Assessing the Effectiveness of Managed Lane Strategies for the Rapid Deployment of Cooperative Adaptive Cruise Control Technology

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Biographic Sketch

2005-2009

- **B.Eng. in Environmental Engineering, Jinan University, P.R. China**

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- **M.S. in Civil Engineering, NJIT**

2011-2013

- **LMW Engineering Group, LLC**

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- **Ph.D. Candidate, NJIT**
  - **2017 Outstanding Graduate Student Award, ITS NJ**
  - **2015 The Future of ITS-NJ Scholarship Award, ITS NJ**

Journal Papers	Z. Zhong, L. Joyoung, and L. Zhao, "Multiobjective Optimization Framework for Cooperative Adaptive Cruise Control Vehicles in the Automated Vehicle Platooning Environment," Transp. Res. Rec. J. Transp. Res. Board, vol. 2625, pp. 32–42, 2017.
	J. Lee, Z. Zhong, B. Du, S. Gutesa, and K. Kim, "Low-cost and energy-saving wireless sensor network for real-time urban mobility monitoring system," J. Sensors, vol. 2015, pp. 1–8, 2015.
Peer-review Conference Papers	Lee, J., Zhong, Z., Singh, J., Dimitrijevic, B., Chien, S., Spasovic, L. "Real-time performance measure monitoring system for long-term freeway work zone," in *Intell. Transp. Syst. World Congress 2017*, Montreal, Canada
	Lee, J., Gutesa, S., Zhong, Z., Dimitrijevic, B., Spasovic, L., Singh, J. "Evaluation of freeway merging assistance system using driving simulator," in *Intell. Transp. Syst. World Congress 2017*, Montreal, Canada
	Z. Zhong, L. Joyoung, 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.
	J. Lee, Z. Zhong, B. Du, S. Gutesa, and K. Kim, "Low-cost and energy-saving wireless sensor network for real-time urban mobility monitoring system," *J. Sensors*, vol. 2015, pp. 1–8, 2015.
	Z. Zhong and J. Lee, "Development of CID-free hardware-in-the-loop simulation framework," in *96th Transp. Res. Board Annu. Meeting*, Washington, DC, USA, 2017.
	J. Lee *et al.*, "WIMAP: work zone interactive monitoring application," in *94th Transp. Res. Board Annu. Meeting*, Washington, DC, USA, 2015, no. 15–4257.
	J. Lee, Z. Zhong, K. Kim, B. Dimitrijevic, B. Du, and S. Gutesa, "Examining the applicability of small quadcopter drone for traffic surveillance and roadway incident monitoring," in *94th Transp. Res. Board Annu. Meeting*, Washington, DC, USA, 2015, no. 15–4184.
	Zhong, Z., and Lee, J. Estimation of real-time origin-destination flow using mobile sensor network, "in *21st Intell. Transp. Syst. World Congress*, Detroit, MI, USA, 2014

Presentation Outline

- Introduction
- Literature Review Summary
- CACC Control Algorithm
- Integrated Simulation Framework
- Simulation Results
- Conclusions & 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 1

Level 2

Here Today

Level 3

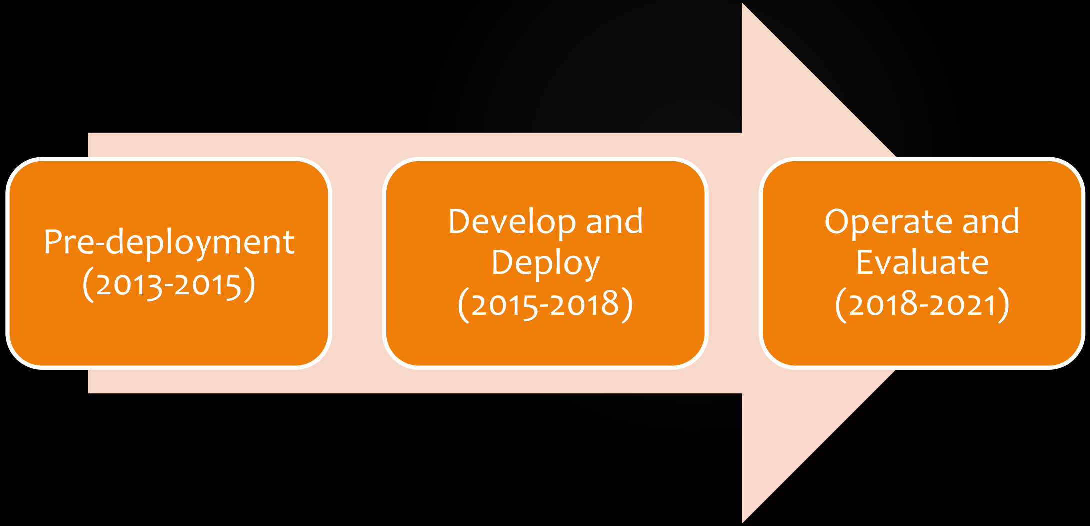
Level 4

In Testing

NHTSA Level of Automation

Level 5 Someday (?)

- The USDOT has initiated the Connected Vehicle Pilot Deployment Program with 3 major pilot sites for testing C/AV technologies



Pre-deployment (2013-2015)

Develop and Deploy (2015-2018)

Operate and Evaluate (2018-2021)

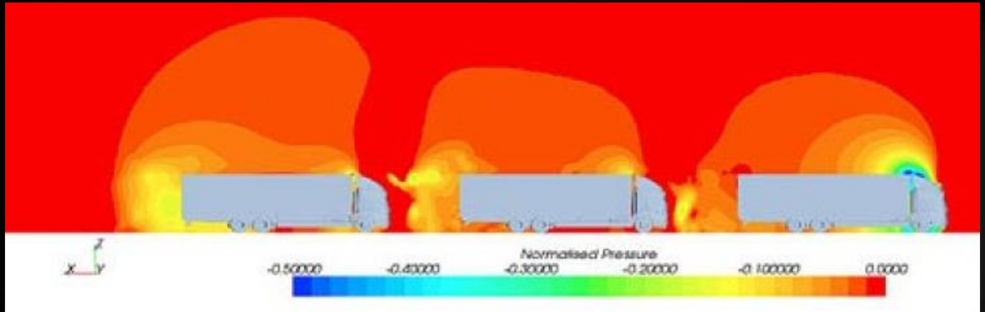
- The near-term large-scale deployment of CACC can be facilitated by managed lane strategies

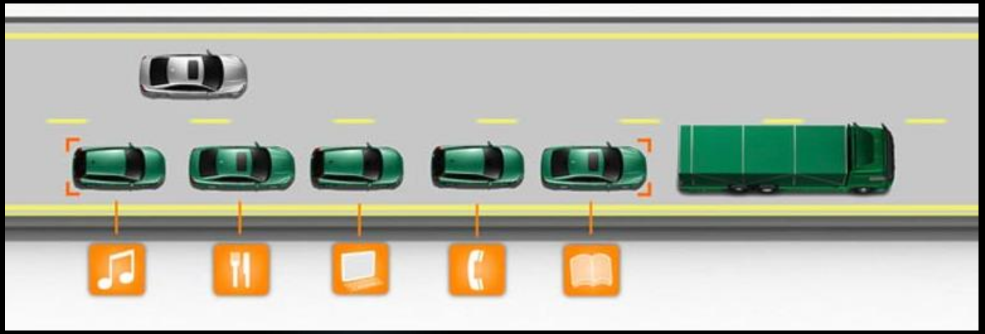
**Managed lanes are freeway lanes that are set aside and operated under a variety of strategies responding to local goals as well as objectives*

Motivations for CACC Deployment

Cooperative Adaptive Cruise Control (CACC) is an extension of the adaptive cruise control with an extra layer of vehicle-to-vehicle communication.

1. To reduce traffic congestion by improving highway capacity and attenuating traffic flow disturbances
2. To reduce fuel consumption by decreasing air resistance via a tightly coupled platoon
3. To improve safety, comfort, and convenience





LETERATURE REVIEW SUMMARY

Summary: Field Experiment of CACC

1. Large-scale field experiments are expensive and only possible to limited entities
    - European Truck Platooning Challenge (2016)
    - USDOT Pilot Deployment Programs (2015)
    - Grand Cooperative Driving Challenge (2011)
    - Safe Road Train for the Environment (2009)
    - Energy ITS Project(2008)

Summary: Simulation Studies CACC

2. Traffic simulators provide realistic vehicle behaviors & interactions, whereas network simulators deal with packet-level simulation with various communication protocols

  - Studies only focused on the packet-level communication simulation and vehicle movements are overly simplified
  - Studies post-process the communication simulation and, as such, the wireless communication has no influence on vehicle movements
  - Studies used synchronizers to gain the advantages of traffic simulator and network simulator, but the simulation scale are limited due to the computational burden

3. A microscopic simulation framework that is able to implement CACC vehicle behaviors, provide realistic vehicular interaction, and take into account the communication impacts at large-scale, is desired

Research Goal & Objectives

- Research Goal
  - To evaluate the impacts of deploying CACC vehicles into existing traffic and the operational benefits of implementing managed lane strategies

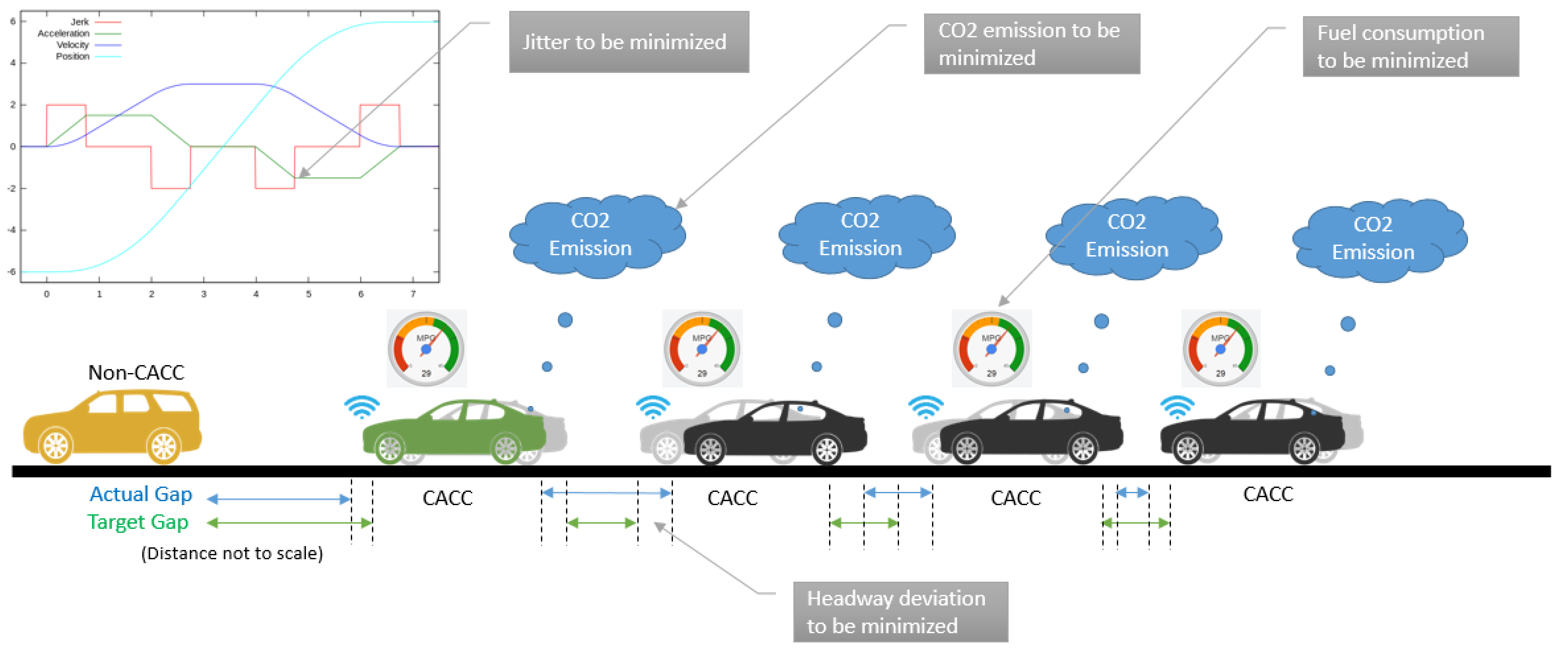
- Objectives
  - To develop a realistic and flexible microscopic simulation testbed for testing CACC technology under mixed traffic condition
  - To formulate a platoon-wide multi-objective based CACC control algorithm that is able to accommodate various operational objectives
  - To assess a variety of available managed lane strategies for CACC under imperfect wireless communication
  - To investigate the suitable performance measures for CACC traffic

Multi-objective Optimization CACC Control Algorithm

Why multi-objective optimization for CACC Control?

- Human car-following behavior typically focus on single and often perceptible objective (e.g., safe gap, desired speed)
- CACC system can obtain precise outcomes of multiple objectives, such as fuel consumption, emission, and headway deviation.
- The MOOP-based control provides a flexible platform for obtaining the optimal action for multiple operational needs

MOOP-based Control Algorithm



Jitter to be minimized

CO2 emission to be minimized

Fuel consumption to be minimized

CO2 Emission

CO2 Emission

CO2 Emission

CO2 Emission

Non-CACC

CACC

CACC

CACC

CACC

Actual Gap

Target Gap

(Distance not to scale)

Headway deviation to be minimized

MOOP-based Control Algorithm (Cont’d)

$$\min\{(\text{Headway}) \quad \sum_{i=1}^{n} \left| H_i - h_i(\text{t}+1) \right|,$$

$$(\text{Jitter}) \quad \sum_{i=1}^{n} \beta \bullet \frac{\left| \ddot{x}_i(t+1) - \ddot{x}_i(t) \right|}{\ddot{x}_{comfort}},$$

$$(\text{CO2 \& Fuel}) \begin{cases} \text{e}^{\sum_{i=0}^{3} \sum_{j=0}^{3} (L_{i,j}^{e} \times \dot{x}_i \times \ddot{x}_j))} & \text{for } \ddot{x} \geq 0 \\ \text{e}^{\sum_{i=0}^{3} \sum_{j=0}^{3} (\text{M}_{i,j}^{e} \times \dot{x}_i \times \ddot{x}_j)} & \text{for } \ddot{x} < 0 \end{cases} \}$$

subject to

$$(\text{min. gap}) \quad \frac{x_i\,(t+1)}{\dot{x}_i\,(t+1)} \geq h_{\text{i,min}}$$

$$(\text{acceleration}) \quad \ddot{x}_{\text{i,min}} \leq \ddot{x}_i(t+1) \leq \ddot{x}_{\text{i,max}}$$

$$(\text{speed limit}) \quad \dot{x}_{\text{min}} \leq \dot{x}_i(t+1) \leq \dot{x}_{\text{max}}$$

$$(\text{E-IDM}) \quad f(T_i, s_{0,i}) = \ddot{x}_i$$

H_i – target headway for vehicle i within a platoon, s

$h_i(t+1)$ – headway of vehicle i at time interval t+1, s

n – the total number of vehicles within a platoon

β – adjustment coefficient for speed

$\ddot{x}_i(t+1)$ – acceleration of vehicle i at t+1, m/s^2

$\ddot{x}_i(t)$ – acceleration of vehicle i at t,

$\ddot{x}_{comfort}$ – comfortable threshold for acceleration, m/s^2

$L_{i,j}^{e}$ – regression coefficients for emission and fuel consumption

$\text{M}_{i,j}^{e}$ – regression coefficients for emission and fuel consumption

$h_{i,\text{min}}$ – user-defined minimum headway for vehicle i, s

$x_i\,(t+1)$ – front distance for vehicle i to preceding vehicle at time interval t+1, m

$\dot{x}_i(t+1)$ – speed for vehicle I at time interval t+1, m/s

$\ddot{x}_{\text{i,min}}$ – minimum acceleration of vehicle i, m/s^2

$\ddot{x}_{\text{i,max}}$ – maximum acceleration of vehicle i, m/s^2

$\dot{x}_{\text{min}}$ – minimum allowable speed on a particular roadway, m/s

$\dot{x}_{\text{max}}$ – maximum allowable speed on a particular roadway, m/s

MOOP-based Control Algorithm (Cont’d)

The Enhanced Intelligent Driver Model (Kesting et al., 2010)

$$\ddot{x} = \begin{cases} a\left[1-\left(\frac{\dot{x}}{\dot{x}_{des}}\right)^{\delta} - \left(\frac{s_0+\dot{x}T+\frac{\dot{x}(\dot{x}-\dot{x}_{lead})}{2\sqrt{ab}}}{s_0}\right)^2\right], \ddot{x}_{IDM} \geq \ddot{x}_{CAH} \\ (1-c)\ddot{x}_{IDM}+c\left[\ddot{x}_{CAH}+b\tanh\left(\frac{\ddot{x}_{IDM}-\ddot{x}_{CAH}}{b}\right)\right], \quad \text{otherwise} \end{cases}$$

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

$\ddot{x}$ – acceleration of ego vehicle, m/s^2

$\ddot{x}_{IDM}$ – acceleration calculated by IDM model, m/s^2

$\ddot{x}_{CAH}$ – acceleration calculated by CAH component, m/s^2

$\ddot{x}_{lead}$ – accleration of leading vehicle, m/s^2

$\dot{x}_{lead}$ – current speed of leading vehicle, m/s

$\dot{x}$ – current speed of ego vehicle, m/s

$\dot{x}_{des}$ – desired speed of ego vehicle, m/s

x – gap between the ego and leading vehicle, m

s_0 – minimum distance, m

s^* – effective minimum gap, s

Θ – Heaviside step function

a – maximum accleration, m/s^2

b – desired deceleration, m/s^2

c – coolness factor

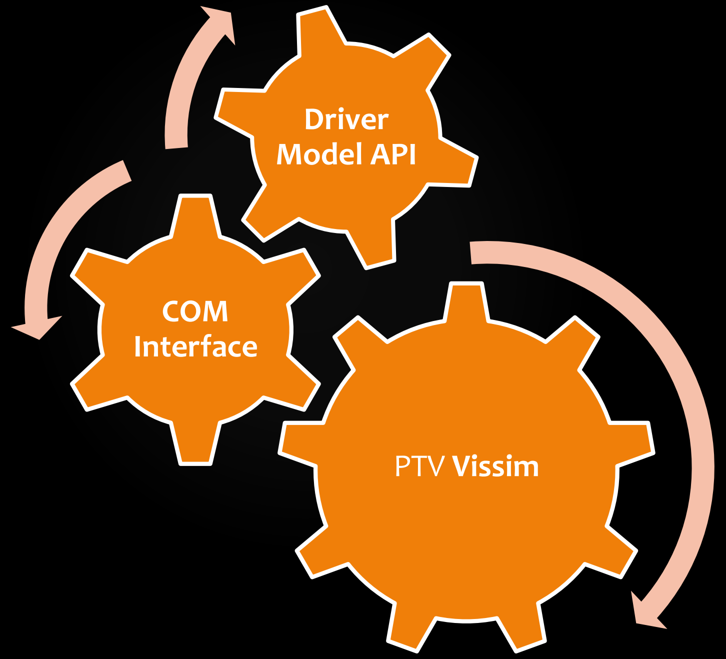
T – desired time gap, s

δ – free accelration exponent

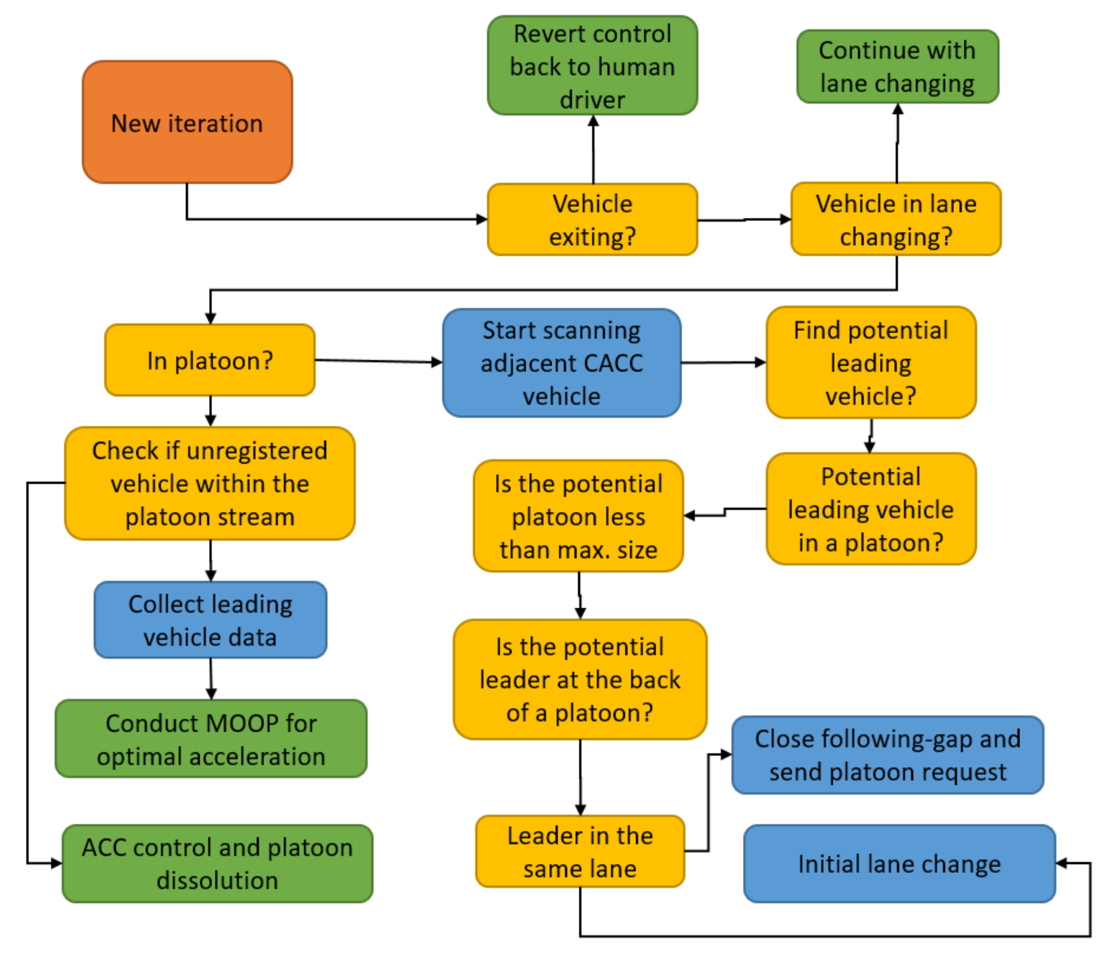
MOOP-CACC Simulation Framework

Simulation Framework

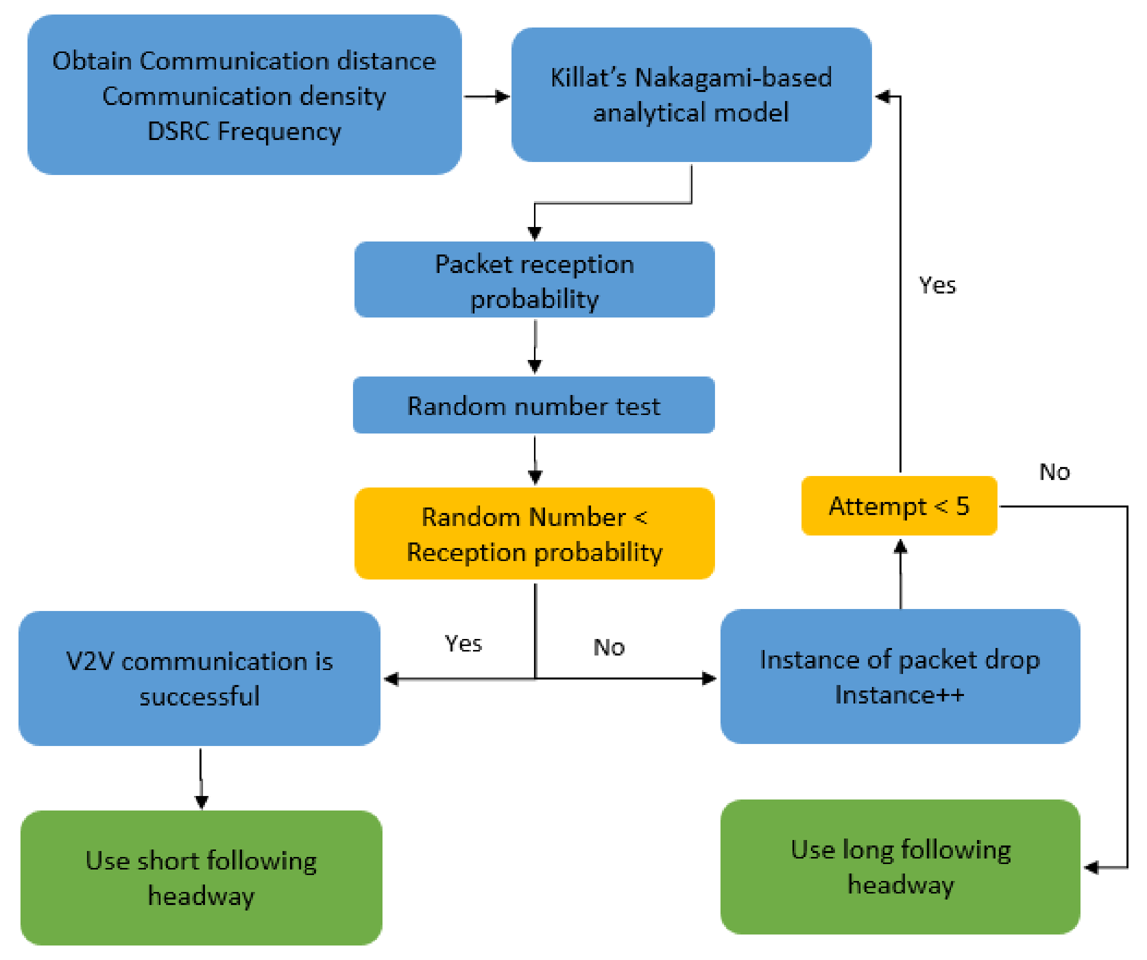
- Currently, no traffic simulators is able to offer CACC driving behavior model by default.
- PTV Vissim is customized by using its Component Object Model (COM) Interface and its Driver Model API for implementing MOOP-based CACC control



Customizations

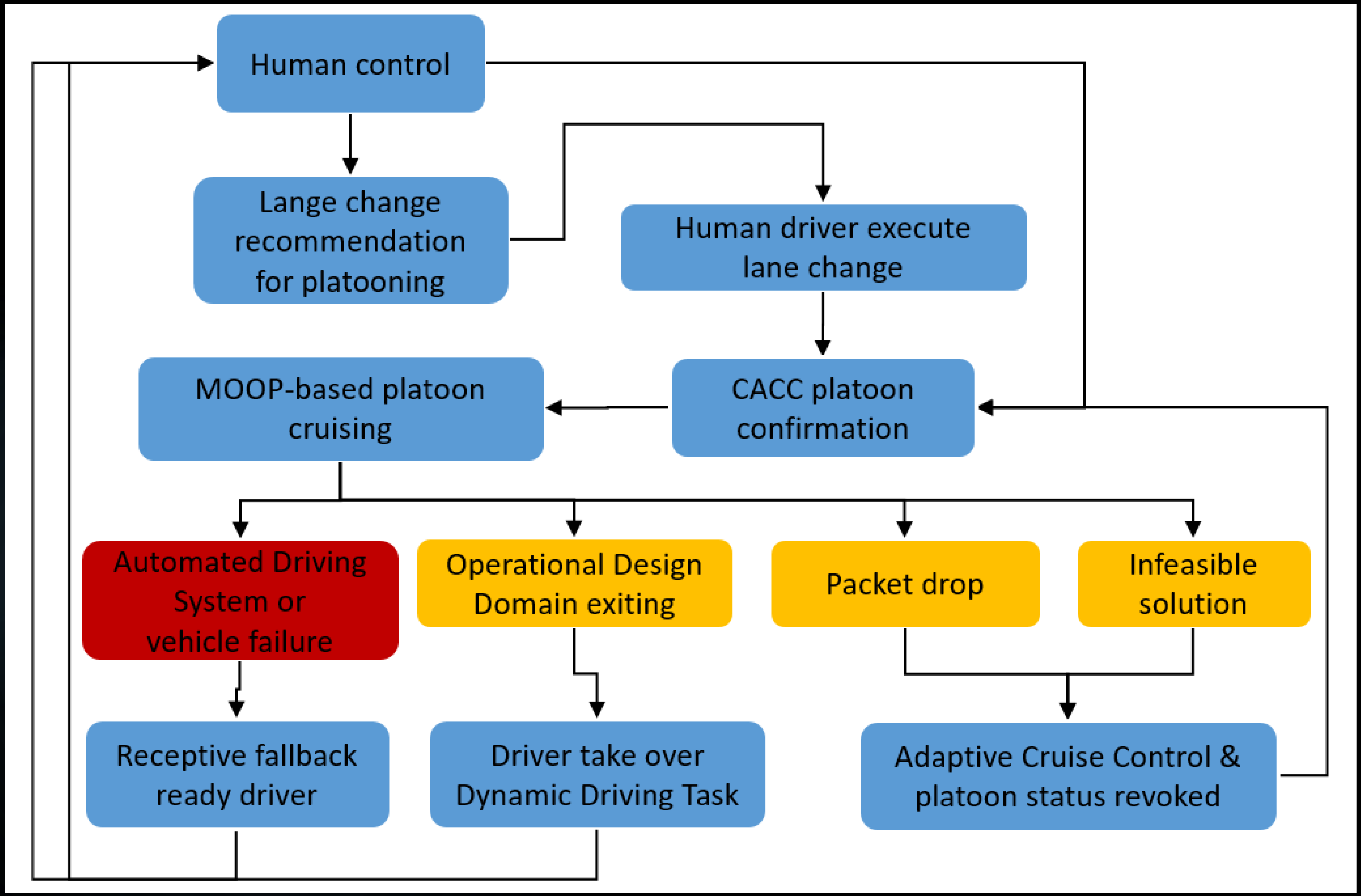


CACC platooning algorithm



DSRC communication test

CACC System Fallback



- Operational Design Domain exiting
  - A CACC vehicle reaches its destination and performs lane change to exit a platoon
  - Under congestion where speed is lower than the pre-defined speed
- Packet drop or Infeasible solution
  - CACC falls back to Adaptive Cruise Control
  - Platoon status is revoked temporarily

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
  - Calibrated driving behaviors by TMC data (travel time) and RTMS (speed-flow) data of PM-peak hours

CACC Managed Lane Strategies

	4th (leftmost)	3rd	2nd	1st	Access Control
Base Case (BASE)	HOV	GP	GP	GP	N
Unmanaged lane (UML)	GP+CACC	GP+CACC	GP+CACC	GP+CACC	N
Mixed Managed Lane (MML)	CACC + HOV	GP	GP	GP	N
Dedicated Lane (DL)	CACC	GP	GP	GP	N
Dedicated Lane w/ Access Control (DLA)	CACC	GP	GP	GP	Y

*GP: general purpose/ human-driven vehicles

Simulation Environment

Vissim Simulation

- Simulation Period: 3900s
- Warm-up period: 300s
- Replication: 5
- Market Penetration Rate: 0% - 50%

Optimization

- Optimization Interval: 2.5s
- NSGA-II Solver: Python Platypus
- Pipelining package: Python Joblib

Communication

- Transmission density update: 0.5s
- Max. transmission attempts: 5

Hardware

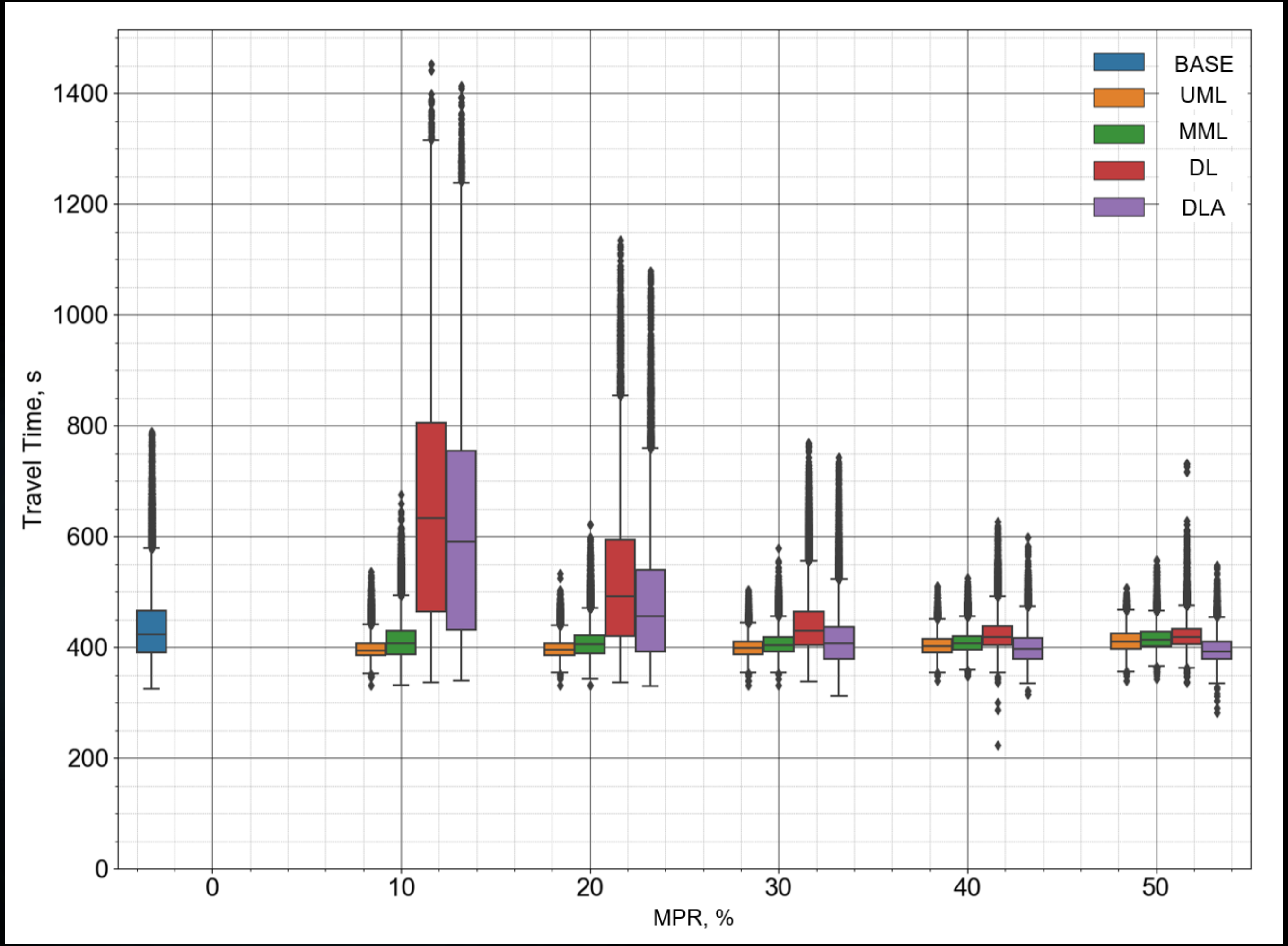
- Dual-Xeon CPUs with 32 logical cores
- 96 GB RAM

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)

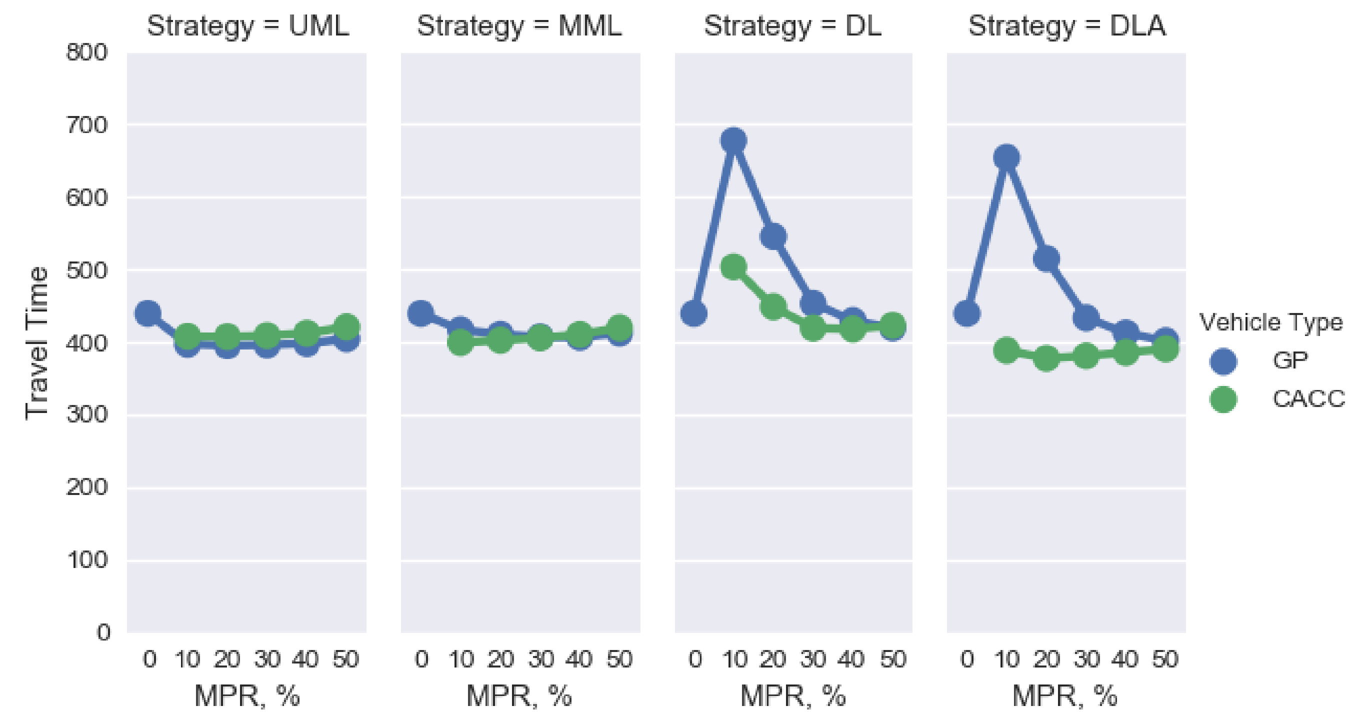
Simulation Results

Mainline Travel Time



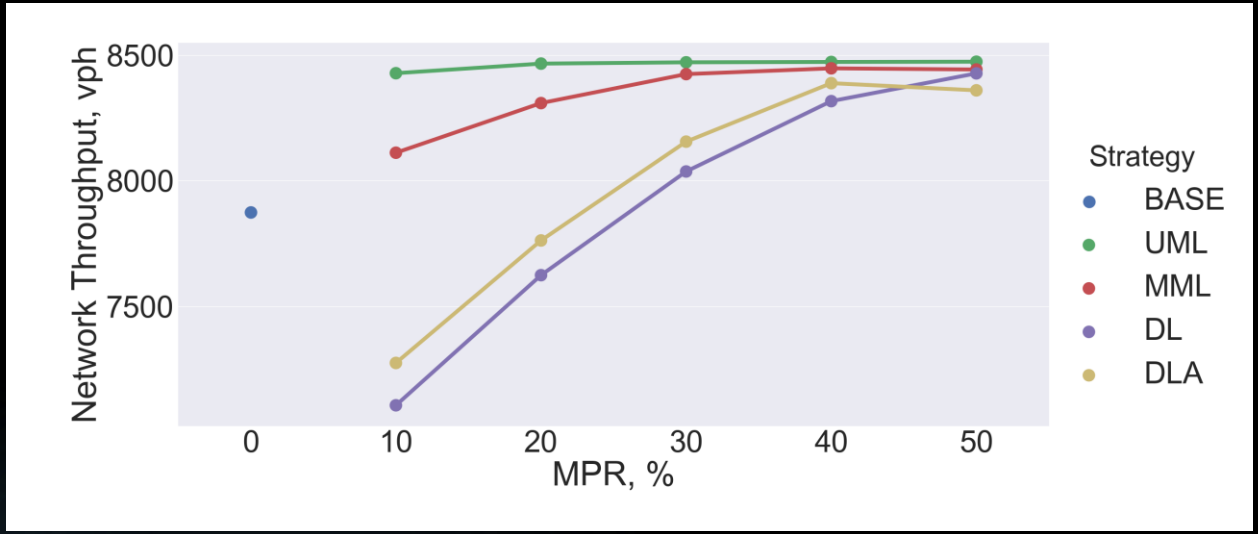
- Travel time in UML and MML have lower variance than BASE among all MPRs
- The break-even market penetration rate (MPR) for DL and DLA in comparison to the BASE is 30%.
- DLA consistently outperforms DL among all levels of MPR by yielding a lower travel time median.

Equity Aspect of CACC Deployment

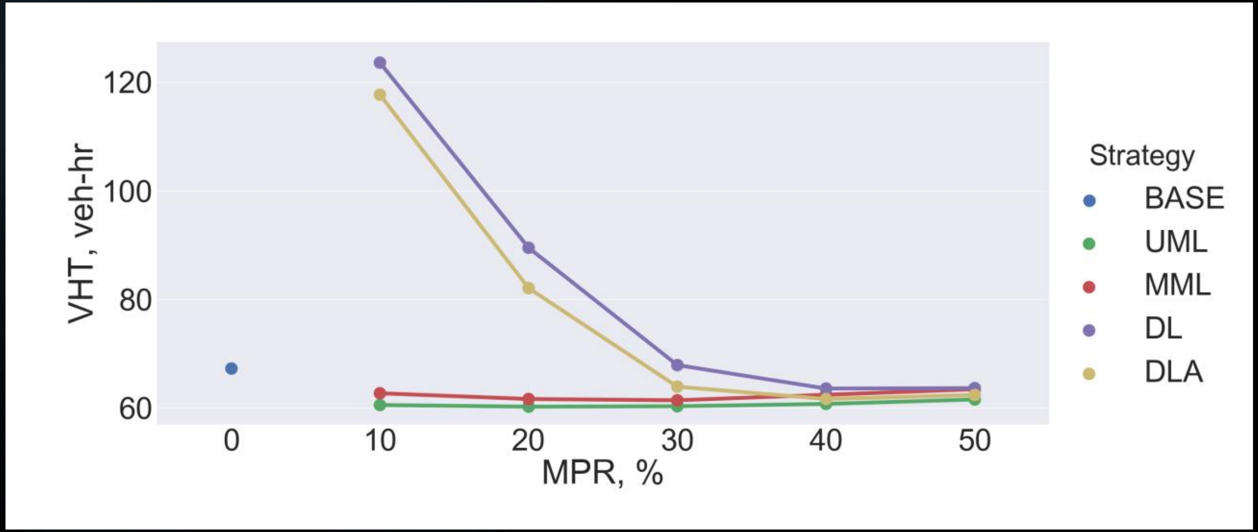


- The introduction of CACC is able to reduce mainline travel time for both CACC and GP vehicles.
- The spike in travel time at low MPR for DL and DLA indicates that equity issue may become a concerns for GP vehicles

Network Performance Measure



Network Throughput

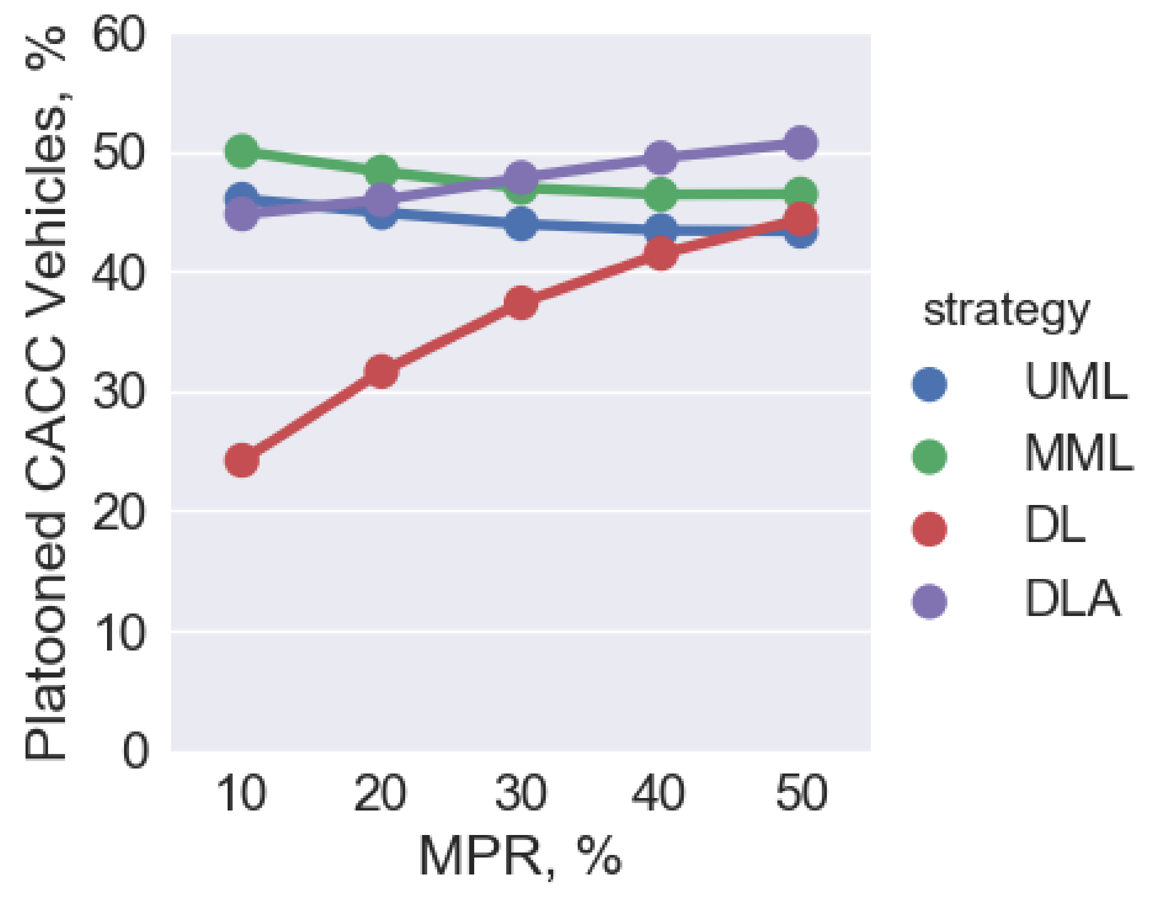


Vehicle-hour-traveled (VHT)

- Currently, the network serves approximately 7900 vph.
- Greatest throughput improvement:
  - UML: by 7.6% (600 vph) at 20% MPR
  - MML: by 7% (550 vph) at 40% MPR
  - DL: by 7% (550 vph) at 50% MPR
  - DLA: by 6.3% (500 vph) at 40% MPR

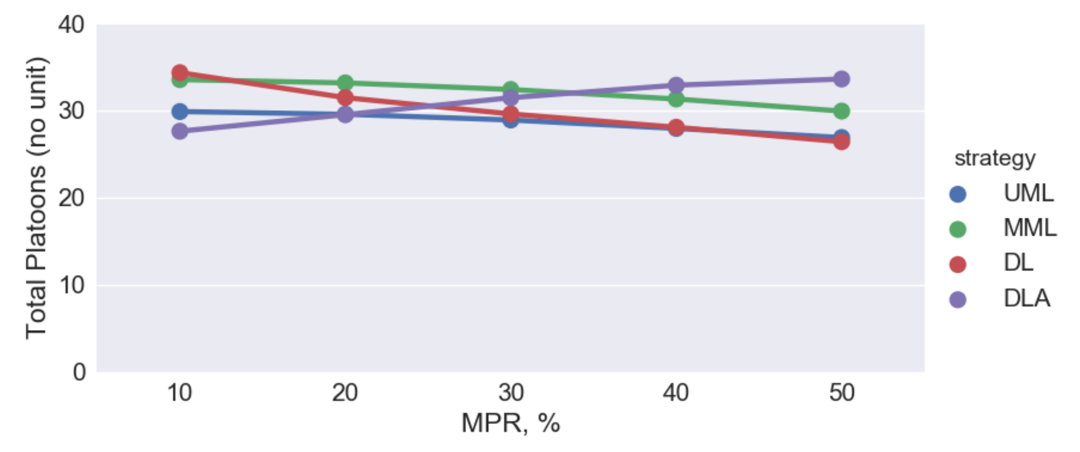
- UML and MML achieve the best reduction in VHT at 30% MPR by 7.7 veh-hr to 60.5 veh-hr
- The break-even MPR for DL and DLA compared to BASE is 30%.
- The overall trend indicates that the efficiency of the network is increased steadily by the introduction of CACC

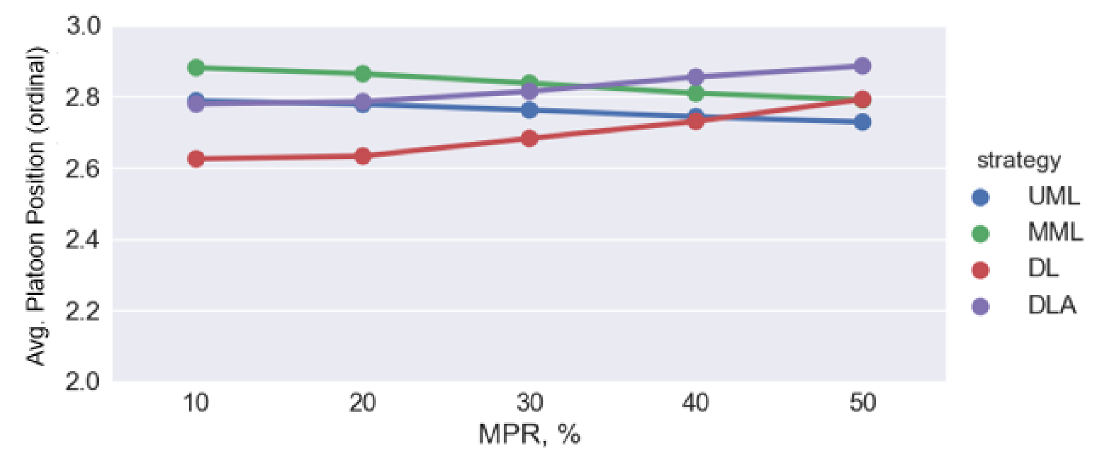
Platoon Performance Measure



- The percentage of platooned CACC in UML is consistently lower than that of MML
- Unlike in UML and MML, the percentage of platooned CACC vehicles is positively correlated to MPR in DL and DLA
- The low percentage of platooned CACC in DL is caused by the cut-ins when CACC vehicles merge on to the managed lane in the absence of access control

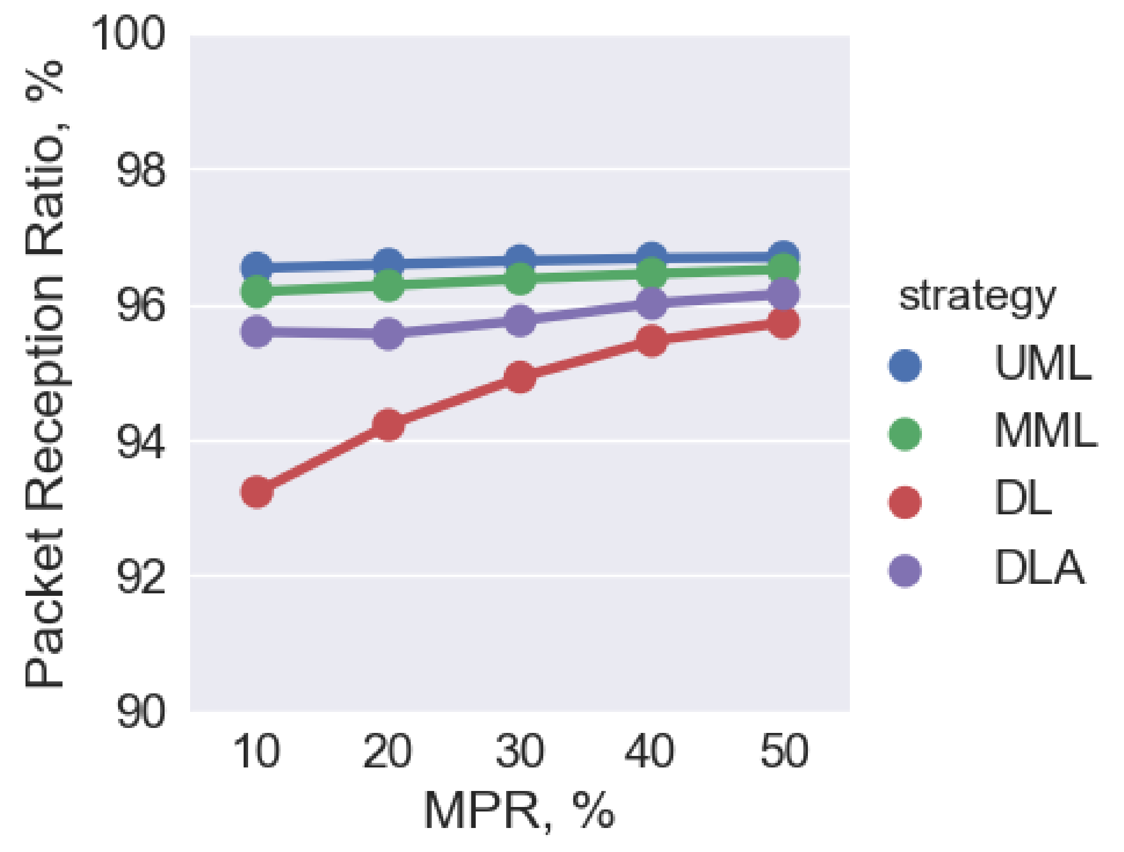
Platoon Performance Measure (cont'd)





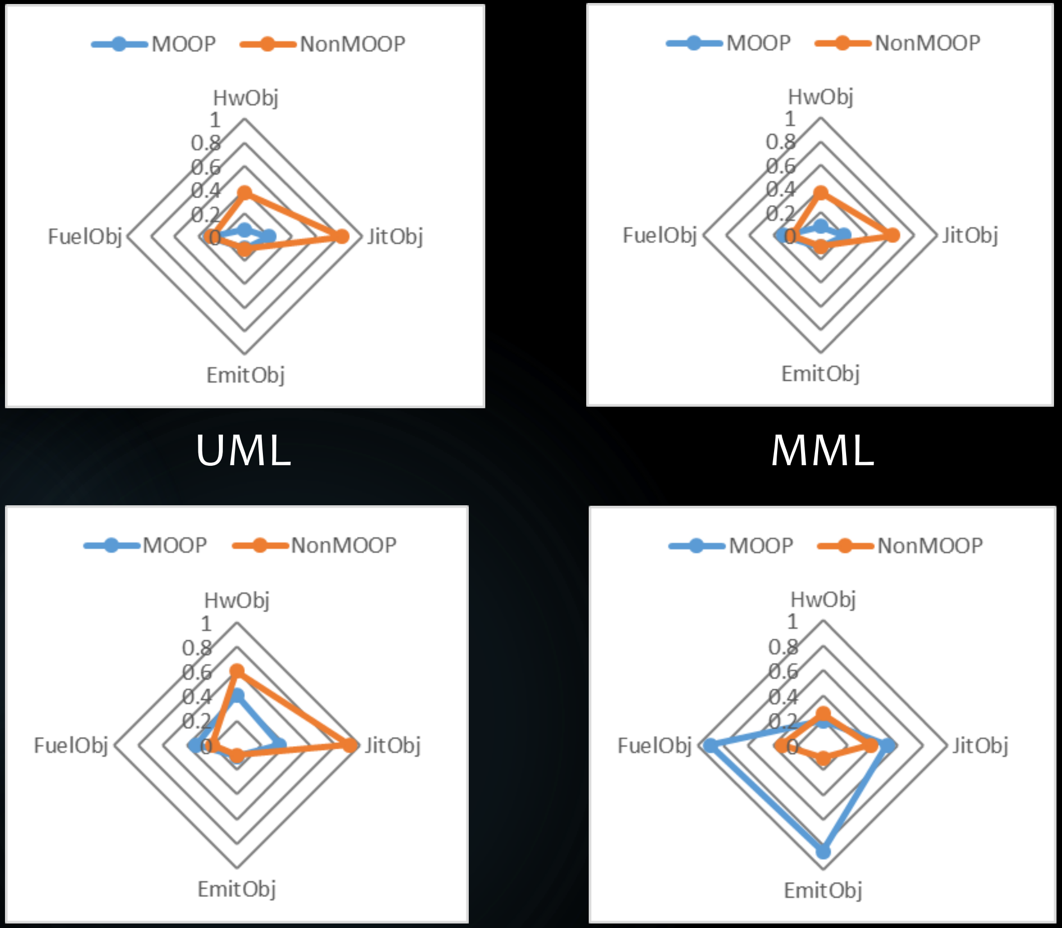
	MPR	Total Platoon	Avg. Platoon Position	Correlation	Note
UML	+	-	-	positive	less and smaller platoons
MML	+	-	-	positive	less and smaller platoons
DA	+	-	+	negative	less but larger platoons
DLA	**+**	**+**	**+**	**positive**	**more and larger platoons**

Communication Performance Measure



- The reception probability is above 92.5% for all cases.
- The reception ratio becomes a less impactful factor in choosing strategies.
- DL has the lowest probability among all strategies at any given MPR, due to the affect of induced weaving onto the managed lane.

Optimization Results



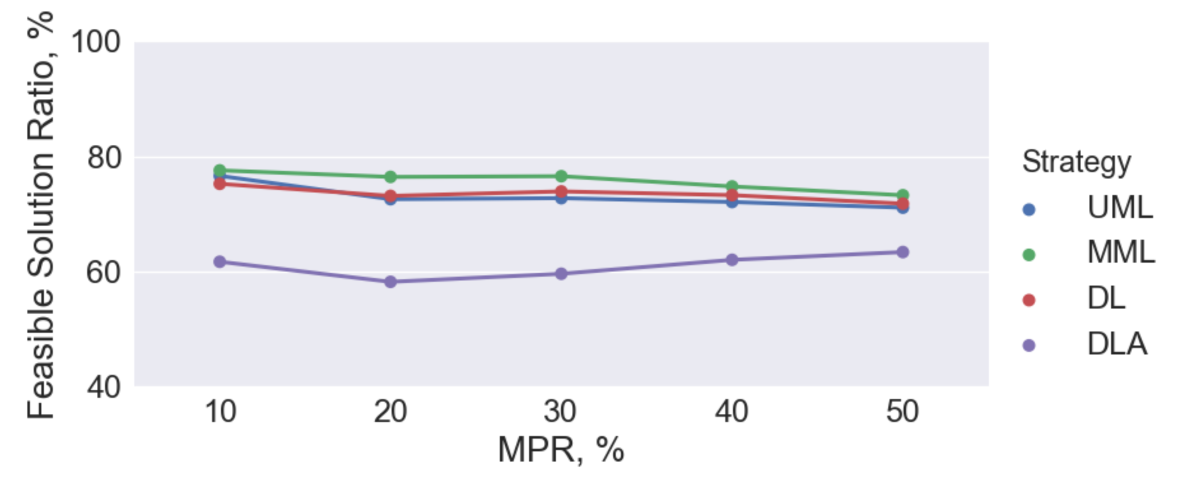
UML

MML

DL

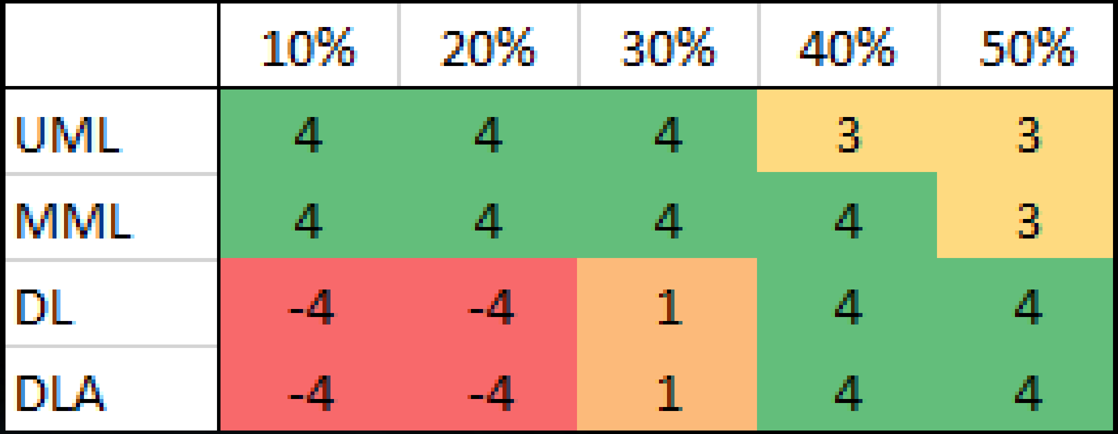
DLA

Normalized objective values



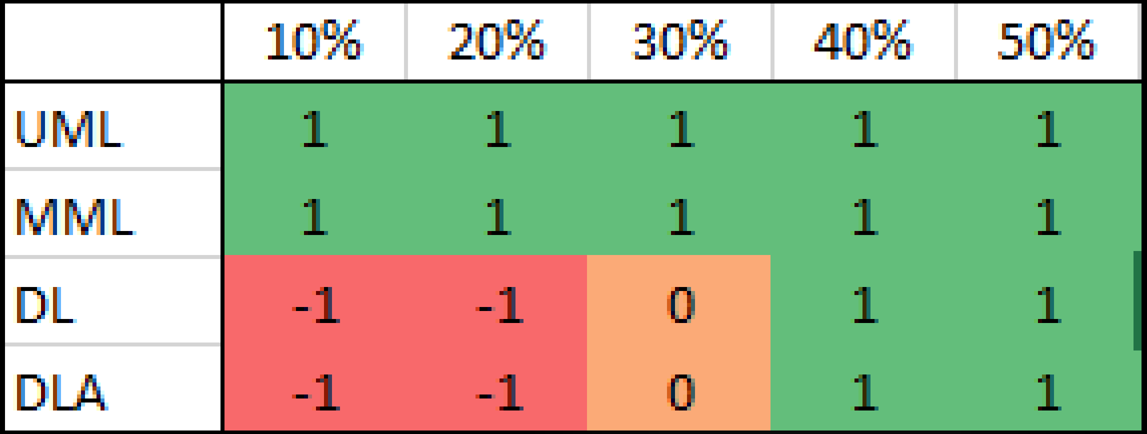
- For UML, MML, and DL, MOOP achieves more balanced objective values by the indication of smaller area of the MOOP polygon.
- In DLA, the average objective function values in MOOP are higher than those of the non-MOOP, except in Headway objective.
- The size of the platoon grows with the aid of DLA.

Policy Recommendations



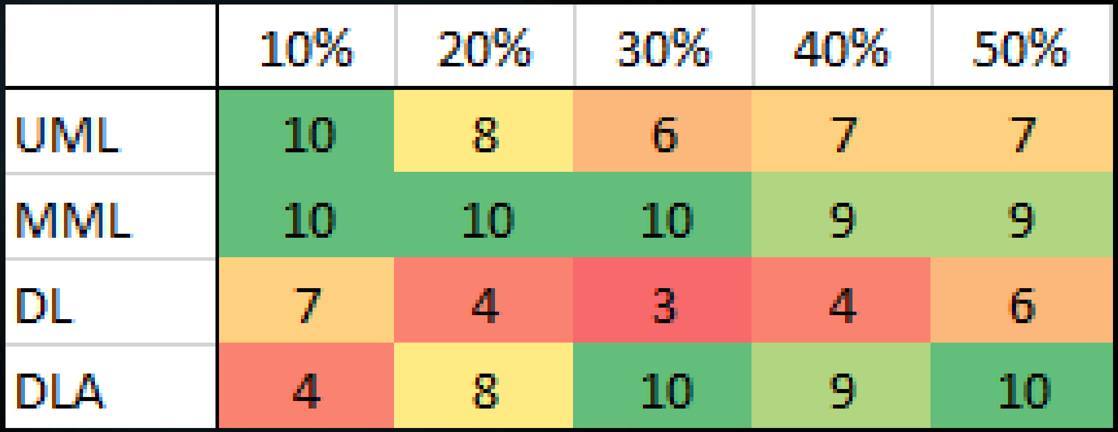
	10%	20%	30%	40%	50%
UML	4	4	4	3	3
MML	4	4	4	4	3
DL	-4	-4	1	4	4
DLA	-4	-4	1	4	4

Mobility



	10%	20%	30%	40%	50%
UML	1	1	1	1	1
MML	1	1	1	1	1
DL	-1	-1	0	1	1
DLA	-1	-1	0	1	1

Equity

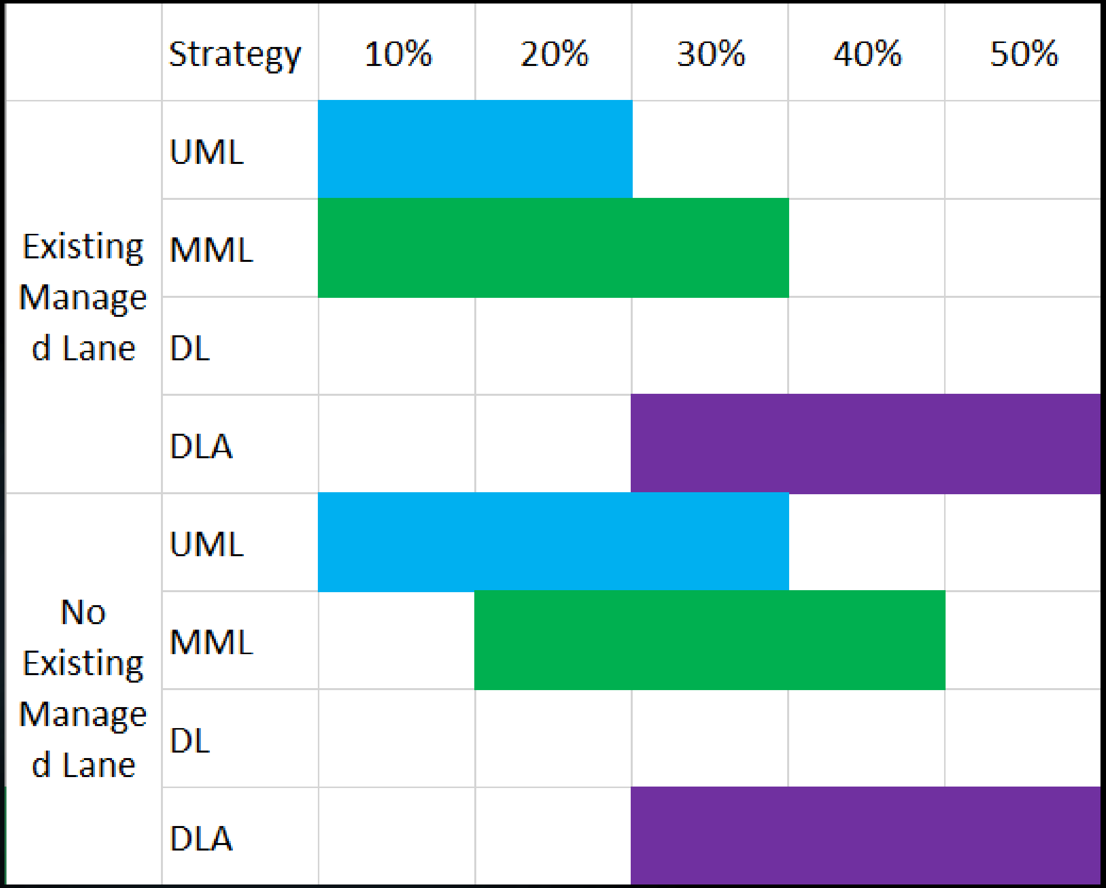


	10%	20%	30%	40%	50%
UML	10	8	6	7	7
MML	10	10	10	9	9
DL	7	4	3	4	6
DLA	4	8	10	9	10

Platoon performance

- Mobility & equity score
  - Improvement: +1
  - Neutral: 0
  - Degradation: -1
- Platoon performance score
  - Ranked from 4 to 1, with 4 being the best among the four strategies

Policy Recommendations (cont’d)



	Strategy	10%	20%	30%	40%	50%
Existing Managed Lane	UML	🟦	🟦			
	MML	🟩	🟩	🟩		
	DL					
	DLA			🟪	🟪	🟪
No Existing Managed Lane	UML	🟦	🟦	🟦		
	MML		🟩	🟩	🟩	
	DL					
	DLA			🟪	🟪	🟪

Policy Recommendation

- For roadway with an existing managed lane facility, mixed managed lane is a suitable strategy, but unmanaged lane still produces acceptable results.
- For locations without an existing managed lane, the unmanaged lane is preferred at low MPR, until mixed managed lane or dedicated lane w/ access is warranted by the MPR of CACC.
- Dedicated lane w/ access control should be implemented when the MPR reaches 30% or above.

Conclusions

- The introduction of CACC even at low MPR (i.e., 10%) helps to increase the mobility of the network.
- The break-even point of whether to use dedicated CACC lane is 30% MPR. Implementing dedicated lane prematurely could potentially raise serious equity concern
- Unmanaged lane is an acceptable option when the MPR is no more than 20%
- Mixed managed lane is the choice for deploying CACC when MPR is less than 30%, for the location with existing managed lane facility
- The MOOP-based control algorithm can achieve balanced values among all given objectives, in comparison to non-MOOP-based control algorithm, when the feasible solution ratio is above 75%

Contributions

Development of an integrated simulation framework capable of

- Performing cooperative platoon maneuvering based on multi-objective optimization
- Simulating DSRC communication and its impact in simulation runtime in mixed traffic operation at a large-scale network
- Collecting CACC-oriented performance measures

Evaluation of deployment of CACC vehicles in mixed traffic

- Operational impacts of managed lane strategy
- Near-term deployment recommendations for stakeholders

Future Research

- Operational strategies to accommodate the induced weaving activity due to lateral movements of CACC vehicles for platooning
- Search techniques for the multi-objective optimization (e.g., NSGA-III, Grid-based EA, MOEA/D-PBI)
- Incorporation of vehicle dynamics model in longitudinal control for extra degree of realism

Thank you for your time

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