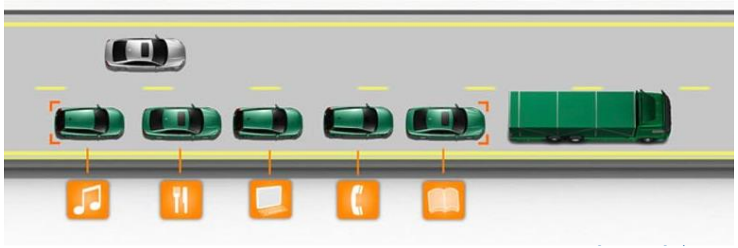
# Benefits of CACC

Cooperative Adaptive Cruise Control (CACC) is a promising application of CAV technology with the primary benefits of:

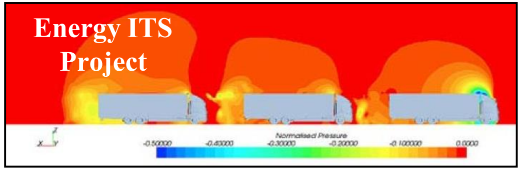
- Increase highway capacity by short intra-platoon headway
- Reduce fuel consumption by decreasing air resistance via a tightly coupled platoon
- Improve safety by attenuating traffic disturbances
- Increase riding comfort and convenience

# CACC Field Experiment

- 1996 — KONVOI
- 1997 — Automated Highway System Demonstration
- 2008 — Energy ITS Project
- 2009 — Safe Road Train for the Environment
- 2011 — Grand Cooperative Driving Challenge
- 2015 — USDOT CV Pilot Deployment Program
- 2016 — European Truck Platooning Challenge

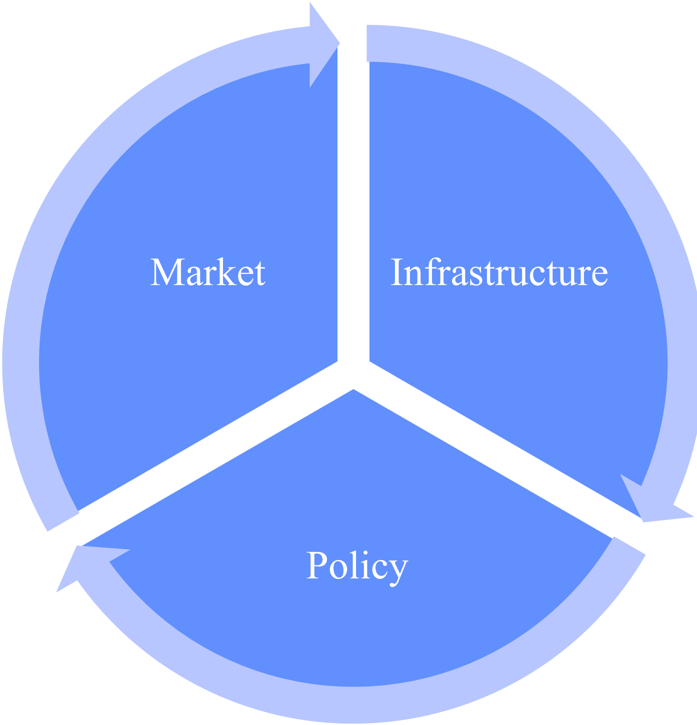






# NEAR-TERM CACC DEPLOYMENT

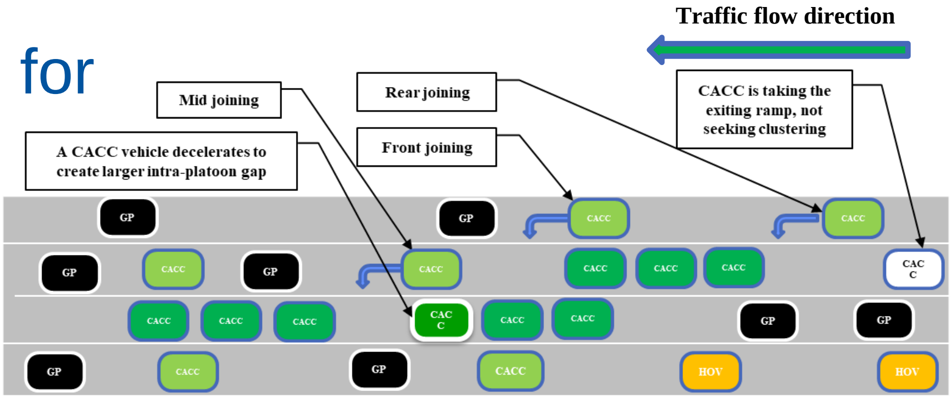
# Transition to CAV

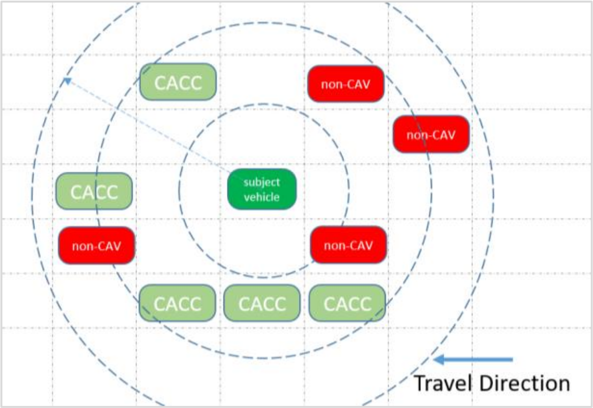
- Infrastructure
  - DSRC-enabled Roadside Units
  - Automated Driving System
- Policy
  - Preferential lane use
  - Technical accommodation
- Market
  - Incentive to upgrade & retrofit



# CACC Vehicle Clustering

- Three clustering strategies for CACC platoons
  - Ad hoc coordination
  - **Local coordination**
  - Global coordination
- Managed lane policy for CACC
  - Creates a local high market penetration region
  - Increases traffic homogeneity

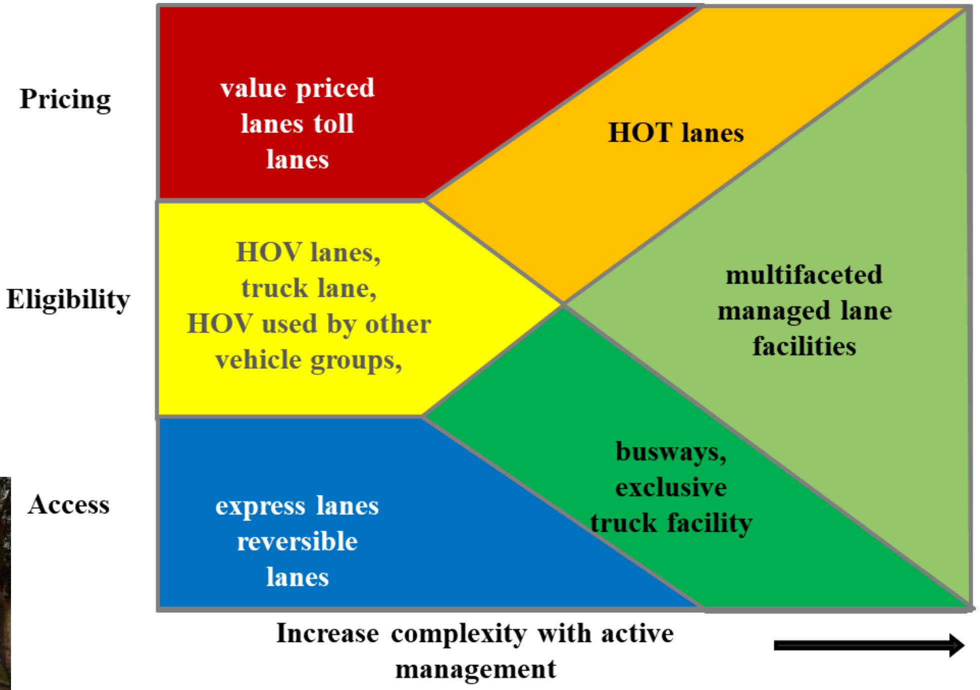


# Managed Lane

**Managed lanes: freeway lanes that are set aside and operated under a variety of fixed and/or real-time strategies responding to local goals as well as objectives (e.g., improving mobility, promoting air quality, or enhancing safety)**



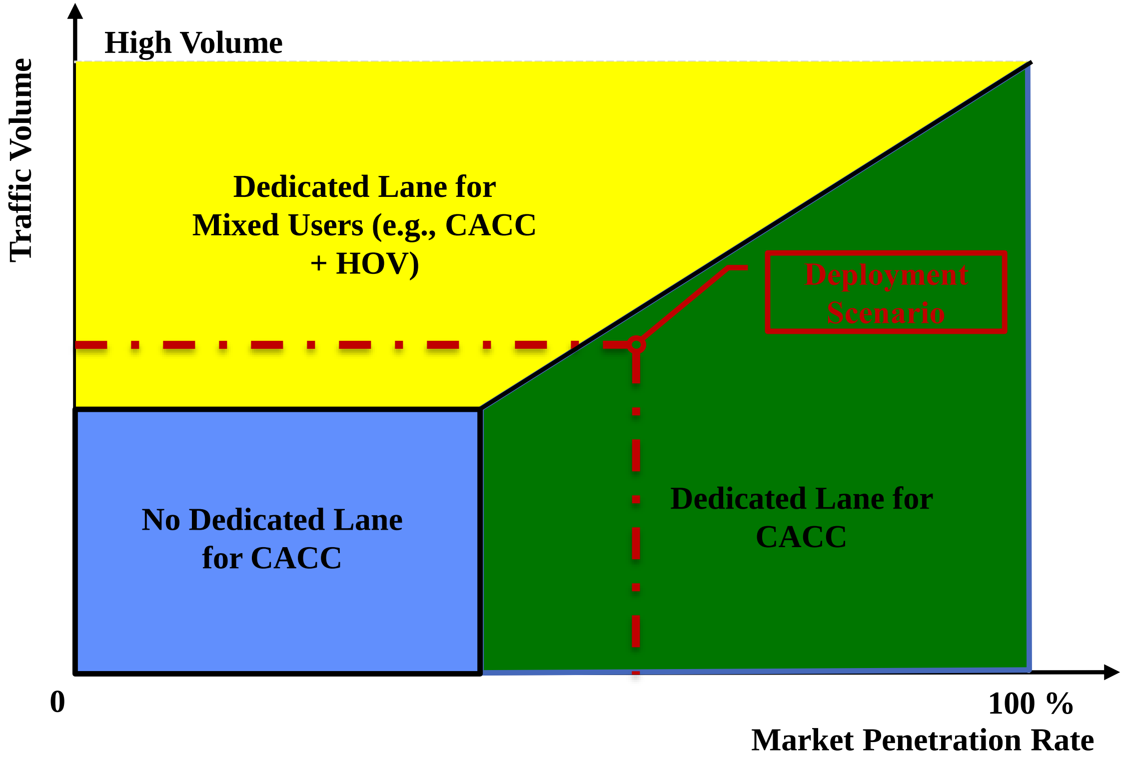


# Deployment Roadmap for CAV-ML

- Managed Lane
  - **Phase 1**: Provide free CAV use of the managed lane to incentivize customers to purchase/retrofit CACC vehicles until reaching unacceptable operating condition in managed lane
  - **Phase 2**: Allow CACC platoons with sufficient safety gaps to share the managed lane with non-CACC vehicles.
  - **Phase 3**: Transition to dedicated CACC lane once MPR warrants and permit automated high-performance driving (with higher cursing speed, shorter following distance, etc.)

# CASE STUDY: THE EFFECTIVENESS OF MANAGED LANE

# Suitable Managed Lane Strategy




- Managed lane can facilitate CACC clustering to harness the short following distance enabled by V2V communication
- The boundary under various traffic conditions could be determined via simulation

# Simulation-based Approach

- CACC Vehicle Longitudinal Control:
  Enhanced-Intelligent Driver Model (Kesting et al. 2010)

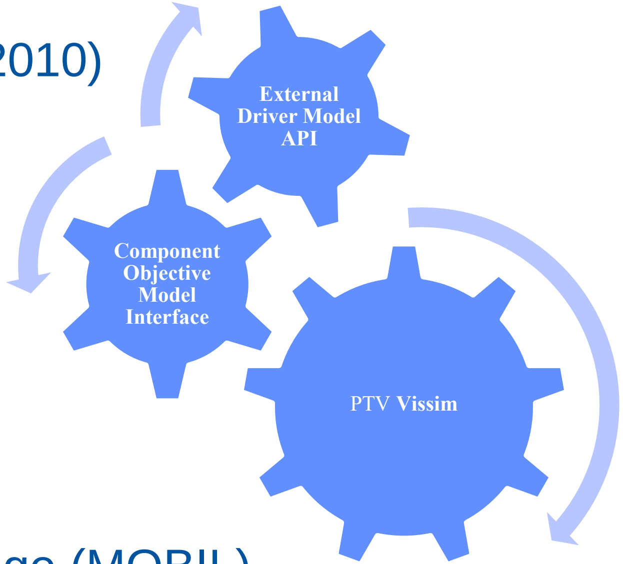
$$\ddot{x} = \begin{cases} a[1-(\frac{\dot{x}}{\dot{x}_{des}})^{\delta} - (\frac{s^*(\dot{x},\dot{x}_{lead})}{s_0})] & \text{if } x = \ddot{x}_{IDM} \geq \ddot{x}_{CAH} \\ (1-c)\ddot{x}_{IDM} + c[\ddot{x}_{CAH} + b \cdot tanh(\frac{\ddot{x}_{IDM}-\ddot{x}_{CAH}}{b})] & \text{otherwise} \end{cases}$$

$$s^*(\dot{x}, \dot{x_{lead}}) = s_0 + \dot{x}T + \frac{\dot{x}(\dot{x} - \dot{x_{lead}})}{2\sqrt{ab}}$$

$$\ddot{x}_{CAH} = \begin{cases} \frac{\dot{x}^2 \cdot \min(\ddot{x}_{lead}, \ddot{x})}{\dot{x}_{lead}^2 - 2x \cdot \min(\ddot{x}_{lead}, \ddot{x})} & \dot{x}_{lead}(\dot{x} - \dot{x}_{lead}) \leq -2x \min(\ddot{x}_{lead}, \ddot{x}) \\ \min(\ddot{x}_{lead}, \ddot{x}) - \frac{(\dot{x} - \dot{x}_{lead})^2 \Theta(\dot{x} - \dot{x}_{lead})}{2x} & \text{otherwise} \end{cases}$$

- CACC Vehicle Lateral Control:
  Minimizing Overall Braking Induced by Lane Change (MOBIL) Model (Kesting et al. 2007)

$$\tilde{\ddot{x}} - \ddot{x} + p(\tilde{\ddot{x}}_n - \ddot{x}_n + \tilde{\ddot{x}}_o - \ddot{x}_o) > \Delta\ddot{x}_{th}$$



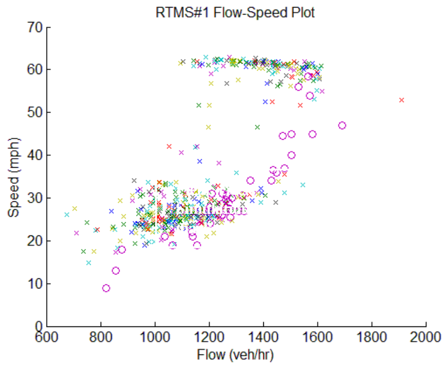

$x$

# I-66 Simulation Test Bed

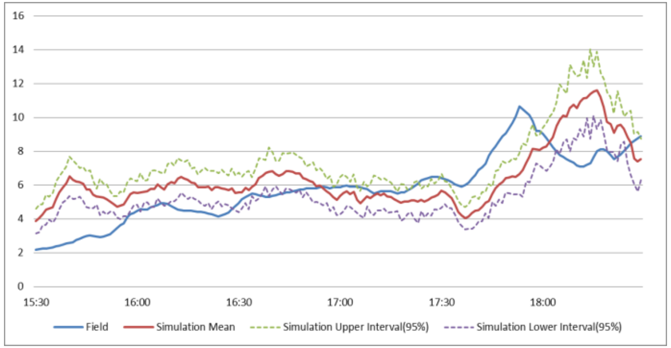
- The I-66 Segment, VA
  - A major commuter corridor outside of the beltway of Washington D.C. with recurring congestion during peak hours
  - The chosen segment is 8-km (5-mile)  long with 2 interchanges and 4 lanes in each direction
  - An HOV lane implemented in the leftmost lane

# Network Calibration

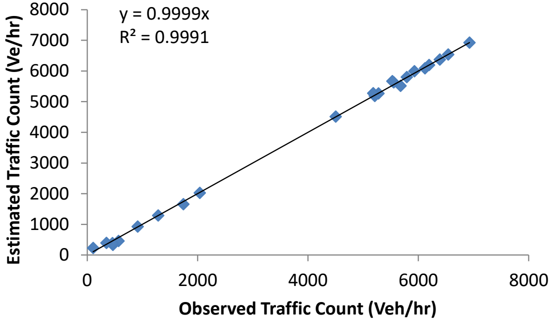
- Data Collection
  - Remote traffic microwave sensors (speed, volume, and occupancy)
  - Video cameras (ramp volume)
  - INRIX probe vehicle data (TMC travel time)




Speed-flow diagram




Travel Time (TMC 110+01476)




O-D estimation

# CACC Managed Lane Strategies

<table>
<tr><th>Strategy</th><th>ID</th><th>1st Lane</th><th>2nd Lane</th><th>3rd Lane</th><th>4th Lane (leftmost)</th><th>MPR, %</th><th>Access Control</th></tr>
<tr><td>Base case</td><td>BASE</td><td colspan="3">GP+ HOV</td><td>HOV</td><td>N/A</td><td rowspan="4">No</td></tr>
<tr><td>Unmanaged lane</td><td>UML</td><td colspan="4">GP +CACC</td><td rowspan="4">10~50</td></tr>
<tr><td>Mixed managed lane</td><td>MML</td><td colspan="3">GP +HOV + CACC</td><td>CACC + HOV</td></tr>
<tr><td>CACC lane w/o access control</td><td>DL</td><td colspan="3">GP + CACC</td><td>CACC</td></tr>
<tr><td>CACC lane w/ access control</td><td>DLA</td><td colspan="3">GP + CACC</td><td>CACC</td><td>Yes</td></tr>
</table>

**GP: General Propose**

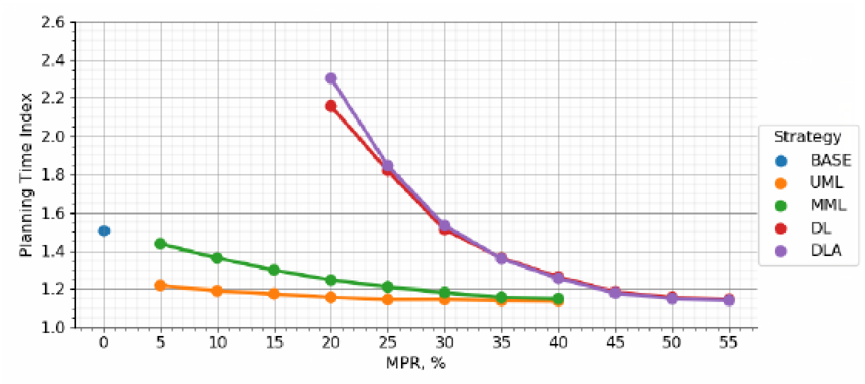
**HOV: High occupancy vehicle**

# Simulation Assumptions

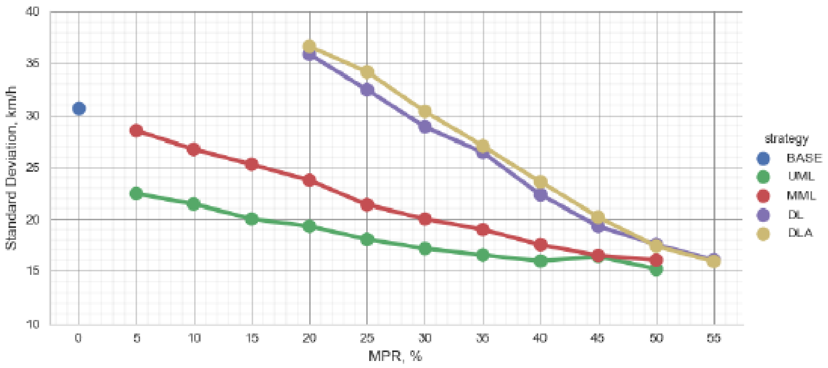
- Calibrated vehicle behaviors in Vissim realistically represent the road users' driving behaviors.
- The vehicle controller is free of control errors.
- The lateral control for platoon formation is conducted by human drivers with recommendations for lane change from the CACC system.
- Human-driven vehicles treat CACC vehicles as another human-driven vehicles. (no indication whether a vehicle is equipped with CACC system)

# Results

- Five aspects are focused on:
  1) mobility, 2) safety, 3) equity, 4) emission, and 5) platoon clustering performance




1) Mobility: planning time index




2) Safety: std. deviation of speed

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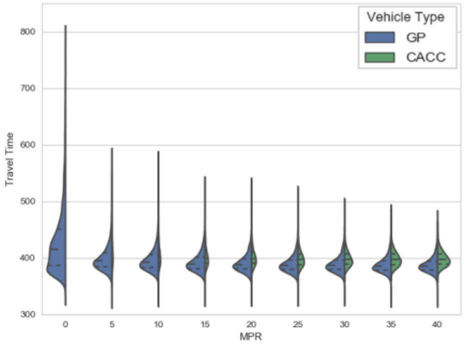
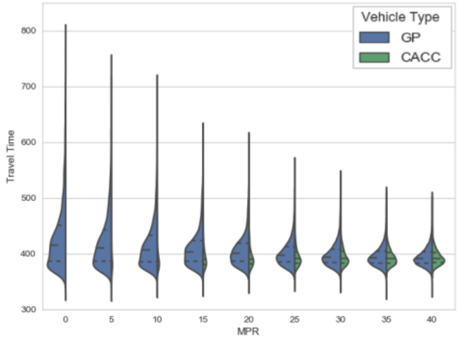
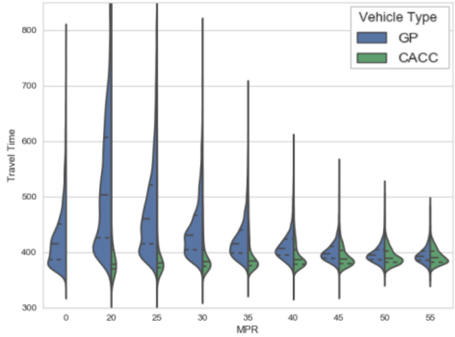
# Results (cont’d)



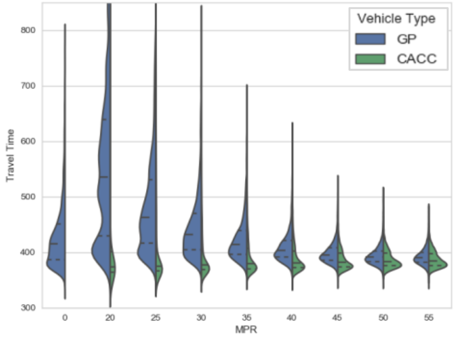

(a) no managed lane




(b) mixed managed lane

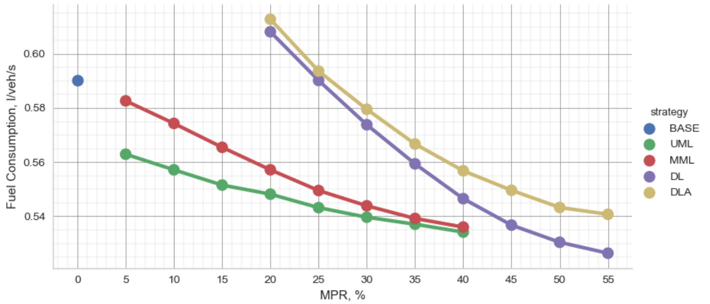



(c) dedicated lane

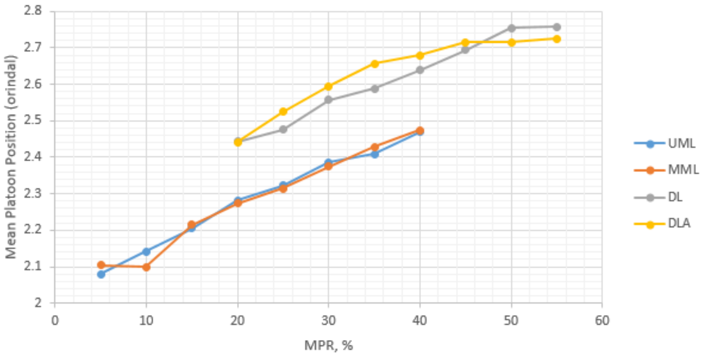



(d) dedicated lane with access control

3) Equity: travel time comparison




4) Environmental: avg. fuel consumption




5) Platoon: avg. platoon size

# Evaluation Score Matrices

| MOEs | Evaluation Score Assignment |
|---|---|
| Mobility, safety, equity, and environmental impact | improvement: 1<br>neutral: 0<br>degradation: -1 |
| CACC platooning | ranked among 4 strategies<br>1st : 4 (best)<br>2nd: 3<br>3rd: 2<br>4th:1 (worst) |

| | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UML | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| MML | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| DL | 0 | 0 | 0 | 0 | -1 | -1 | 1 | 3 | 2 | 4 | 4 | 4 |
| DLA | 0 | 0 | 0 | 0 | -2 | -2 | -2 | 2 | 2 | 3 | 4 | 4 |

(a) traffic performance score

| | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|
| UML | 4 | 4 | 4 | 2 | 2 |
| MML | 4 | 4 | 4 | 5 | 5 |
| DL | 5 | 4 | 4 | 5 | 5 |
| DLA | 7 | 8 | 8 | 8 | 8 |

(b) platooning performance score

| | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|
| UML | 1.33 | 1.33 | 1.33 | 1.00 | 1.00 |
| MML | 1.33 | 1.33 | 1.33 | 1.50 | 1.50 |
| DL | 0.67 | 0.50 | 0.83 | 1.33 | 1.17 |
| DLA | 0.83 | 1.00 | 1.00 | 1.67 | 1.67 |

(c) normalized sum of score

# Policy Recommendations

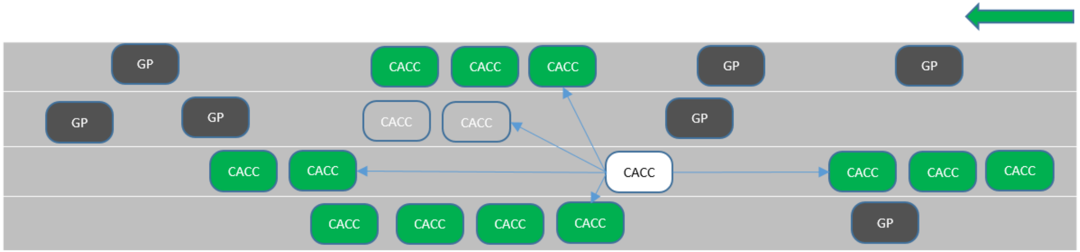
| Strategy/ MPR | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% |
|---|---|---|---|---|---|---|---|---|---|---|
| Unmanaged | | | | | | | | | | |
| Mixed | | | | | | | | | | |
| Dedicated | | | | | | | | | | |
| Dedicated | | | | | | | | | | |

- Mixing CACC traffic across all travel lanes is an acceptable option when the market penetration rate is below 30%.
- Mixed managed lane is a versatile option for providing priority lane usage for CACC
- Dedicated lane starts to show its advantage when mid-rang MPR (30% -55%) is reached

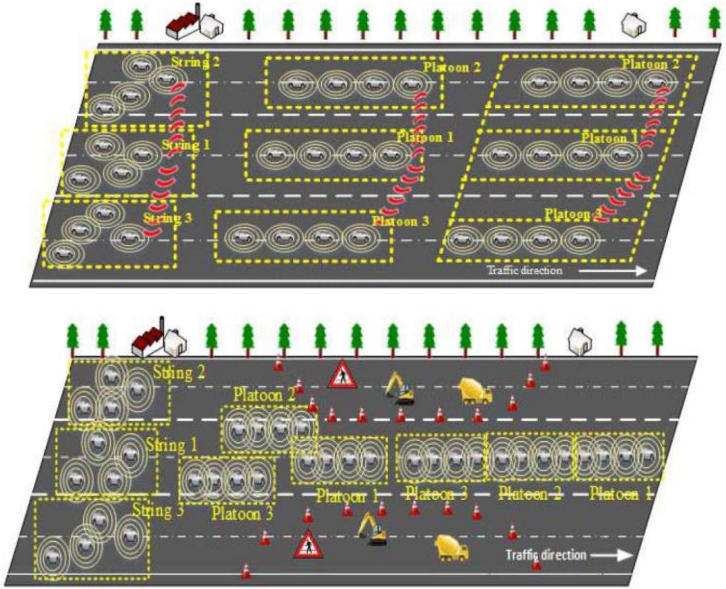
# FUTURE RESEARCH

# CAV Platoon Clustering

- Determine the platoon to join for a free-agent CACC vehicle, considering:
  - O-D information
  - size of the platoon
  - expected maneuvers, etc.
- Cooperative among platoons




**A free-agent CACC vehicle join an existing or form a new platoon**

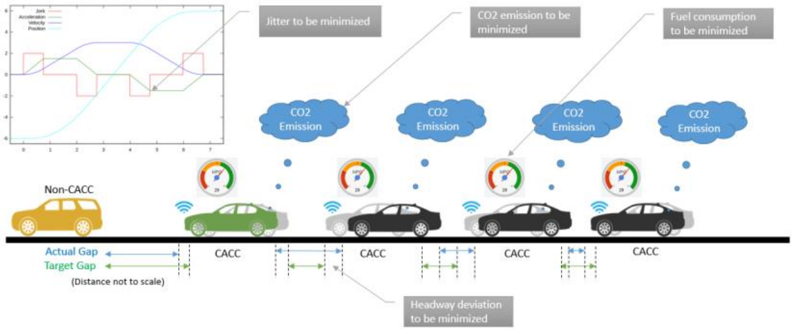



**CACC Platoon Coordination (source: Li et al. 2018)**

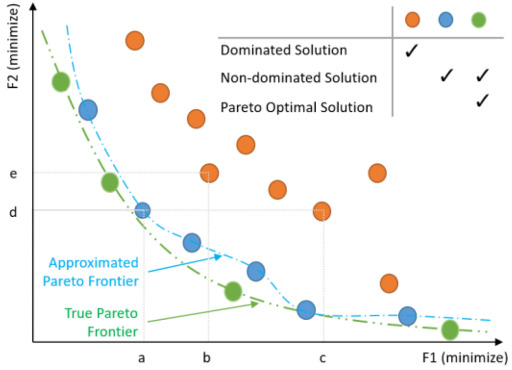
**(potential funding agencies: NSF Civil Infrastructure Systems (CIS) program, Department of Defense)**

# Optimization-based Cooperative Driving

- Framework for conducting cooperative driving at platoon level
- Dynamic prioritization of certain objectives based on operational need




**Multi-objective-based cooperative driving**

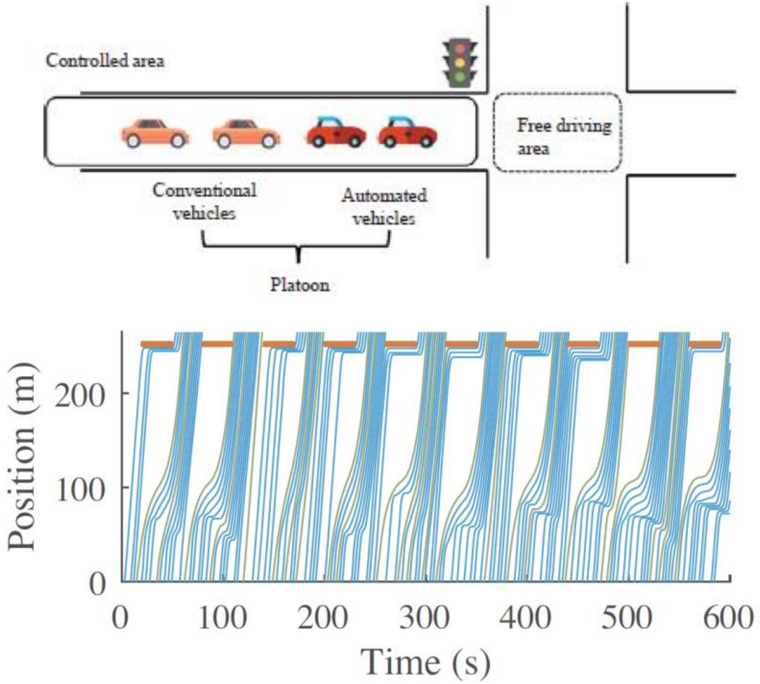



**Pareto-optimality**

**(Potential funding agencies: FHWA, Advanced Research Projects Agency–Energy)**

# CAV at Intersection

- Platoon based cooperative eco-driving
  - The lead vehicle in the platoon received signal phase and timing information via V2I communication
  - The traffic states are available via V2V communication
  - CAVs indirectly control HVs




**Time-space diagram for intersection crossing (Source: Zhao et al. 2018)**

**(Potential funding agencies: ARPA-E, FHWA)**

# Impact on non-CAV Traffic

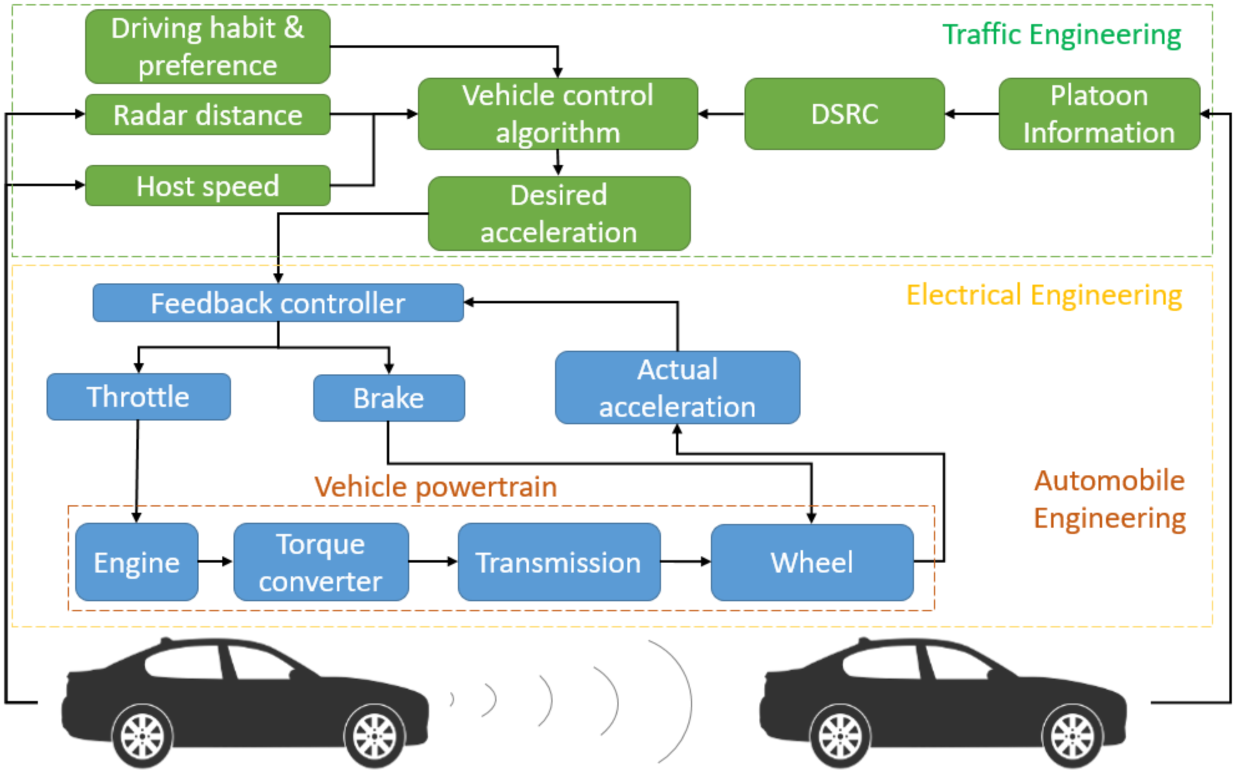
- The presence of closely-coupled CACC vehicles in the proximity of other human drivers
- Influence of the induced lane change when CACC vehicles form platoons
- Impact of user preference aspect of CAV (e.g. aggressiveness setting) on non-CAV traffic

| | |
|---|---|
| **THW14**<br>Distance between vehicles in platoons: 1.4 s. |  |
| **THW03**<br>Distance between vehicles in platoons: 0.3 s. |  |

**Driving next to a CACC platoon (source: Gouy et al. 2014)**

**(Potential funding agencies: NSF-CIS, FHWA)**

# Multidisciplinary Nature of CAV



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# Managed Lane Throughput