Managed Lane Strategies for Near-term Deployment of Cooperative Adaptive Cruise Control

AVS 2020 Breakout Session: The (Dedicated) Road to Deployment: What are the priorities?

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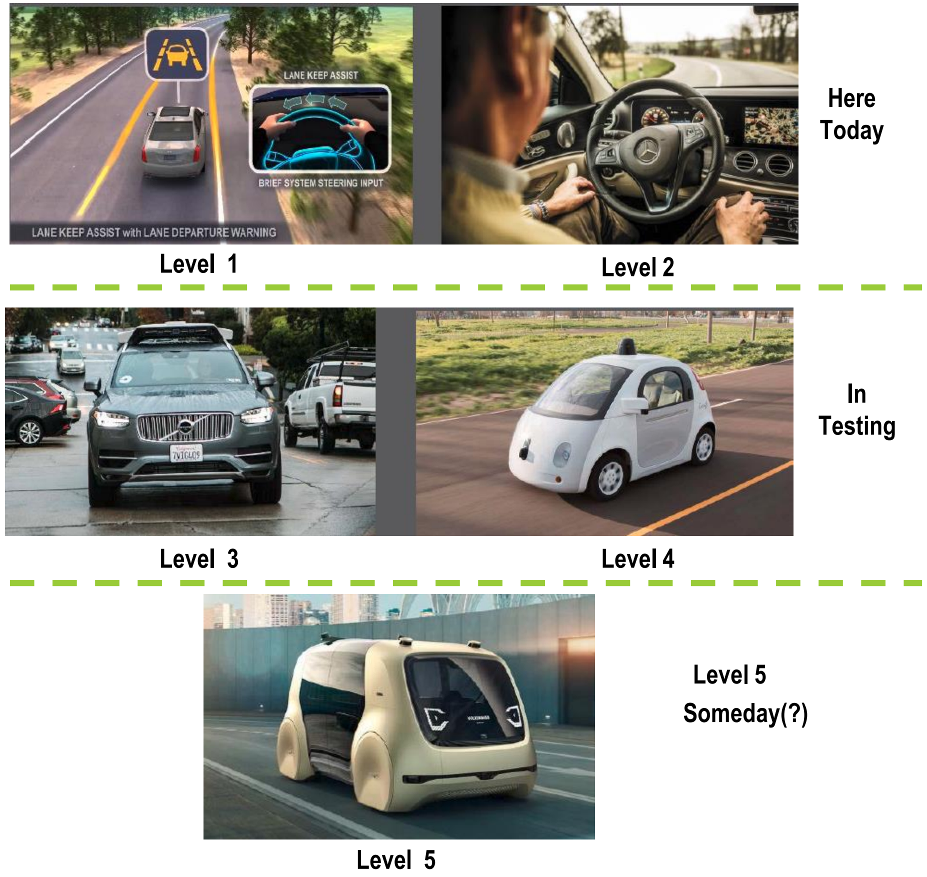
Near-term CACC Deployment

The field testing of CACC has been accelerated in recent years.

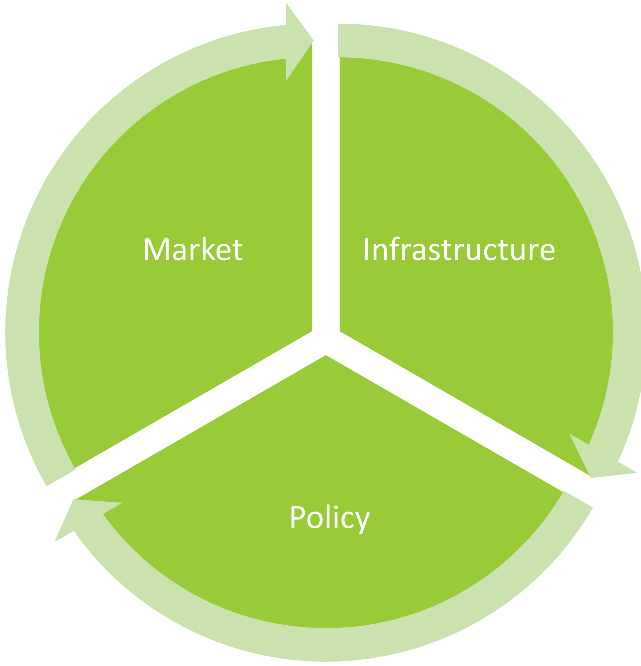
There are still questions:

- The network-wide traffic impact of CACC vehicles under *mixed traffic conditions*
- The potential impacts of CACC to non-equipped vehicle *(e.g., human-driven vehicles)*
- The deployment strategies to accommodate and incentivize CACC adoption under *low market penetration*
- Cooperative driving framework *at scale*
- *Imperfect DSRC communication* in deployment



Transition to Full Market Penetration

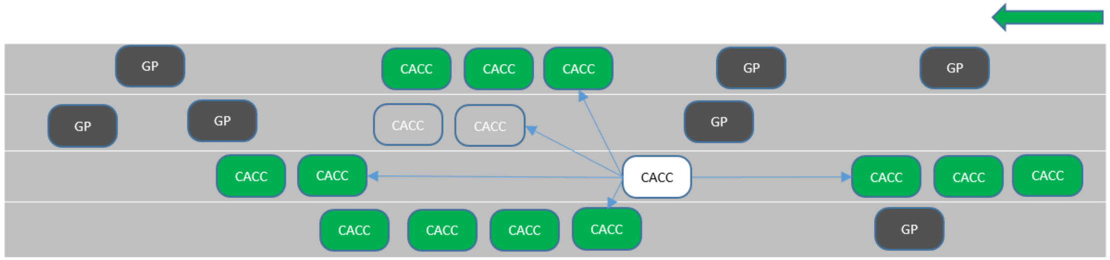
- Infrastructure
  - DSRC-enabled Roadside Units
  - Automated Driving Systems
- Policy
  - Preferential lane use
  - Technical accommodation
- Market
  - Incentive to upgrade & retrofit



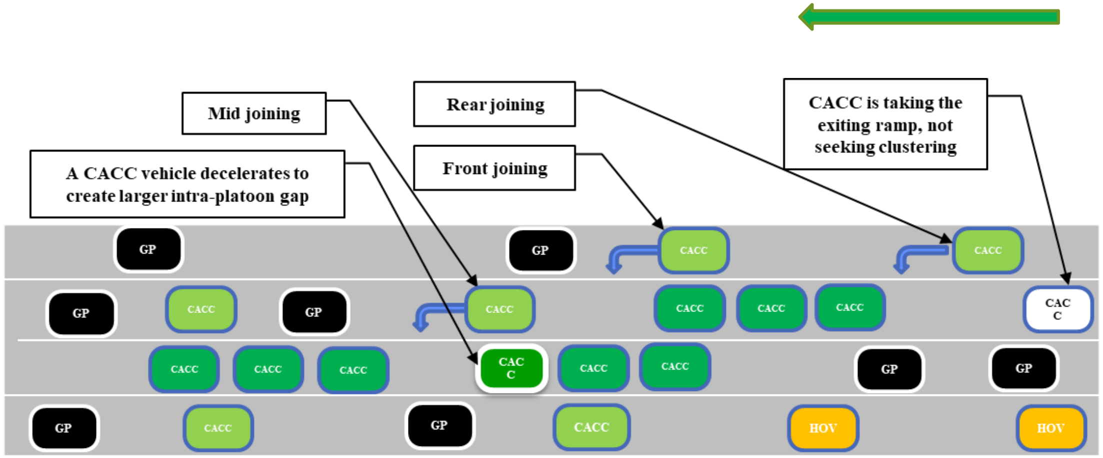
CACC Vehicle Clustering

Clustering strategies for CACC platoons

- Ad hoc coordination
- Local coordination (active platooning)
- Global coordination (end-to-end platooning)



Traffic flow direction

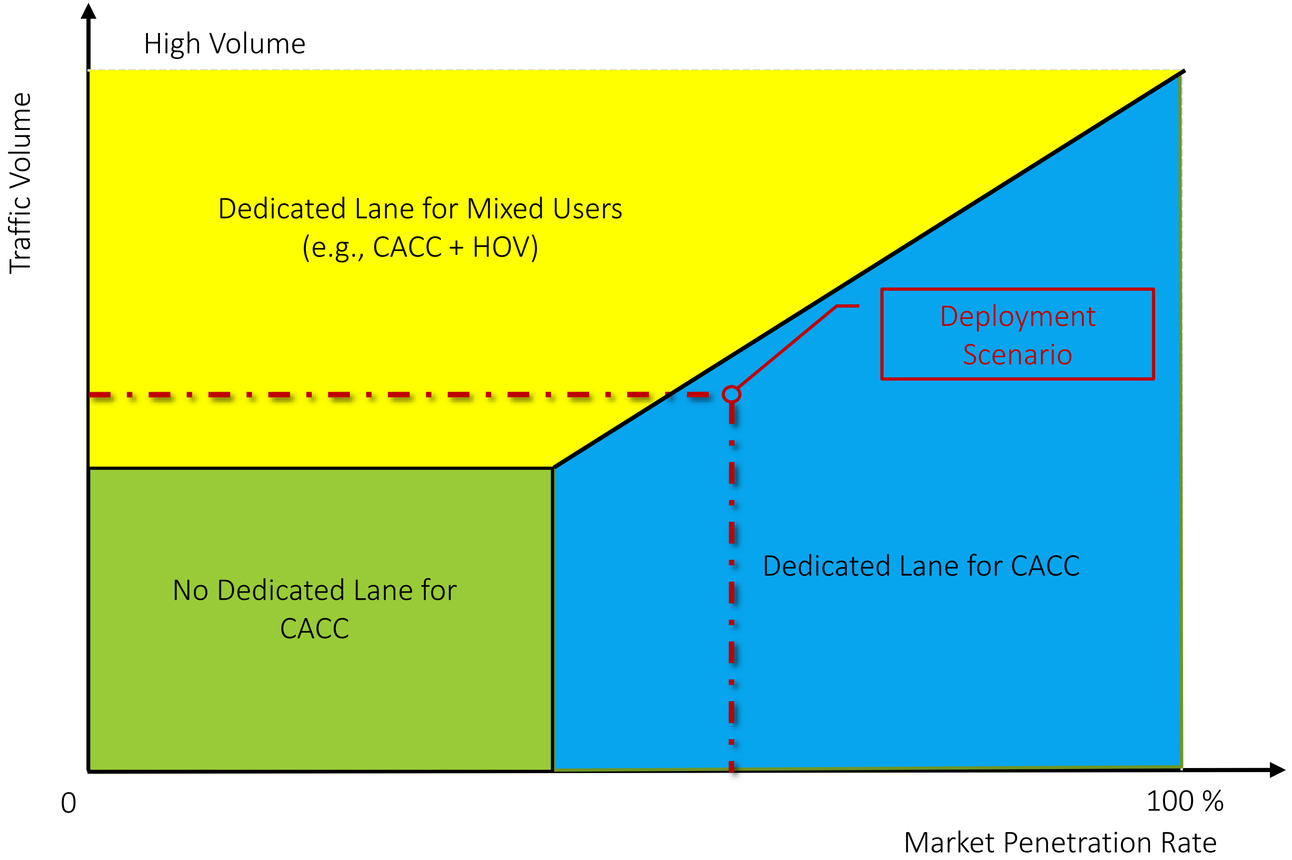


CACC platoon formation

Managed lane policy for CACC

- Creates a local high market penetration region
- Increases traffic homogeneity
- Alleviate vehicle localization issue

Goal: Suitable Managed Lane Strategy



- Managed lane facilitates CACC clustering to *harness 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)*

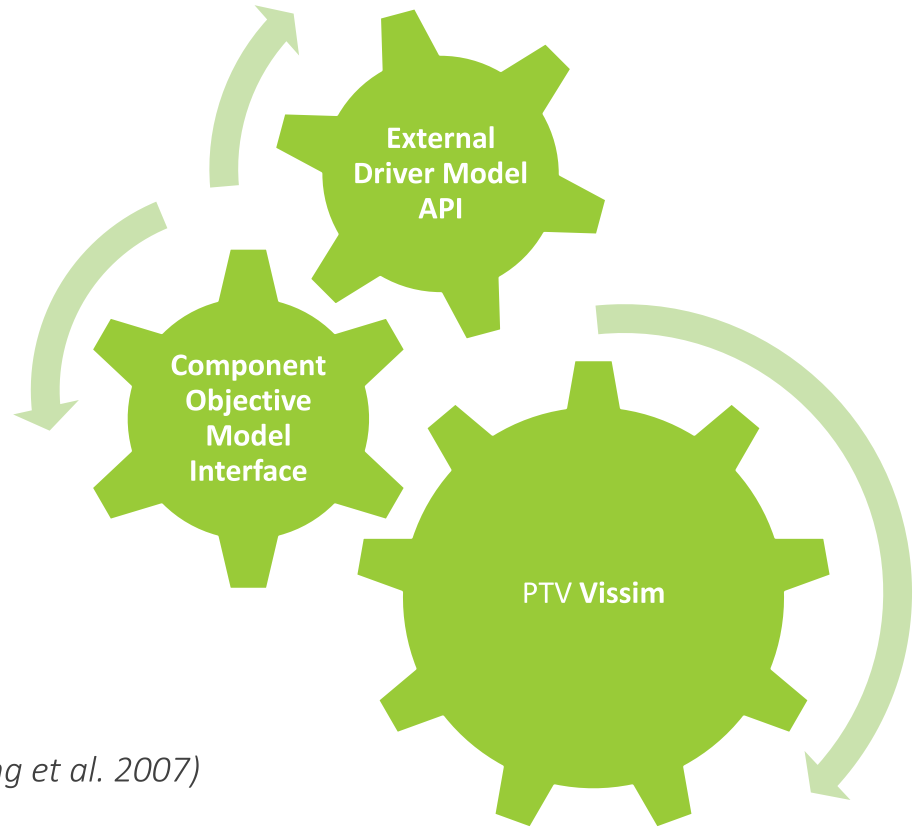
$$\ddot{x} = \begin{cases} a[1-(\frac{\dot{x}}{\dot{x}_{des}})^{\delta} - (\frac{s^*(\dot{x},\dot{x}_{lead})}{s_0})] & \text{if } x = \ddot{x}_{IDM} \geq \ddot{x}_{CAH} \\ (1-c)\ddot{x}_{IDM} + c[\ddot{x}_{CAH} + b \cdot tanh(\frac{\ddot{x}_{IDM}-\ddot{x}_{CAH}}{b})] & \text{otherwise} \end{cases}$$

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

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

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

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



I-66 Simulation Test Bed

- 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

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*

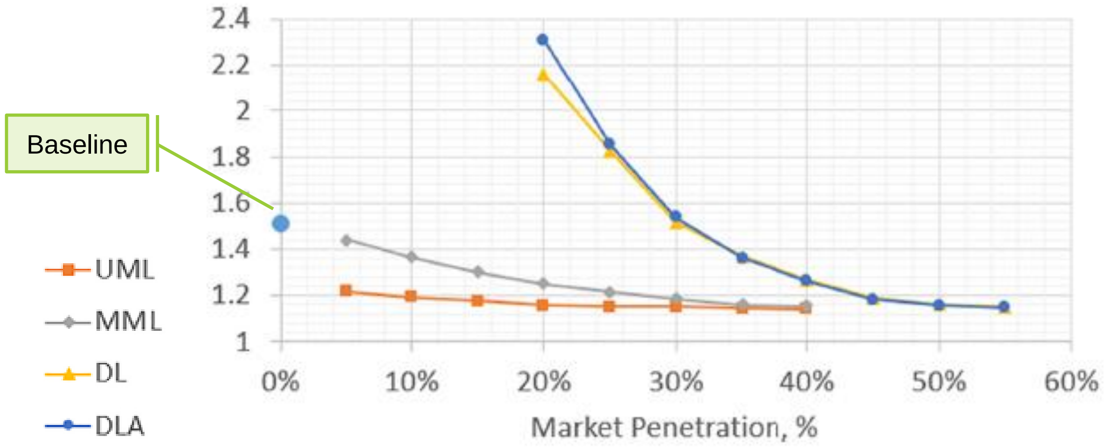
Simulation Assumptions

- Calibrated vehicle behaviors in VISSIM realistically represent the road users' driving behaviors.
- The CACC 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.

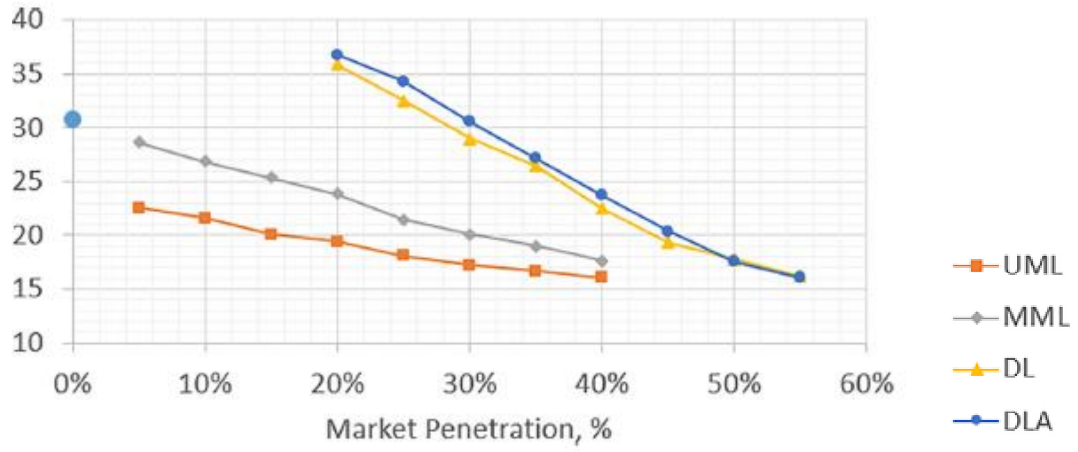
  (no indication whether a vehicle is equipped with CACC system)

Results: Mobility & Safety

Mobility: planning time index



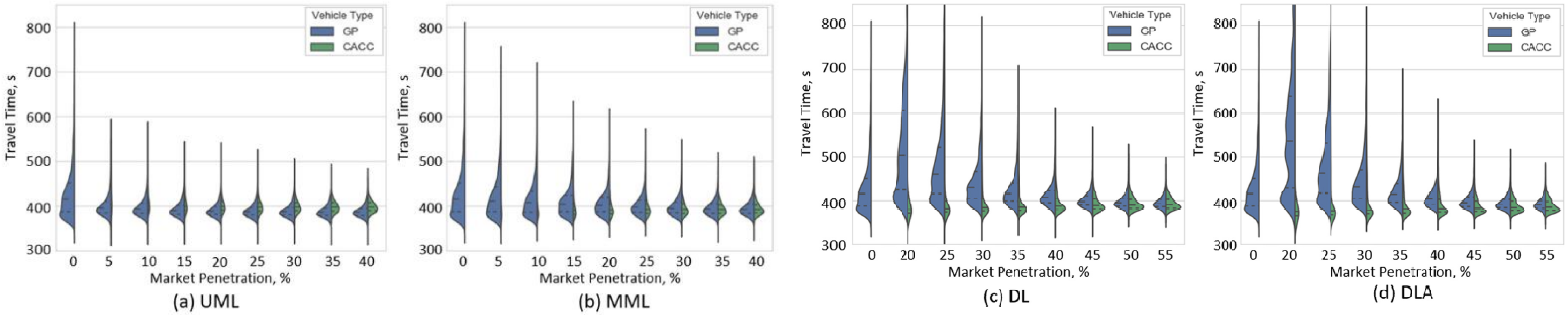
Safety: standard deviation of speed (km/h)



- Performance increases with the gradual increase of the MPR of CACC
- Managed lane needs certain MPR threshold to justify
- Significant difference observed for dedicated CACC lane

Result: Equity

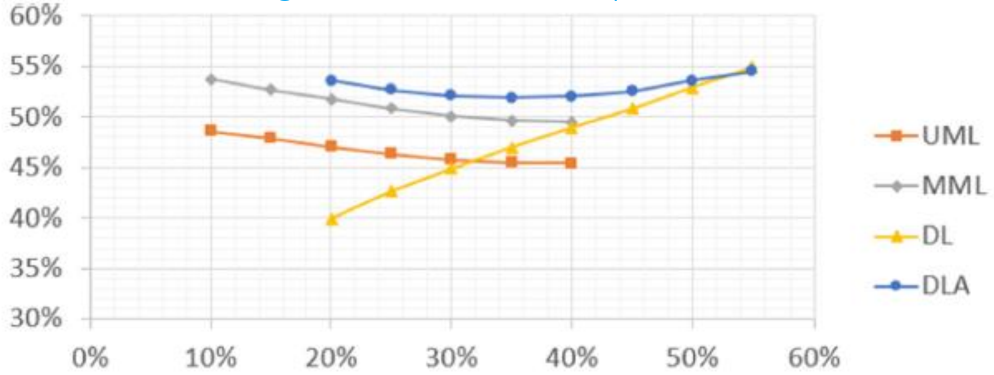
Side-by-side comparison of the travel time distributions of two user groups



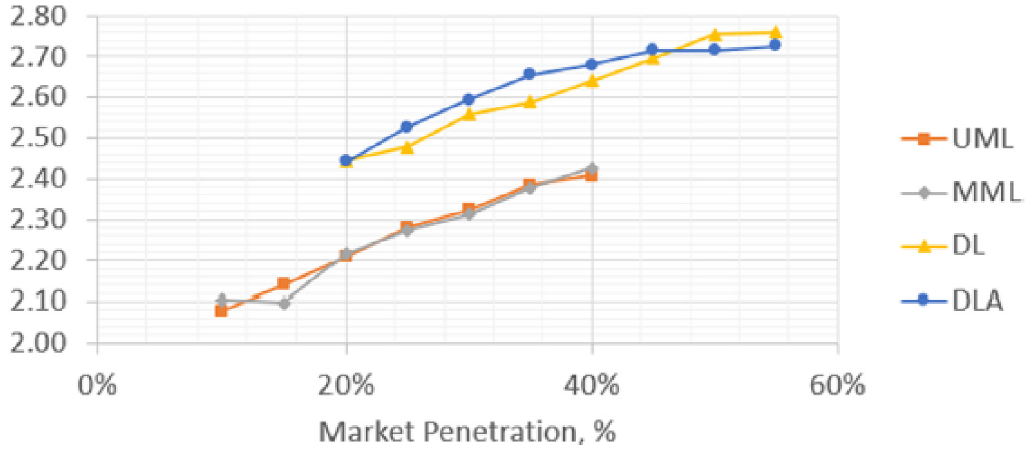
- Fairness in distributing impacts (ML users vs non-ML users)
- Use travel time to gauge the equity between managed lane & general-purpose lane users

Result: Platoon Performance

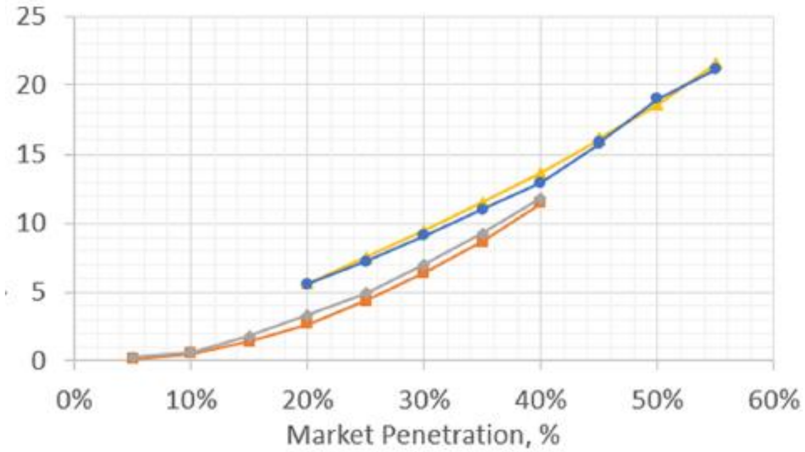
Percentage of CACC vehicles in platoons



Average platoon position (platoon depth)



Vehicle-hour platooned
(CACC vehicles x platooned time)



Conclusions

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

- Mixing CACC traffic across all travel lanes if MPR 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

- Investigate the potential impacts of local coordination of CACC in the absence of managed lane (e.g., induced lane change)
- Enhance multi-anticipative behavior of CACC car-following model
- Incorporate human factor aspect for increase the degree of realism in the CACC behavior model (e.g., ADS authority transition)
- Analyze vehicle trajectory level traffic impact analysis

Relevant Publications

1. **Z. Zhong***, E. E.Lee, M. Nejad and J. Lee, "Influence of CAV Clustering Strategies on Mixed Traffic Flow Characteristics: An Analysis of Vehicle Trajectory Data," Transp. Res. Part C: Emerging Technologies, vol.115, pp.102611, 2020, doi:10.1016/j.trc.2020.102611

2. **Z. Zhong*** and J. Lee, "The Effectiveness of Managed Lane Strategies for the Near-term Deployment of Cooperative Adaptive Cruise Control," Transp. Res. Part A: Policy and Practices, vol.129, pp. 257–270, 2019, doi:1016/J.TRA.2019.08.015

3. **Z. Zhong***, M. Nejad, E. E.Lee, and J. Lee, "Clustering Strategies of Cooperative Adaptive Cruise Control: Impacts on Human-driven Vehicles", in IEEE 2nd Connected and Automated Vehicles Symposium, Honolulu, Hawaii, USA, 2019

4. **Z. Zhong**, J, Lee*, and L. Zhao, "Evaluations of managed lane strategies for arterial deployment of cooperative adaptive cruise control," in 96th Transp. Res. Board Annu. Meeting, Washington, DC, USA, 2017

Contact

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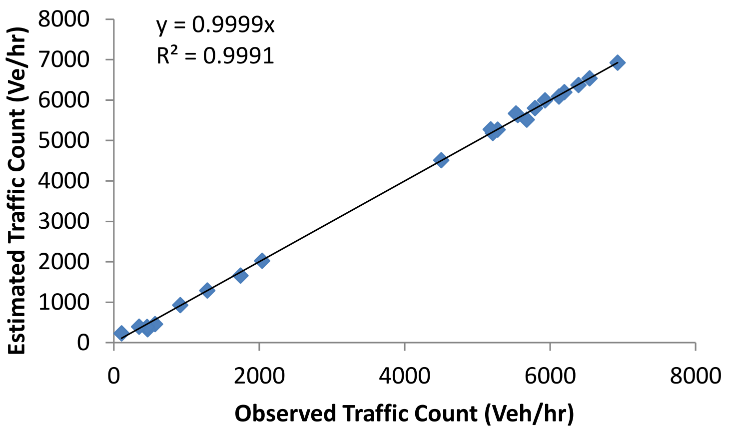
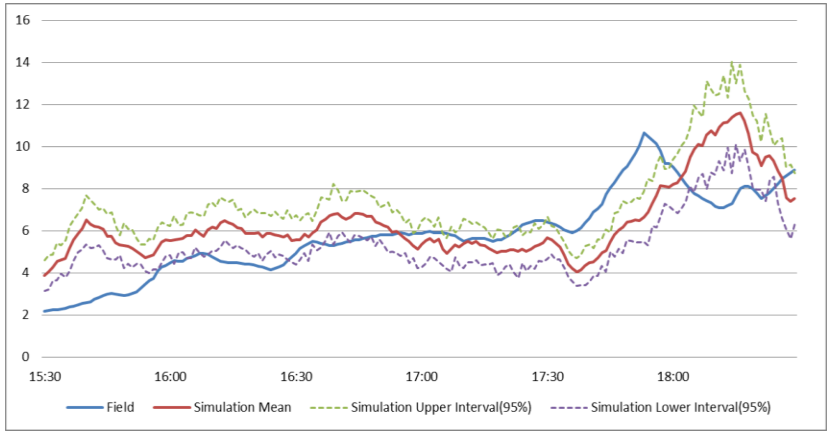
Network Calibration

Data Collection

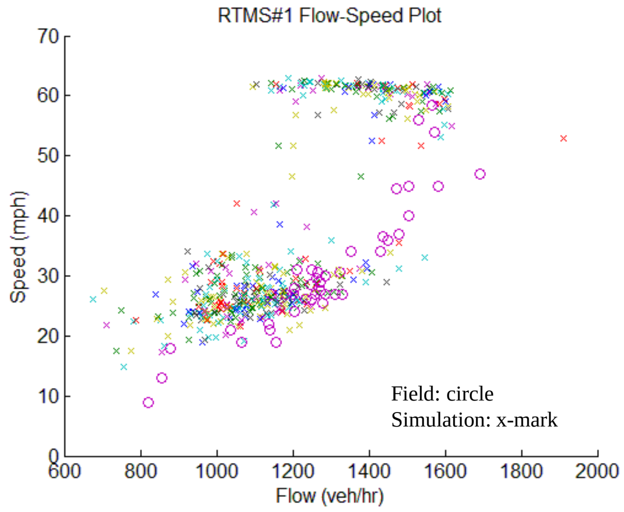
- Remote traffic microwave sensors (speed, volume, and lane occupancy)
- Video cameras (ramp volume)
- INRIX probe vehicle data (TMC travel time)



O-D estimation



Travel Time (TMC 110+01476)



Speed-flow diagram

Managed Lane Evaluation Score

- A simple score system factors in the heterogeneous performance measures
  - Traffic performance score based on comparison with the baseline case
  - Platooning performance score based on the comparison among CACC scenarios (MP>0%)

Parameter	Evaluation Score
Traditional performance measure (mobility, safety, equity, and environmental impact)	improvement: 1 neutral: 0 degradation:-1
CACC platoon formation	ranked among 4 strategies 1st: 4, 2nd: 3, 3rd: 2, 4th: 1

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

(a) traffic performance score

MP	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

MP	20%	25%	30%	35%	40%
UML	1.33	1.33	1.33	1	1
MML	1.33	1.33	1.33	1.5	1.5
DL	0.67	0.5	0.83	1.33	1.17
DLA	0.83	1	1	1.67	1.67

(c) normalized sum of score