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, China

2009-2011
- M.S. in Civil Engineering, NJIT

2011-2013
- LMW Engineering Group, LLC

2013-Present
- Ph.D. Candidate, NJIT
  - 2017 Outstanding Graduate Student Award
  - 2015 The Future of ITS-NJ Scholarship Award

Journal Papers

Z. Zhong, J. Lee, and L. Zhao. "Multi-objective Optimization Framework for **Cooperative Adaptive Cruise Control** Vehicles in the Automated Vehicle Platooning Environment." Transportation Research Record: Journal of the Transportation Research Board 2017. 2625: pp. 32-42

J. Lee, **Z. Zhong**, Bo Du, Slobodan Gutesa, and Kitae Kim. "Low-Cost and Energy-Saving Wireless Sensor Network for Real-Time Urban Mobility Monitoring System." Journal of Sensors, vol. 2015

Peer-review Conference Papers

Z. Zhong and J. Lee. "Simulation Framework for Impacts Assessment of **Cooperative Adaptive Cruise Control** Managed Lane Strategies." the 97th Transportation Research Board Annual Meeting, 2018 (Submitted)

Z. Zhong, J. Lee, B. Singh, B. Dimitrijevic, S. Chien, and L. Spasovic. "Evaluation of Freeway Merging Assistance System Using Driving Simulator." the Intelligent Transportation System World Congress 2017, Montreal, Canada

Z. Zhong and J. Lee. "Development of CID-free Hardware-in-the-Loop Simulation Framework." the 96th Transportation Research Board Annual Meeting, 2017

Z. Zhong, J. Lee, and L. Zhao. "Evaluations of Managed Lane Strategies for the Arterial Deployment of **Cooperative Adaptive Cruise Control**." the 96th Transportation Research Board Annual Meeting, 2017

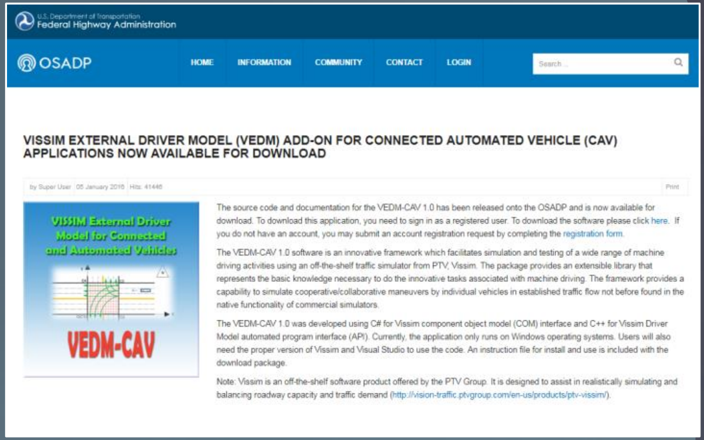
J. Lee, **Z. Zhong** and L. Zhao. "Multi-objective Optimization Controller for **Cooperative Adaptive Cruise Control**." the 95th Transportation Research Board Annual Meeting, 2016

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." the 94th Transportation Research Board Annual Meeting, 2015

J. Lee, **Z. Zhong**, B. Singh, B. Dimitrijevic, K. Kim, B. Du, and S. Chien. "WIMAP: Work Zone Interactive Monitoring Application." the 94th Transportation Research Board Annual Meeting, 2015

J. Lee and **Z. Zhong**. "Estimation of Real-time Origin-destination Flow Using Mobile Sensor Network." Intelligent Transport Systems World Congress 2014, Detroit, MI. 2014

Research Activities


U.S. Department of Transportation
Federal Highway Administration
OSADP
HOME INFORMATION COMMUNITY CONTACT LOGIN

VISSIM EXTERNAL DRIVER MODEL (VEDM) ADD-ON FOR CONNECTED AUTOMATED VEHICLE (CAV) APPLICATIONS NOW AVAILABLE FOR DOWNLOAD

by Super User | 05 January 2016 | Hits: 41446

VISSIM External Driver Model for Connected and Automated Vehicles
VEDM-CAV

The source code and documentation for the VEDM-CAV 1.0 has been released onto the OSADP and is now available for download. To download this application, you need to sign in as a registered user. To download the software please click here. If you do not have an account, you may submit an account registration request by completing the registration form.

The VEDM-CAV 1.0 software is an innovative framework which facilitates simulation and testing of a wide range of machine driving activities using an off-the-shelf traffic simulator from PTV, Vissim. The package provides an extensible library that represents the basic knowledge necessary to do the innovative tasks associated with machine driving. The framework provides a capability to simulate cooperative/collaborative maneuvers by individual vehicles in established traffic flow not before found in the native functionality of commercial simulators.

The VEDM-CAV 1.0 was developed using C# for Vissim component object model (COM) interface and C++ for Vissim Driver Model automated program interface (API). Currently, the application only runs on Windows operating systems. Users will also need the proper version of Vissim and Visual Studio to use the code. An instruction file for install and use is included with the download package.

Note: Vissim is an off-the-shelf software product offered by the PTV Group. It is designed to assist in realistically simulating and balancing roadway capacity and traffic demand (http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/).


Engineers Eye Adaptive Cruise Control as Platooning Enabler

July 21, 2017

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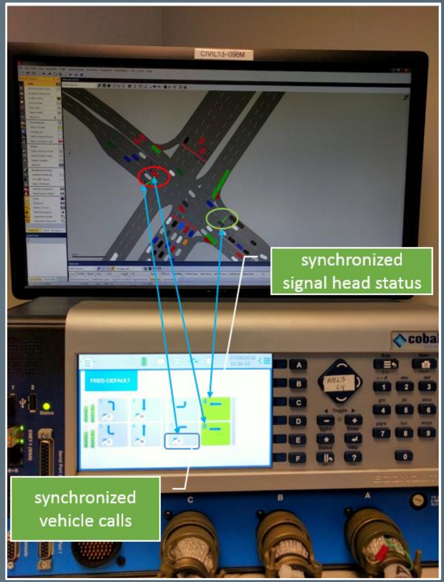
A new study found that adaptive cruise control systems can help maintian mobility, safety, driver comfort, and fuel consumption in platooning operations. *Photo: Peloton*

Is a new, expanded role for adaptive cruise control systems on the horizon? A recent technical paper by engineers Zijia Zhong, Joyoung Lee and Liuhui Zhao at the Newark College of Engineering, New Jersey Institute of Technology, published by the Transportation Research Board suggests so.

C/AV Research Projects

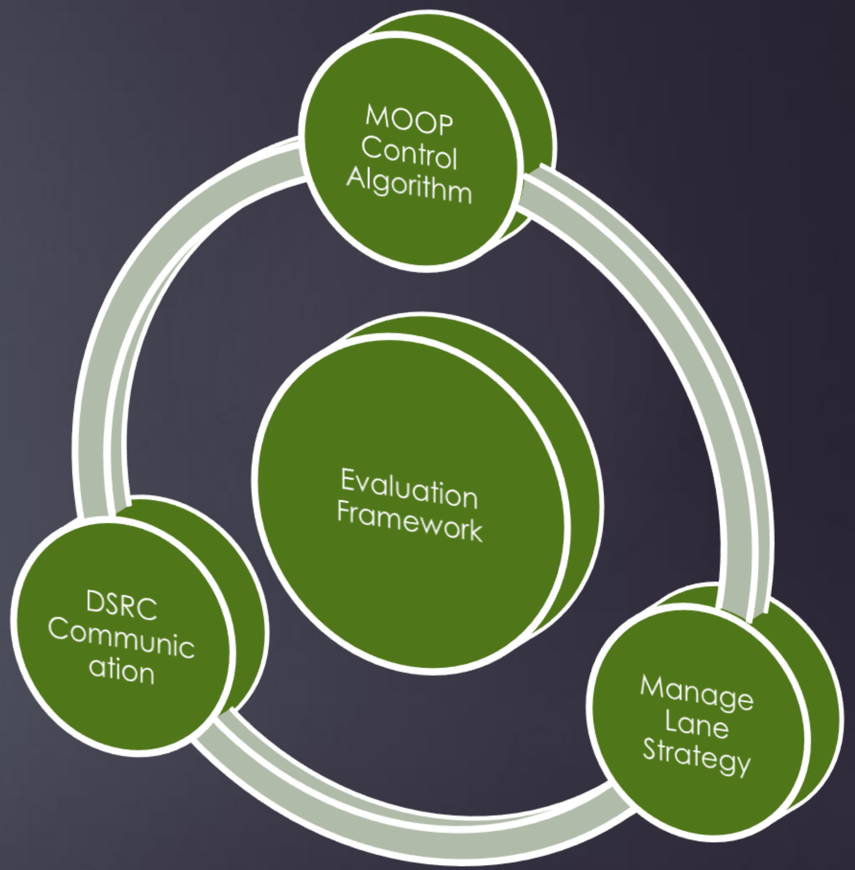
- Technical Support for Connected Vehicle Technology Evaluation and Deployment (NJDOT Sponsored), 2017~present
- Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles (NCHRP Sponsored) 2017~present
- Introduction of Cooperative I2V (Vehicle-Highway) Systems to Improve Speed Harmonization (FHWA Sponsored), 2013-2014
- Saxton Laboratory Simulation Capability (FHWA Sponsored), 2014-2015
- Simulation for Research on Automated Longitudinal Vehicle Control (FHWA Sponsored, source code available on OADP), 2014-2016

Research → Activities



Presentation Outline

- Introduction
- Literature Review
- Integrated Simulation Framework
  - *Multi-objective optimization-based (MOOP) control algorithm*
  - *Wireless communication (WC) module*
  - *Managed lane (ML) strategy*
- Conclusion & Future Research



INTRODUCTION

The Scale of the Problem

Safety

- 35 thousand highway deaths & 3.6 million crashes in 2015 *
- leading cause of death for ages 1-44**

Mobility***

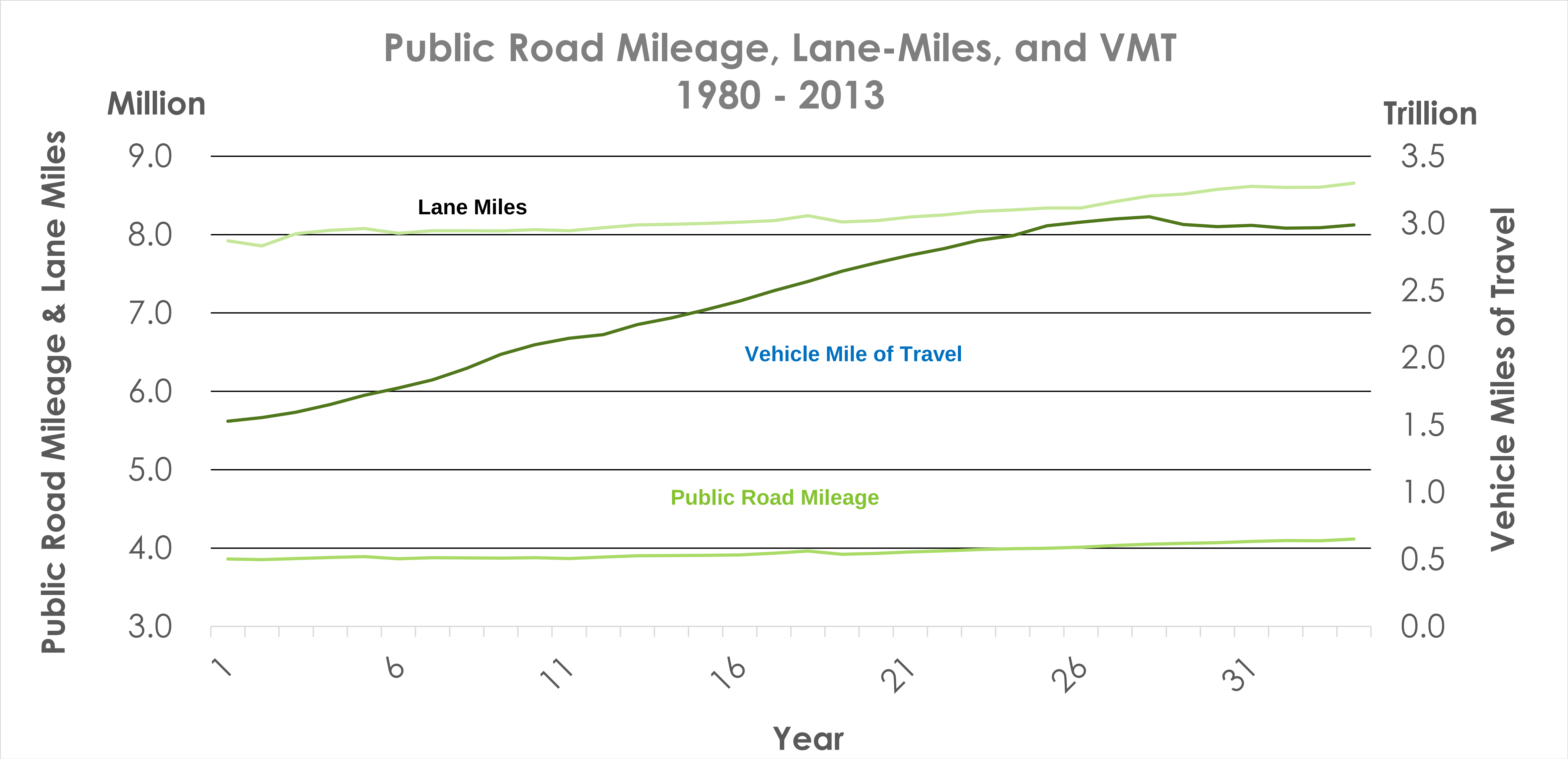
- 6.9 billion hours of travel delay
- $160 billion congestion cost

Environment***

- 3.1 billion gallon of fuel wasted
- 60 billion pounds of additional CO2

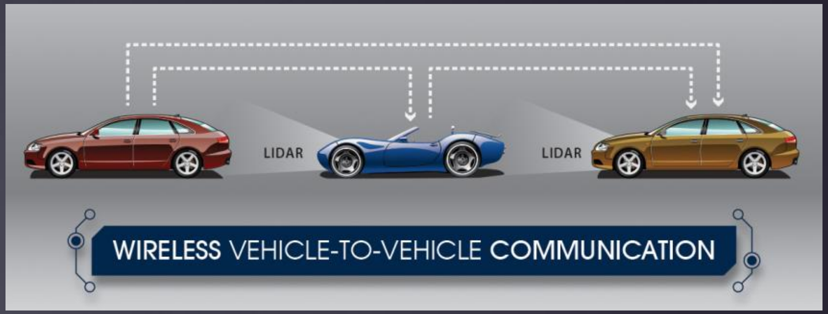
*DOT HS 812 318, Traffic Safety Facts, National Highway Traffic Safety Administration (August 2016)
**10 Leading Causes of Death by Age Group, United States –2014, Centers for Disease Control and Prevention
***2015 Urban Mobility Scorecard, Texas A&M Transportation Institute and INRIX (August 2015)

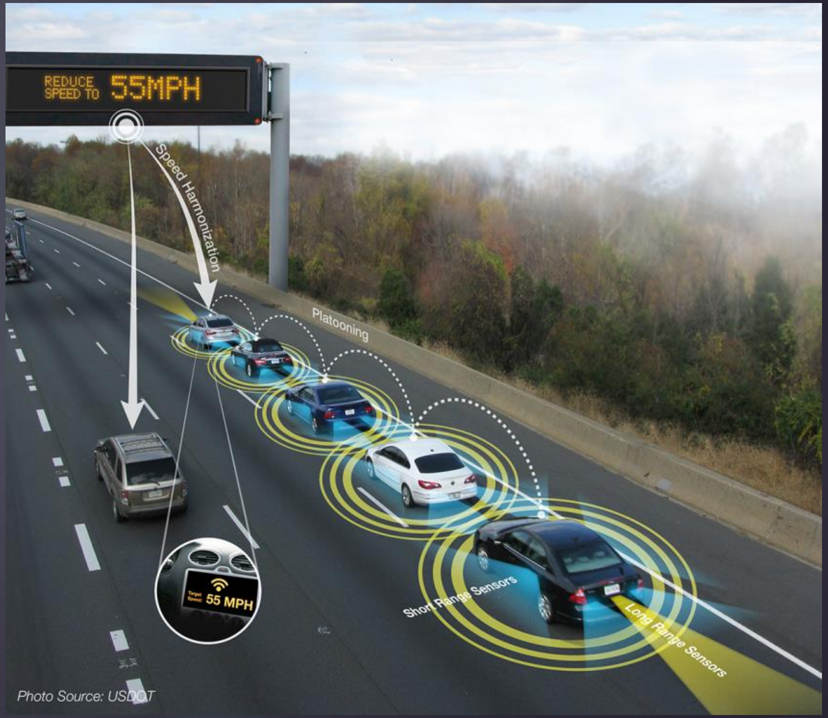
Demand vs. Supply



The Opportunity

- Cooperative Adaptive Cruise Control (CACC)
  - *Enhances driver safety considerably by reducing or even eliminating human error*
  - *Fundamentally increases highway carrying capacity*
  - *Offers high-performance driving even under restricted driving condition*





Near-term Deployment

Level 1

Level 2

Here Today

Level 3

Level 4

In Testing

Level 5 Someday(?)

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

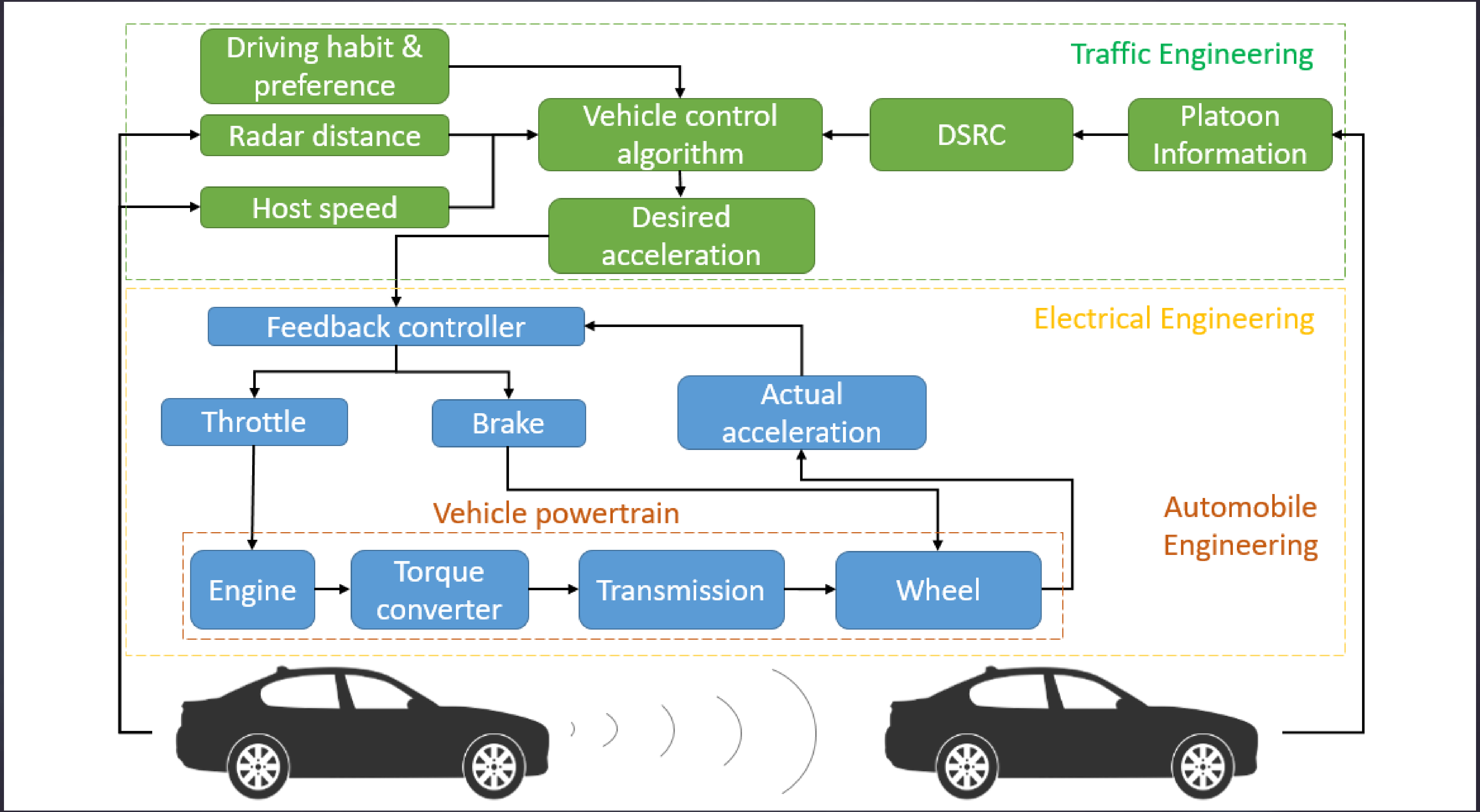
Phase 1
- Pre-deployment (2013-2015)

Phase 2
- Develop and Deploy(2015-2018)

Phase 3
- Operate and Evaluate(2018-2021)

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

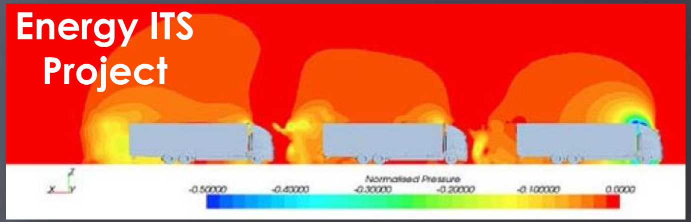
CACC Research Landscape



LETERATURE REVIEW

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



Operation Evaluation via Simulation

- Most of the studies only used hypothetical networks
- The longitudinal control of CACC vehicles do not include a platoon-level cooperation where all the CACC vehicles intelligently negotiate, and make necessary concessions to diverse platoon-level goals
- Few simulations implemented local coordination where stand-alone CACC vehicle actively seeking for platoon opportunity

Research	Transportation Network	Longitudinal Control	Lateral Control
Zhong et al. (2017)	5-km 2-lane signalized arterial, Fairfax Co. Parkway, VA	Predetermined accelerations with conditional switching	Rear-, mid, front joining
Li et al. (2017)	Hypothetical 15-km freeway w/ 1 on-ramp	IDM factoring in the leader and 2nd vehicle	No implemented
Songchitruksa et al. (2016)	42-km 3-lane, I-30 segment, TX (un-calibrated)	Transfer function based on the preceding vehicle(s)	Rear-joining
Lee & Park (2014)	Hypothetical15-km, 4-lane freeway w/ 1 on-ramp	Predetermined accelerations with conditional switching	Rear-, mid, front joining
Arnaout and Bowling (2014)	Hypothetical 6-km 4-lane U-shape highway w/ 1 on-ramp	Intelligent Driver Model (IDM)	MOBIL(Kesting et al. 2007)

CACC under Imperfect Communication

- Traffic simulator provide realistic vehicle behavior & interactions, whereas network simulator deals with packet-level simulation with various communication protocol
- Some studies only focus on the packet-level communication simulation and did no deal with the vehicle movements.
- Some studies post-process the wireless simulation and as such the wireless communication has no influence on vehicle movement
- Synchronizer has been used in some of the studies, but the simulation scale are limited due to computational burden

Research	Network Simulator	Traffic Simulator	Synchronizer	Scale
Akhtar et al. (2015)	Mathmathcal models	SUMO	N/A (Post process)	6000 vph
Chen et al. (2009)	ns-2	N/A	N/A	400 vehicles
ElBatt et al. (2006)	QualNet	N/A	N/A (Post process)	1920 vehicles
Xu et al. (2004)	ns-2	SHIFT	N/A (Post process)	1,000 vehicles
Ucar et al. (2016)	OMNeT++	SUMO	TCP/IP	10 vehicles
Motro et al. (2016)	OMNeT++	SUMO	TCP/IP	3 vehicles
Segata et al. (2014)	OMNeT++	SUMO	TCP/IP	4 vehicles
Veeraraghavan and Miloslavov (2012)	NCTUns	Vissim	TCP/IP	300 vph
Eichler et al. (2005)	ns-2	CARISMA	TCP/IP	900 vehicles

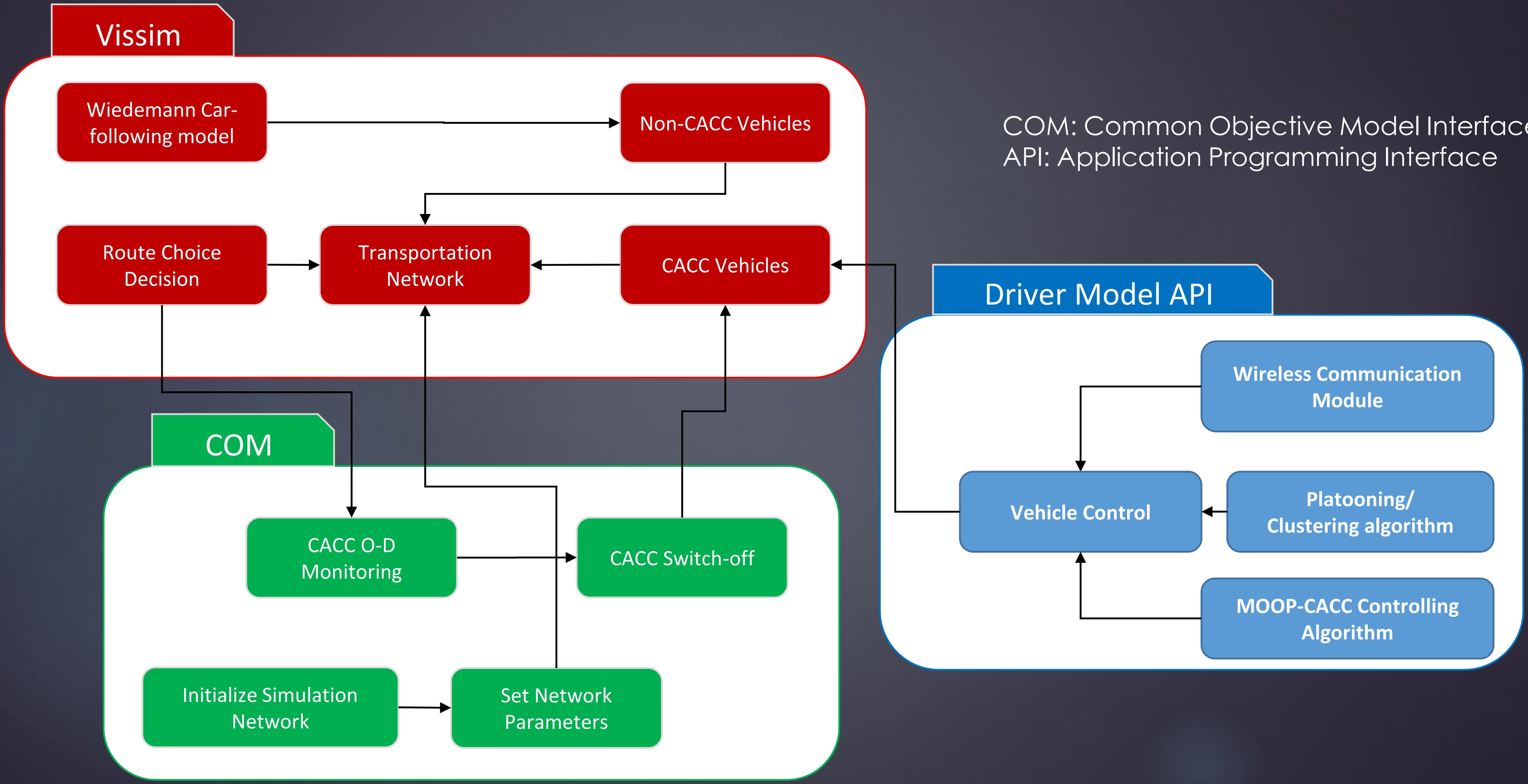
Research Goal & Objectives

The primary goal of this dissertation is to evaluate the impacts of introducing CACC vehicles into the existing roadway and the effectiveness of using managed lane strategies.

1. To formulate a platoon-wide multi-objective based CACC control algorithm that is able to accommodate various operational objectives.
2. To develop a realistic microscopic simulation test bed for testing CACC under mixed traffic condition
3. To assess a variety of available managed lane strategies for CACC under imperfect wireless communication.
4. To investigate the suitable performance measures for CACC traffic.

Integrated Simulation Framework

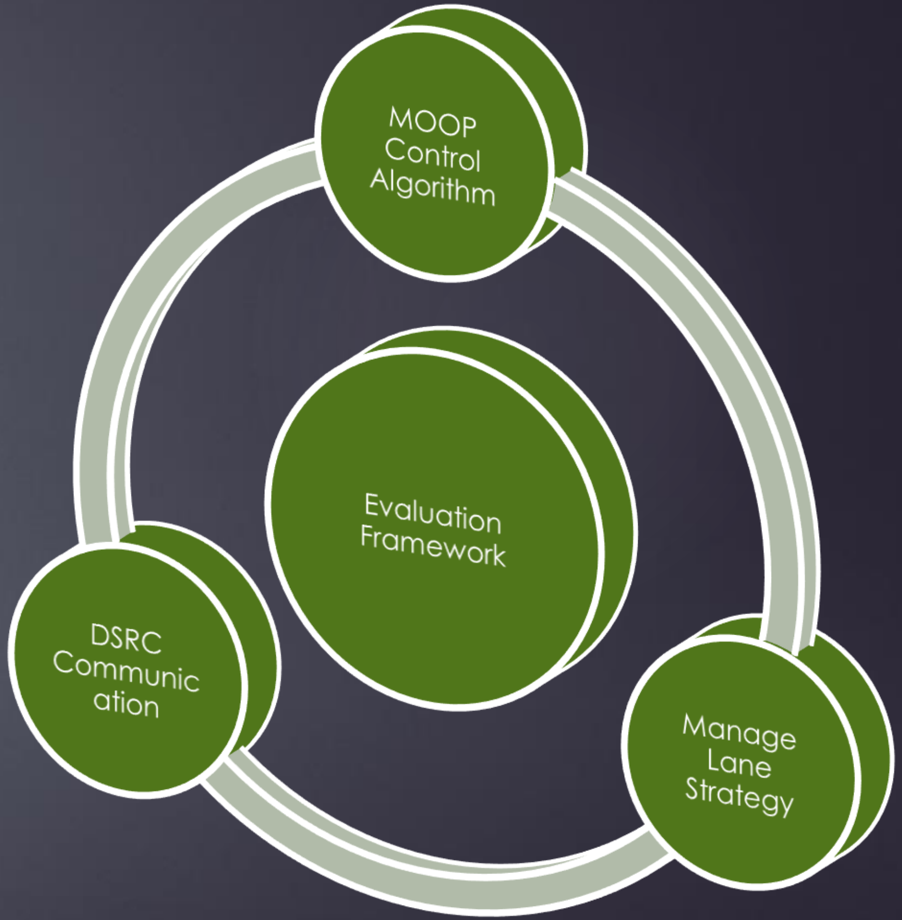
Simulation Framework



COM: Common Objective Model Interface
API: Application Programming Interface

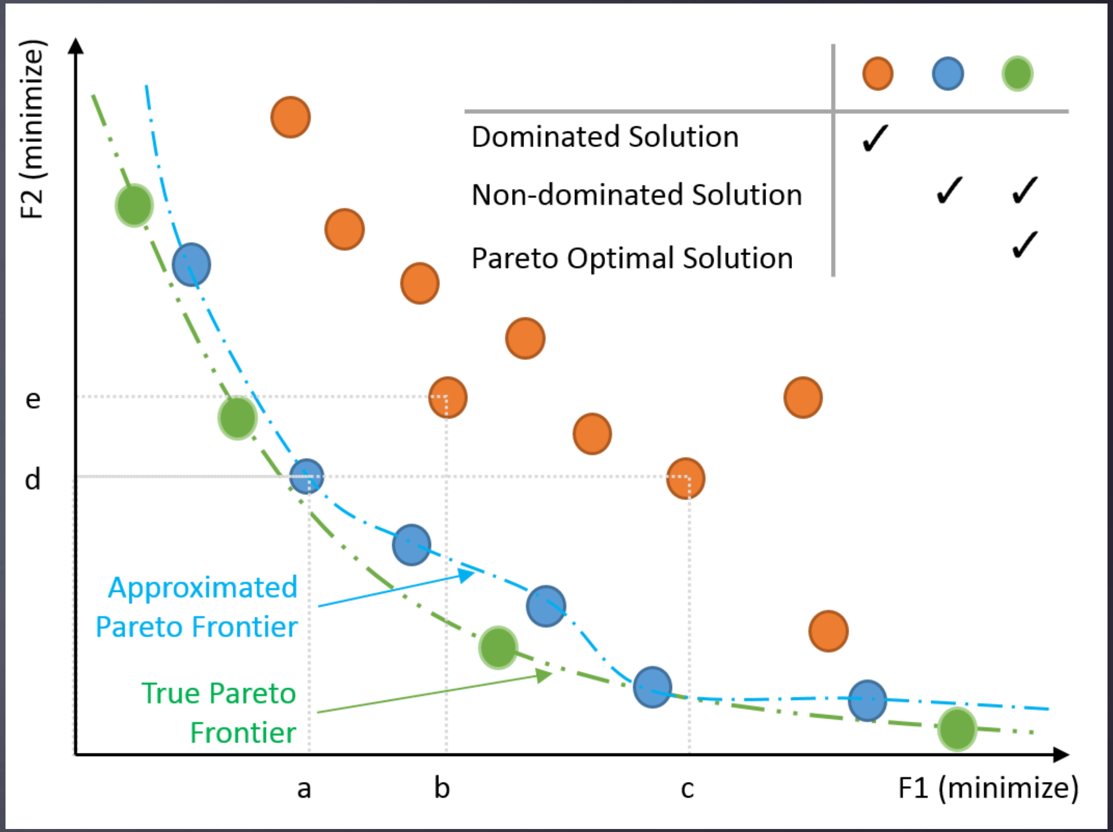
Integrated Simulation Framework

- Multi-objective optimization-based (MOOP) control algorithm
- Wireless communication (WC) module
- Managed lane (ML) strategy



Multi-objective Optimization

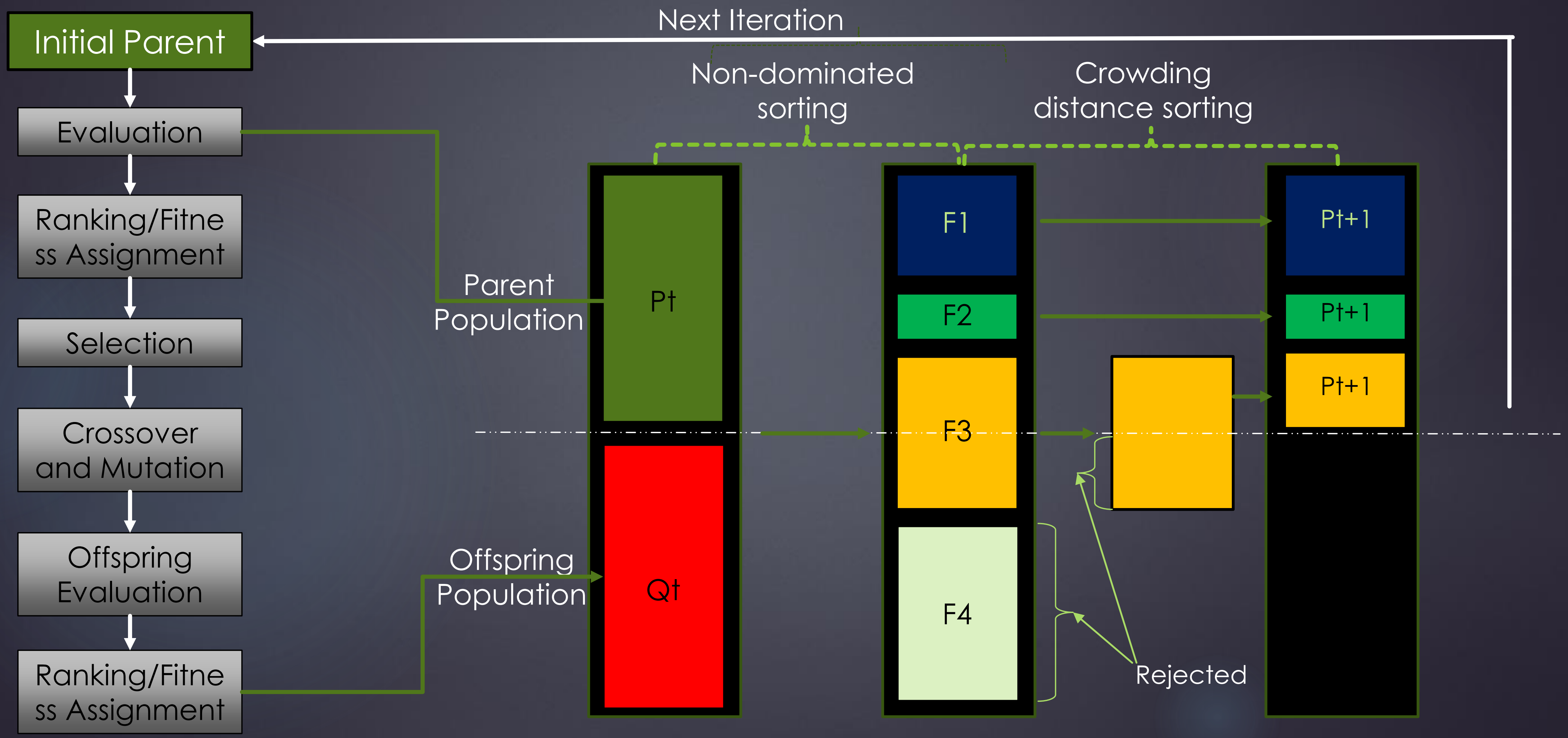
- Multi-objective optimization (MOOP) seeks to optimize multiple conflicting objectives
- The MOOP framework allows CACC vehicles to conduct cooperative driving



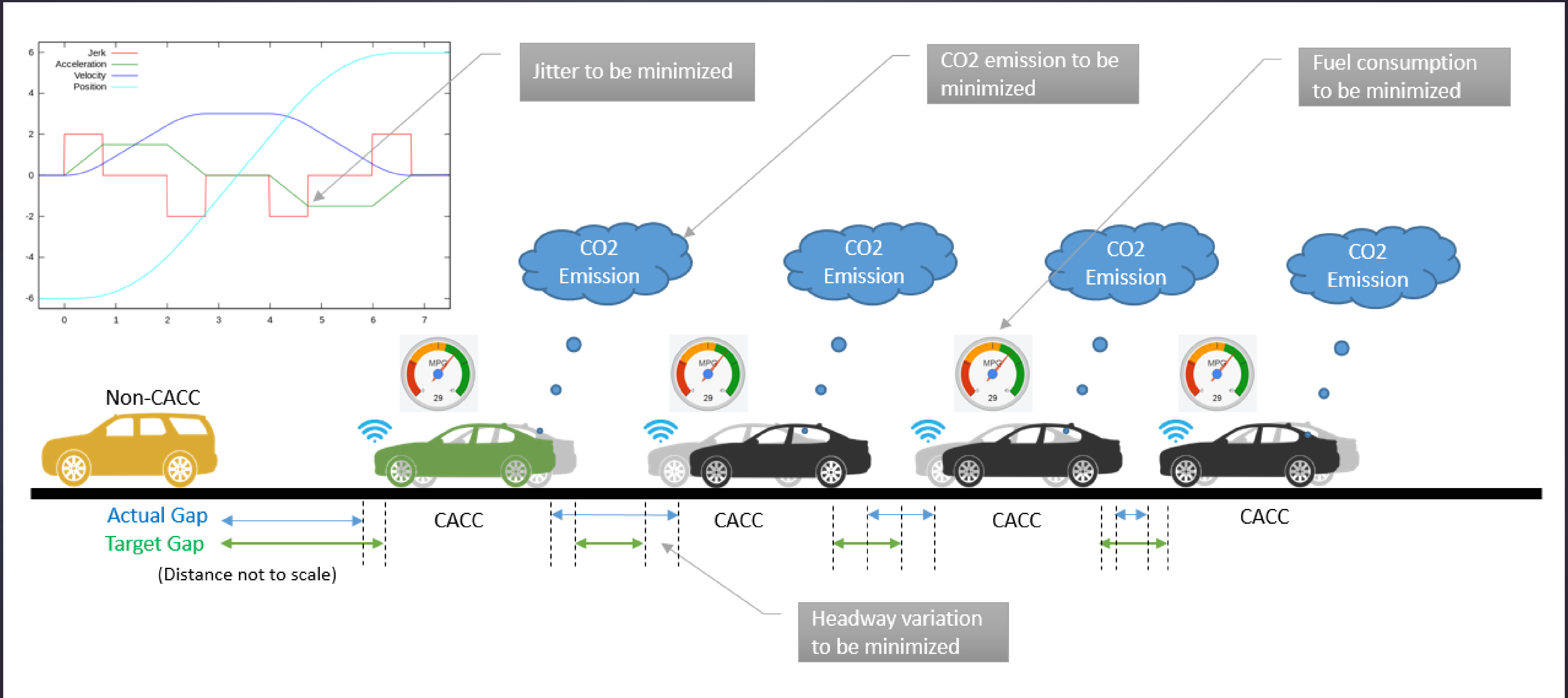
SOOP vs MOOP

Difference	SOOP	MOOP
Goals	• Search for an optimal solution	• Search for a Pareto frontier • Maintain diversity of solutions in the Pareto frontier
Search Space	• Decision variable space	• Decision variable space and objective space
Artificial Approximation	• Need to construct a composite objective by fix-ups methods (e.g., weighted sum, scaling)	• the set of optimal solution can be obtained without applying fix-ups

Non-dominated Sorting Genetic Algorithm (NSGA-II)



MOOP Control Algorithm



MOOP Control Algorithm (Cont'd)

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

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

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

subject to

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

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

(speed limit) $\dot{x}_{\min} \leq \dot{x}_i \leq \dot{x}_{\max}$

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

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

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

$h_{i,\min}$ – 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

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

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

Enhanced Intelligent Driver Model

The Enhanced Intelligent Driver Model (Kesting, 2010)

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

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

$\ddot{x}$ – 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

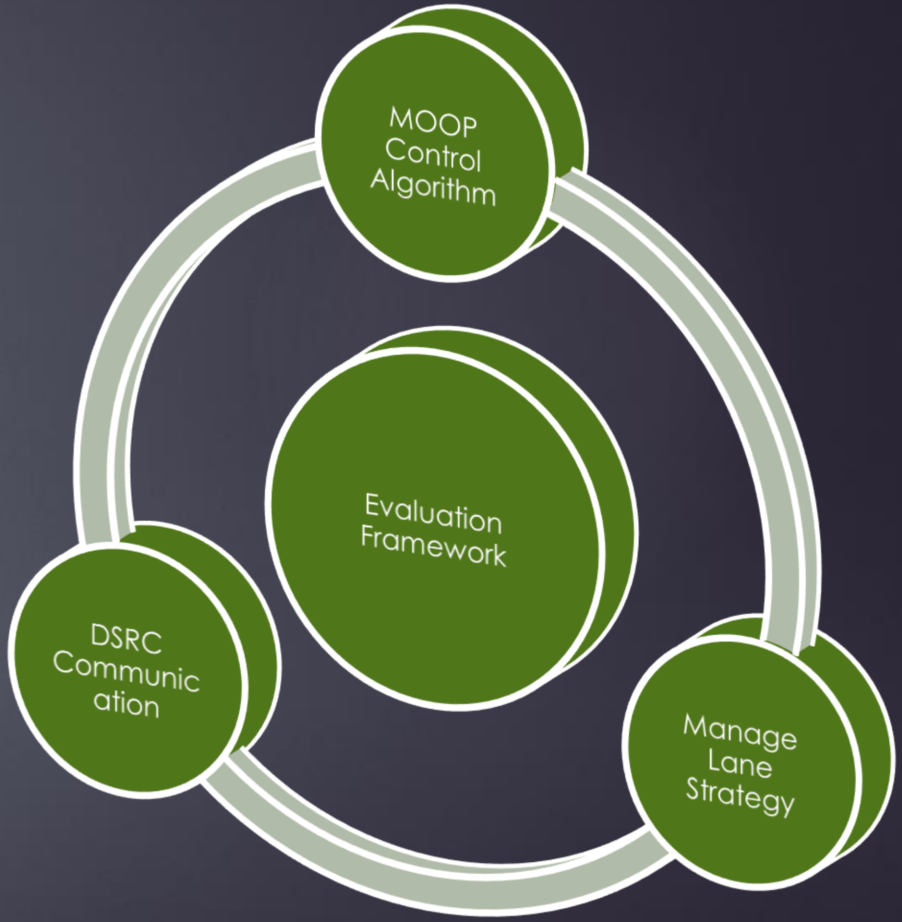
c – coolness factor

T – desired time gap, s

δ – free accelration exponent

Integrated Simulation Framework

- Multi-objective optimization-based (MOOP) control algorithm
- Wireless communication (WC) module
- Managed lane (ML) strategy



Wireless Communication Module

Probability of Sucessful Reception:

$$P_R(x,\delta,\psi,f) = e^{-3(x/\psi)^2}\left(1+\sum_{i=1}^{4} h_i(\xi,\psi)\left(\frac{x}{\psi}\right)^i\right)$$

Communication Density:

$$\xi = \delta \bullet \psi \bullet f$$

where,

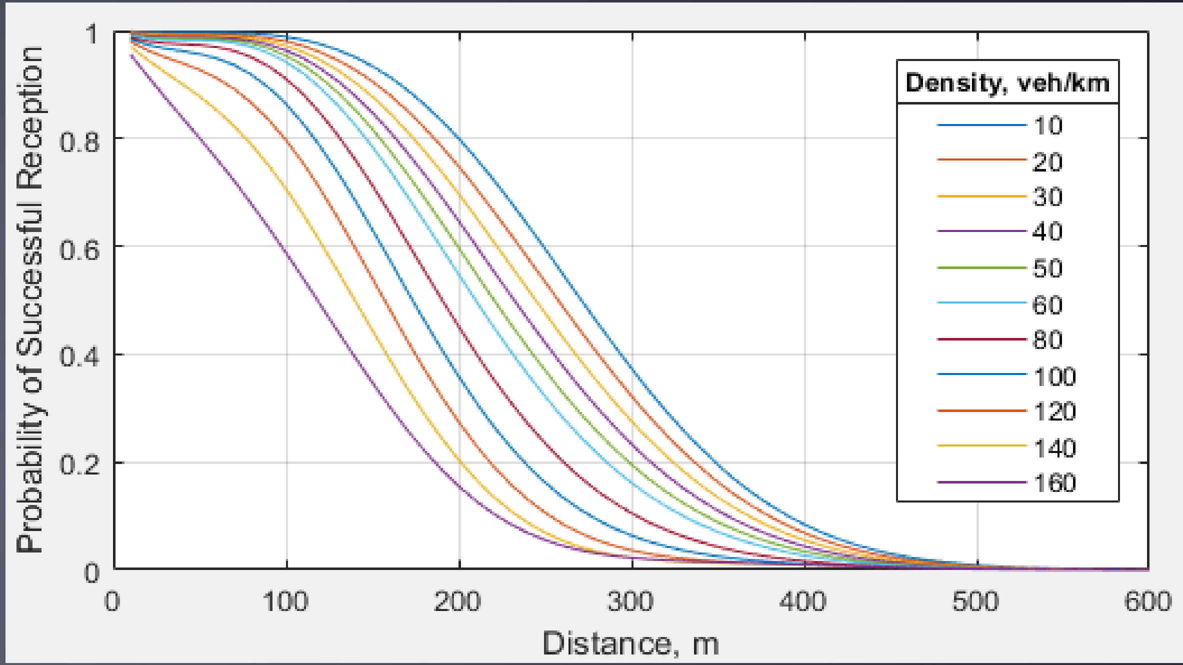
$h_i(\xi,\psi)$ – two-demensional polynomial

ξ – communication density

ψ – transmission power, m

δ – equipped vehicle density, vehicle/km

f – transmission frequency, Hz

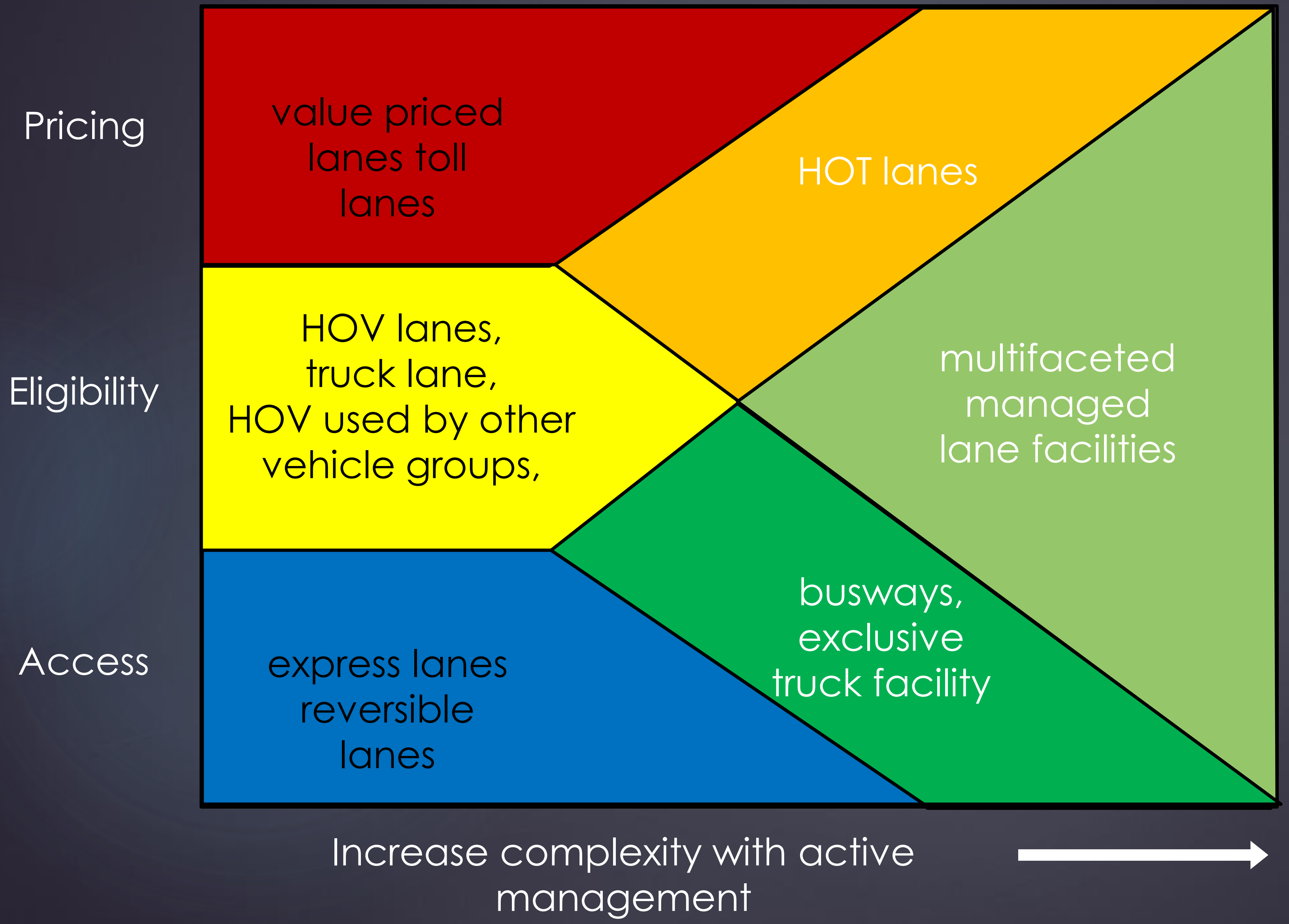


- The analytical model is derived from ns-2 simulator for 5.9GHz DSRC communication by Killat et al. (2009)
- Channel access delay is assumed zero
- Same level of countering noise and interferences are assumed for different data rates

Integrated Simulation Framework

- Multi-objective optimization-based (MOOP) control algorithm
- Wireless communication (WC) module
- Managed lane (ML) strategy

Managed Lane

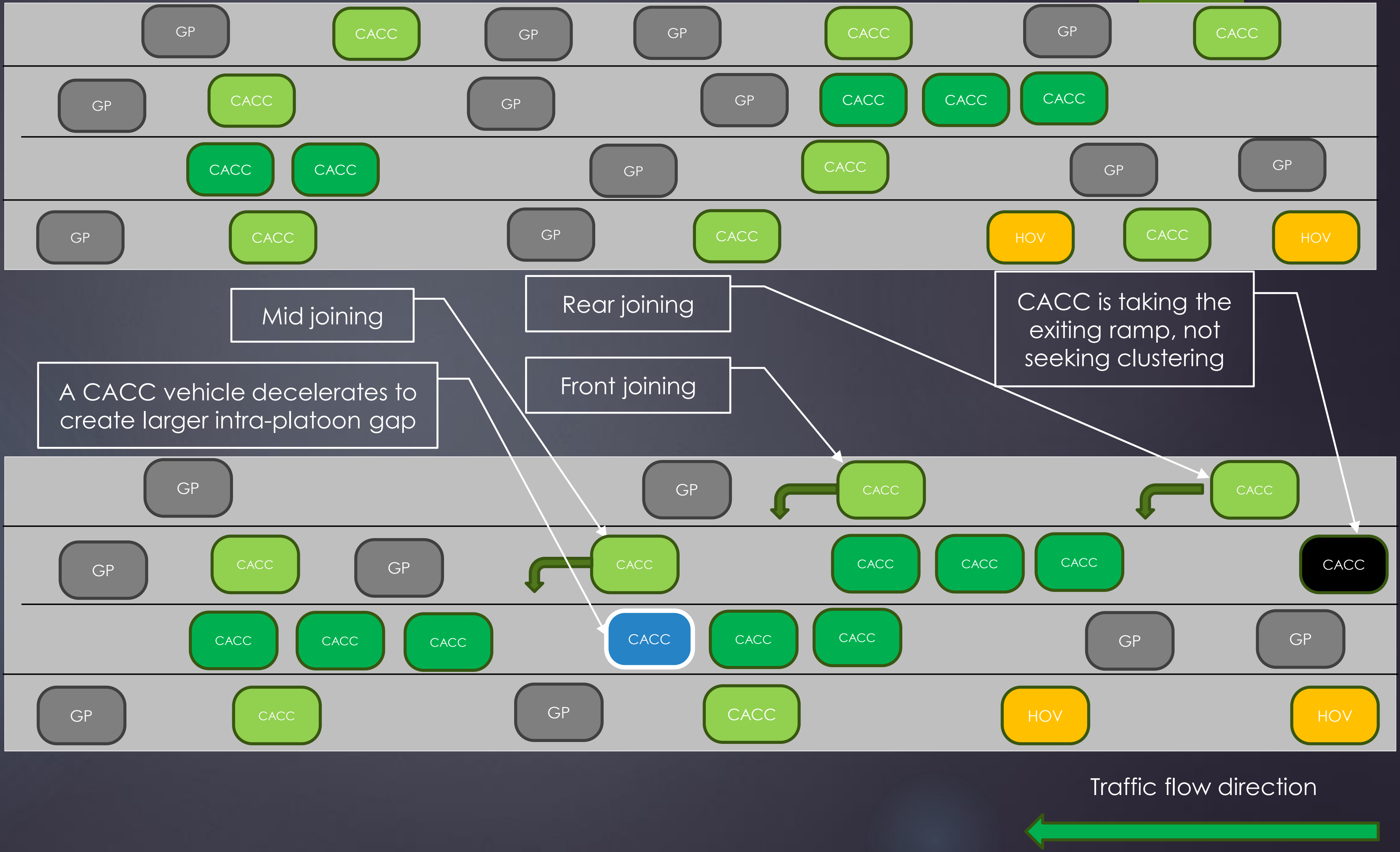


CACC String Operations

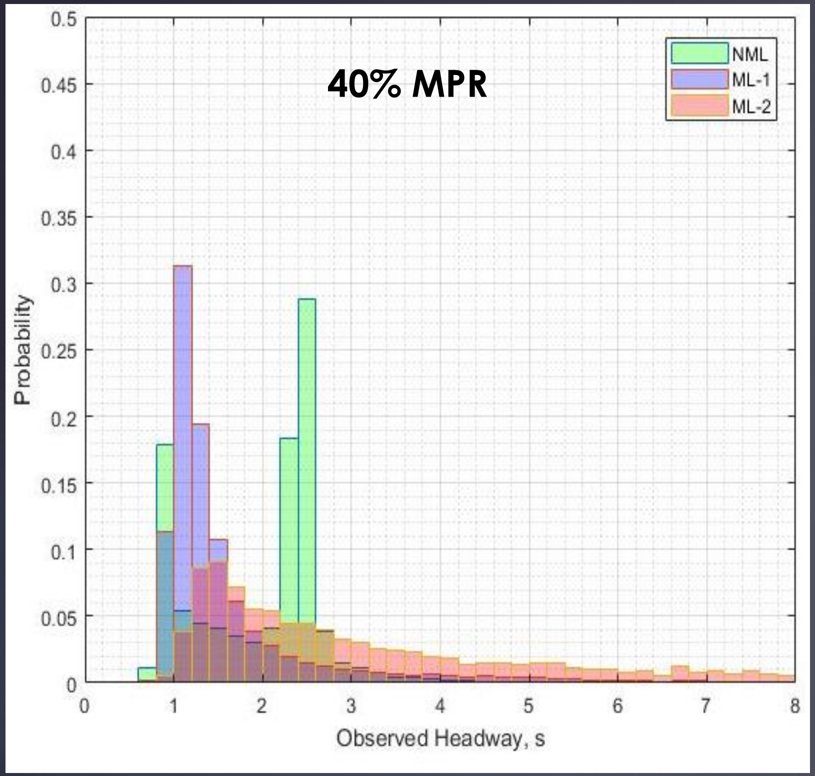
1. Ad hoc clustering

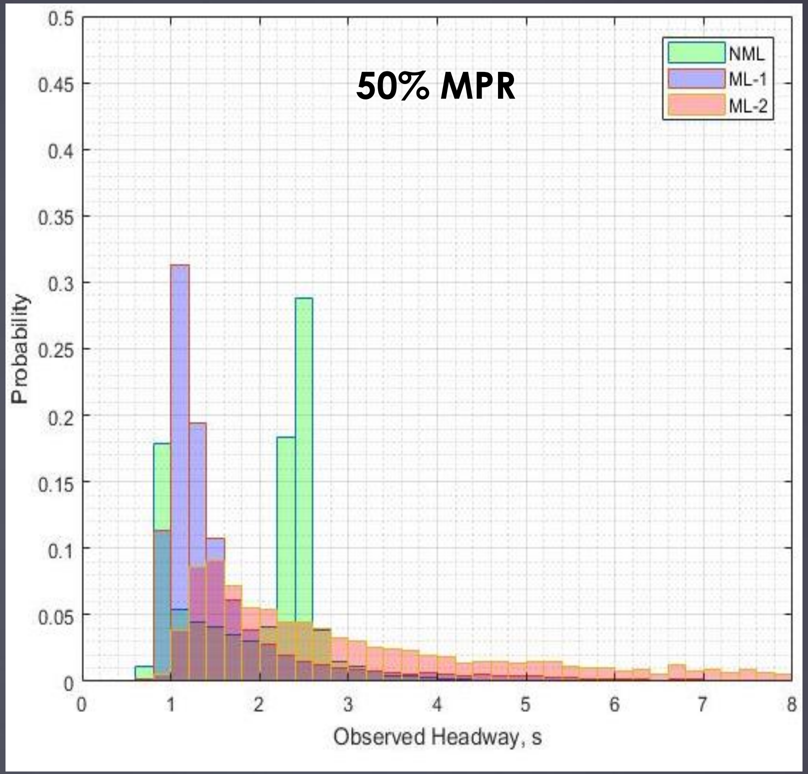
2. Local coordination

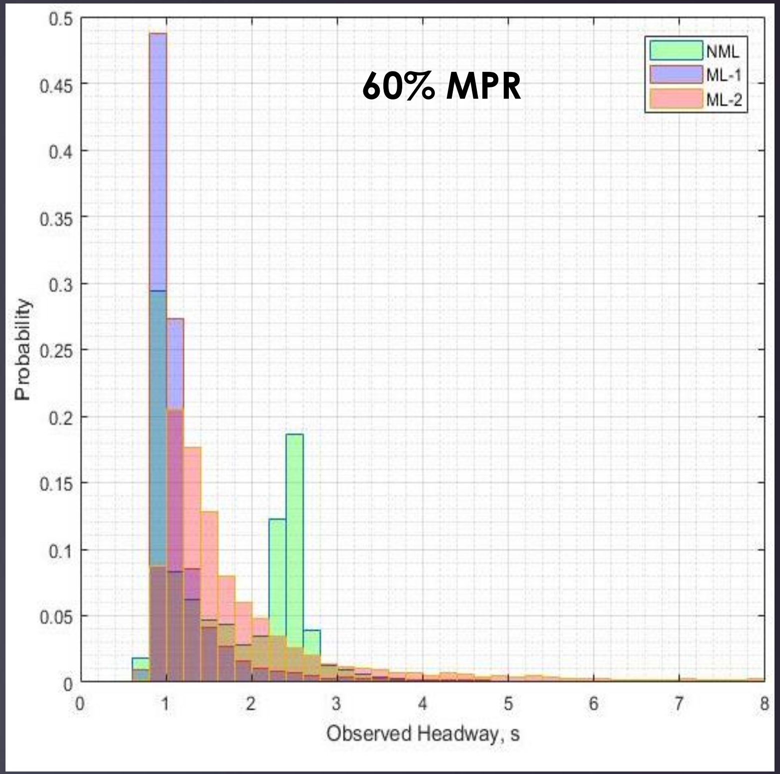
3. Global coordination



Ad Hoc Clustering of CACC

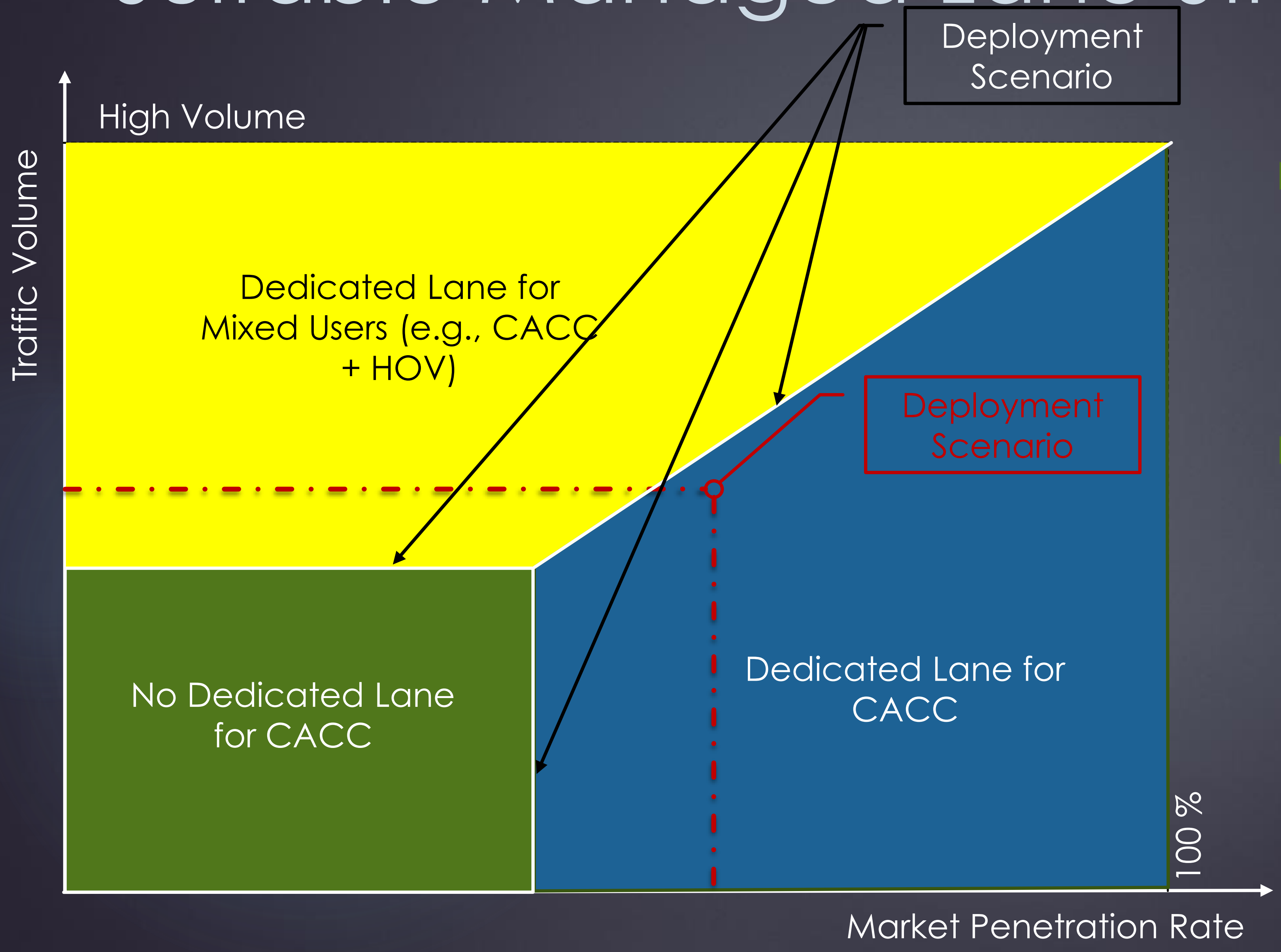






- Simulation result for a 4-lane highway
- Managed lane(s), if implemented, start(s) from the leftmost lane
- The distributions of headway collected for either ML-1 or ML-2 become "narrower"

Suitable Managed Lane Strategy



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

CACC Managed Lane Strategy

Phase 1

- Provide free SOV (single occupancy vehicle) use of the managed lane to encourage customers to purchase/retrofit CACC vehicles until reaching unacceptable operating condition in managed lane

Phase 2

- Allow CACC platooning with safety gaps to share the managed lane with non-CACC vehicles.

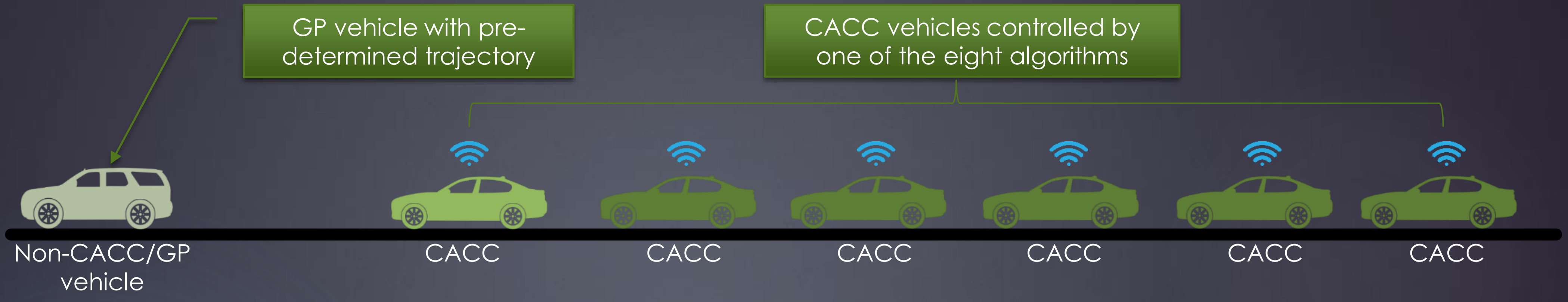
Phase 3

- Transitioning to dedicated CACC lane once MPR warrants
- Allow automated high-performance driving (with higher cursing speed)

Travel Lane / ML Strategy	4th (leftmost)	3rd	2nd	1st (rightmost)
1	HOV	GP	GP	GP
2	CACC + HOV	GP	GP	GP
3	CACC + GP	CACC + GP	CACC + GP	CACC + GP
4	HOV	GP	GP	GP+ CACC
5	HOV	CACC + GP	GP	GP
6	CACC	GP	GP	GP
7	HOV	CACC	GP	GP
8	CACC	HOV	GP	GP

Case Study

Case Study: MOOP Algorithm



Controlling Algorithm	Short Designation	Note
Human	H	Vehicles are controlled by the Vissim Wiedemann car-following model. It yields realistic for **human** driving behaviors.
E-IDM	E	The CACC vehicles are controlled by the E-IDM, which is a representation of **ACC** vehicle behaviors.
SOOP-HW	S-1	The CACC vehicles are controlled by SOOP for **Headway objective only**.
SOOP-Jitter	S-2	The CACC vehicles are controlled by SOOP for **Jittering objective only**.
SOOP-CO2	S-3	The CACC vehicles are controlled by SOOP for **CO2 emission objective only.**
MOOP-HW	M-1	The CACC vehicles are controlled by MOOP with **Headway objective preferred**.
MOOP-Jitter	M-2	The CACC vehicles are controlled by MOOP with **Jittering objective preferred**.
MOOP-CO2	M-3	The CACC vehicles are controlled by MOOP with **CO2 emission objective preferred**.

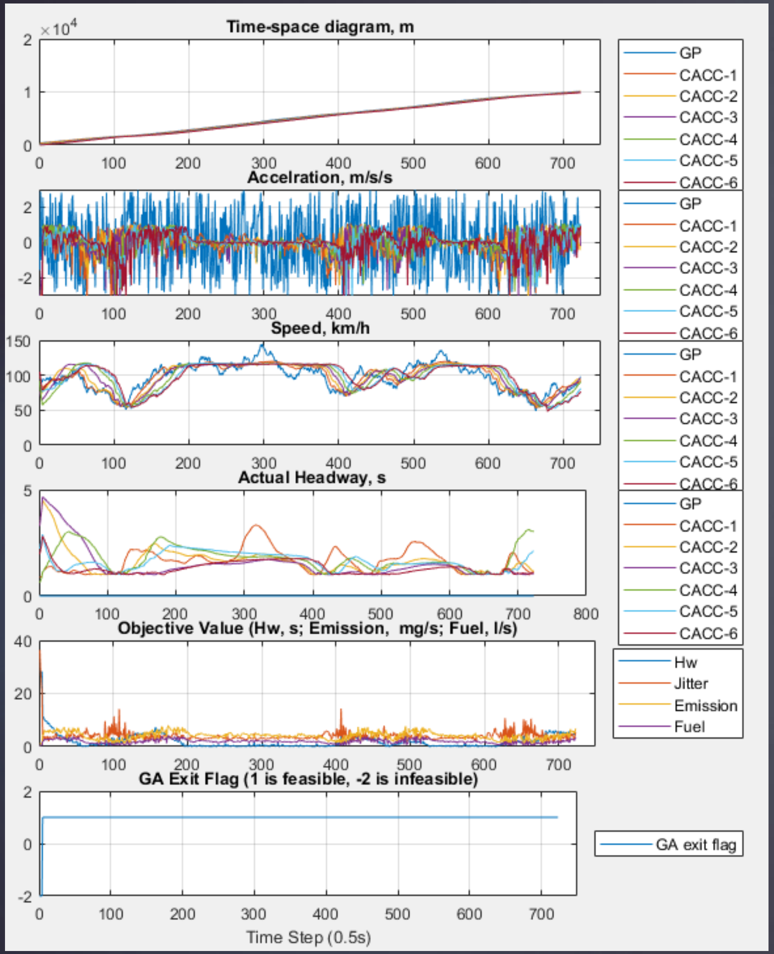
Results

- The MOOP approach achieves better balance by accounting for the optimality of the remaining three objectives. M-1 also produces much less variation of the objective value.

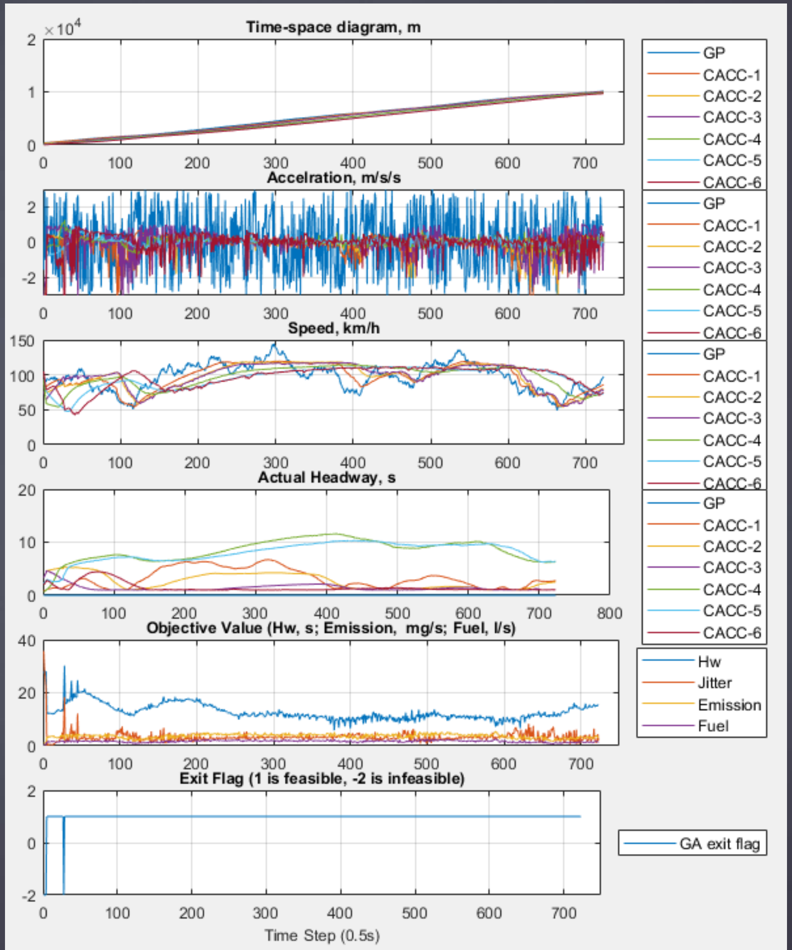
- The S-1 and M-1 can drastically increase highway carrying capacity due to more compact platoons.

MOEs	Human Wiedemann	ACC E-IDM	SOOP S-1 (Headway)	S-2 (Jitter)	S-3 (CO2)	MOOP M- 1 (Headway)	M-2 (Jitter)	M-3 (CO2)
Avg. Headway, s	7.14	2.23	0.85	2.83	5.14	1.07	3.27	6.12
Avg. Platoon Length, m	278	305	116	389	640	145	466	785
Obj-HW, s	32.70	5.68	1.22	12.88	26.87	1.98	14.51	32.78
Obj-Jitter	0.88	3.48	5.46	4.33	4.39	3.94	3.10	3.38
Obj-CO2, l/s	3.42	2.72	3.57	3.16	2.75	3.50	3.03	2.53
Obj-Fuel, mg/s	16.37	12.20	16.86	14.62	12.48	15.94	13.67	11.31

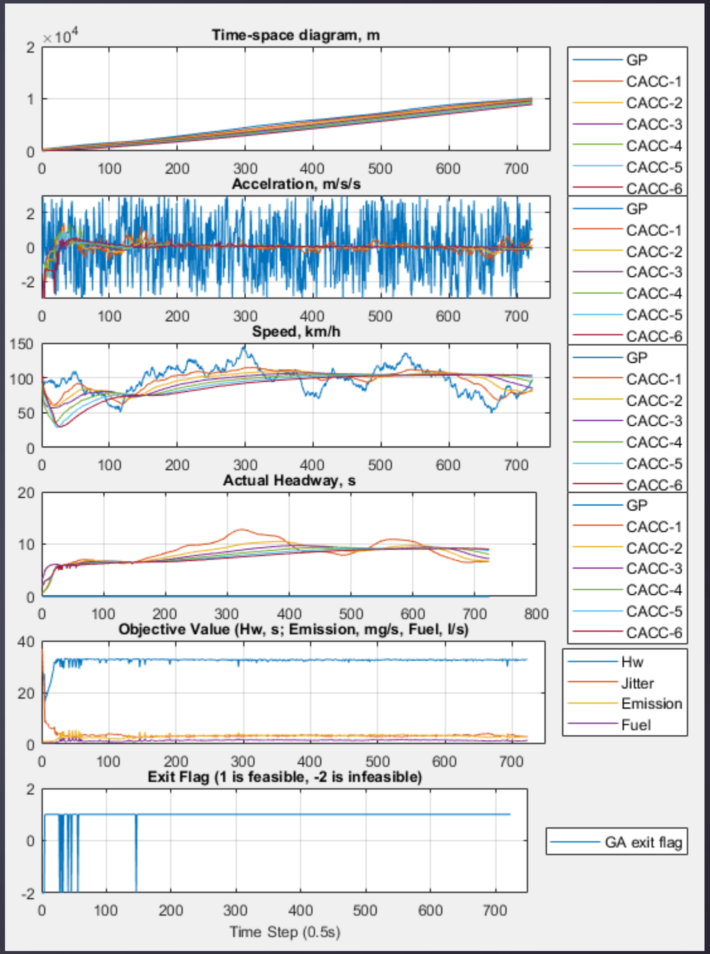
Sensitivity Analysis



MOOP w/ Headway Preferred

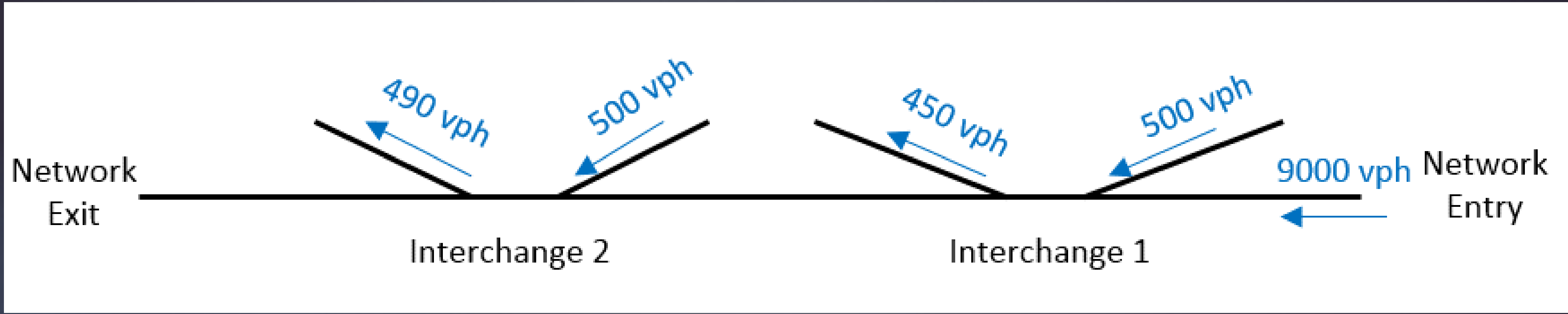


MOOP w/ Jitter Preferred



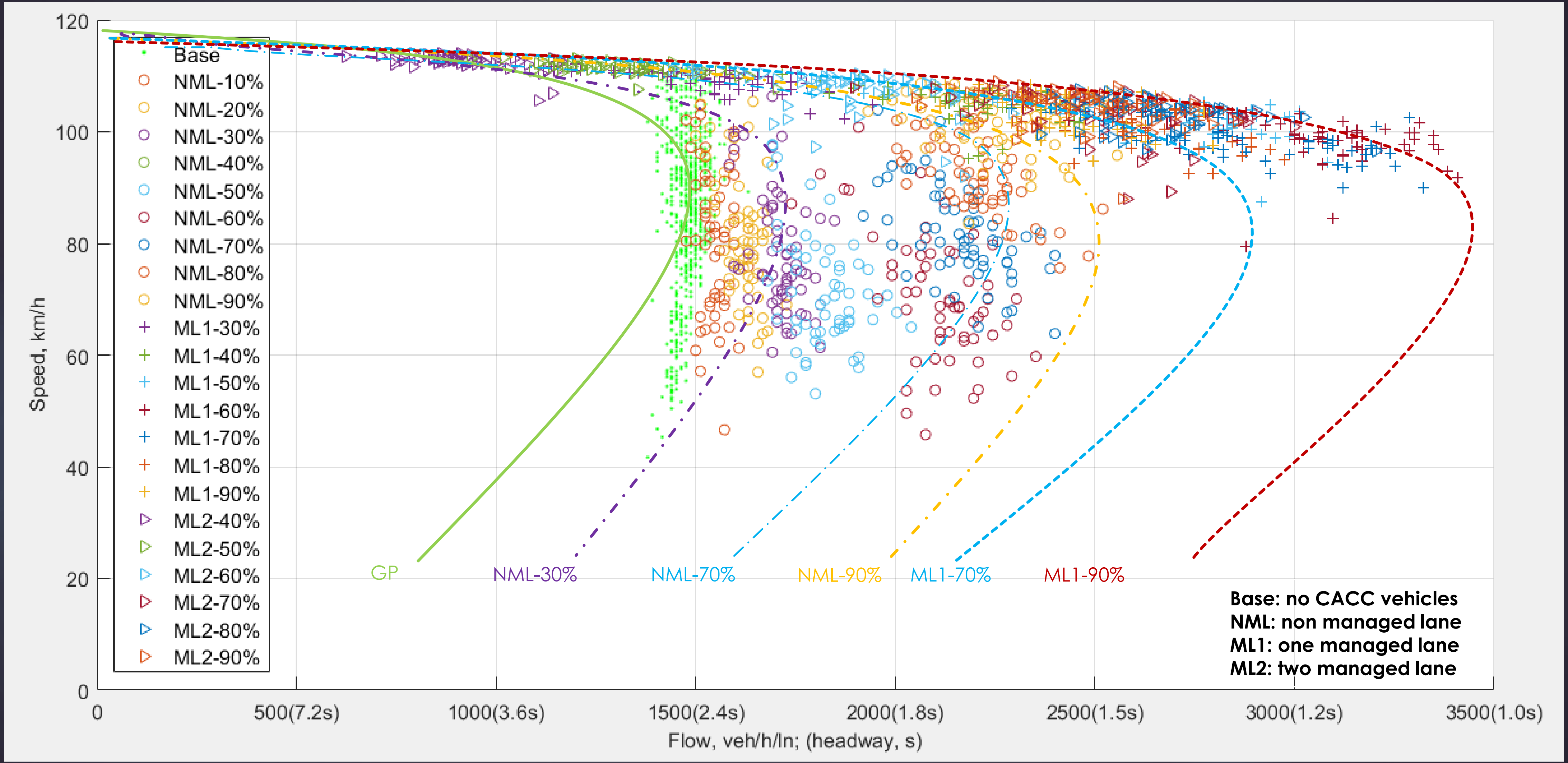
MOOP w/ CO2 Preferred

Case Study: Managed Lane in Imperfect Wireless Communication

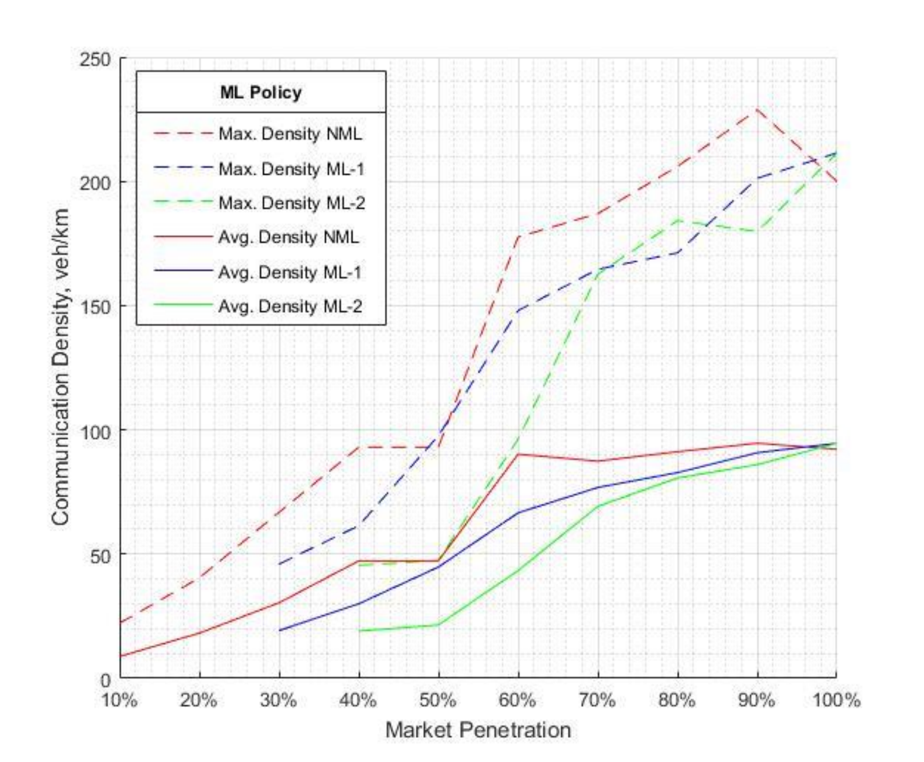


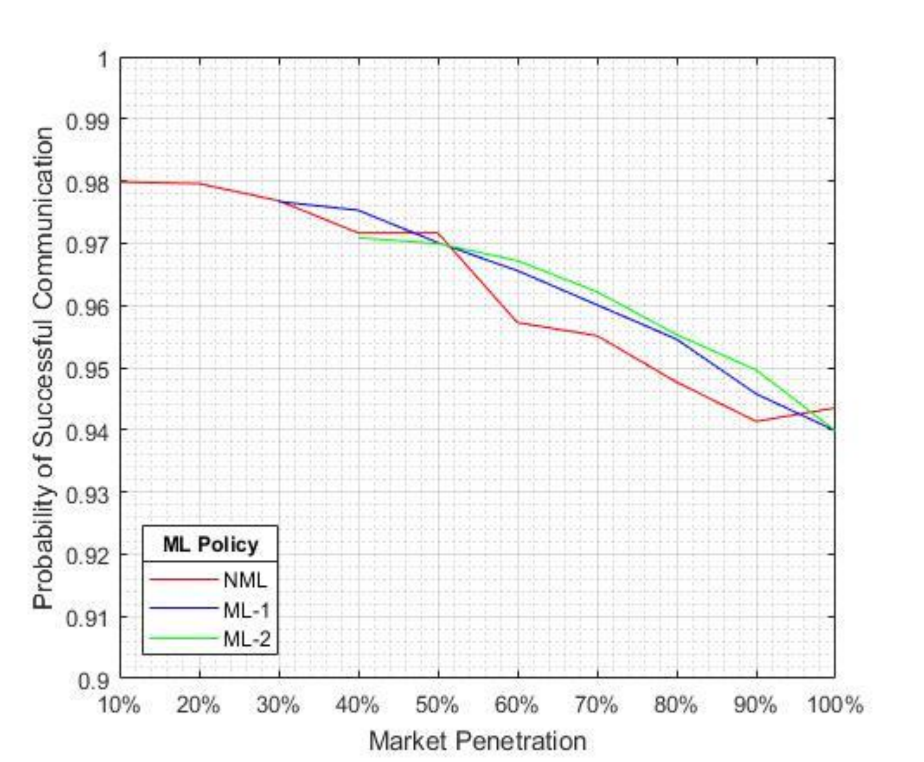
- A 9.3-km 4-lane hypothetical network was created in Vissim with two interchanges located at mile marker 2 km and 6 km respectively.
- The traffic demand for the network is higher than it typically is.
- No managed lane, 1 CACC lane, and 2 CACC lane were tested.
- Wireless communication is evaluated at 10Hz

Speed-flow Diagram with CACC



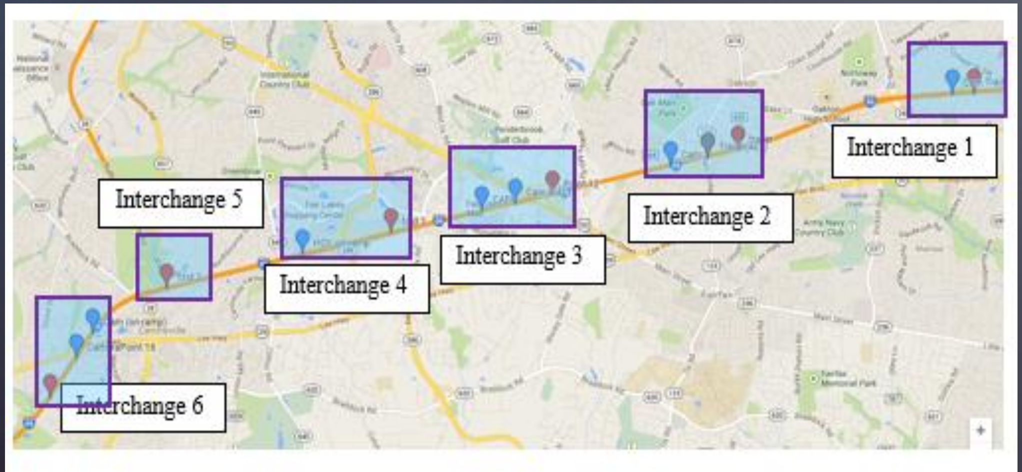
Wireless communication module





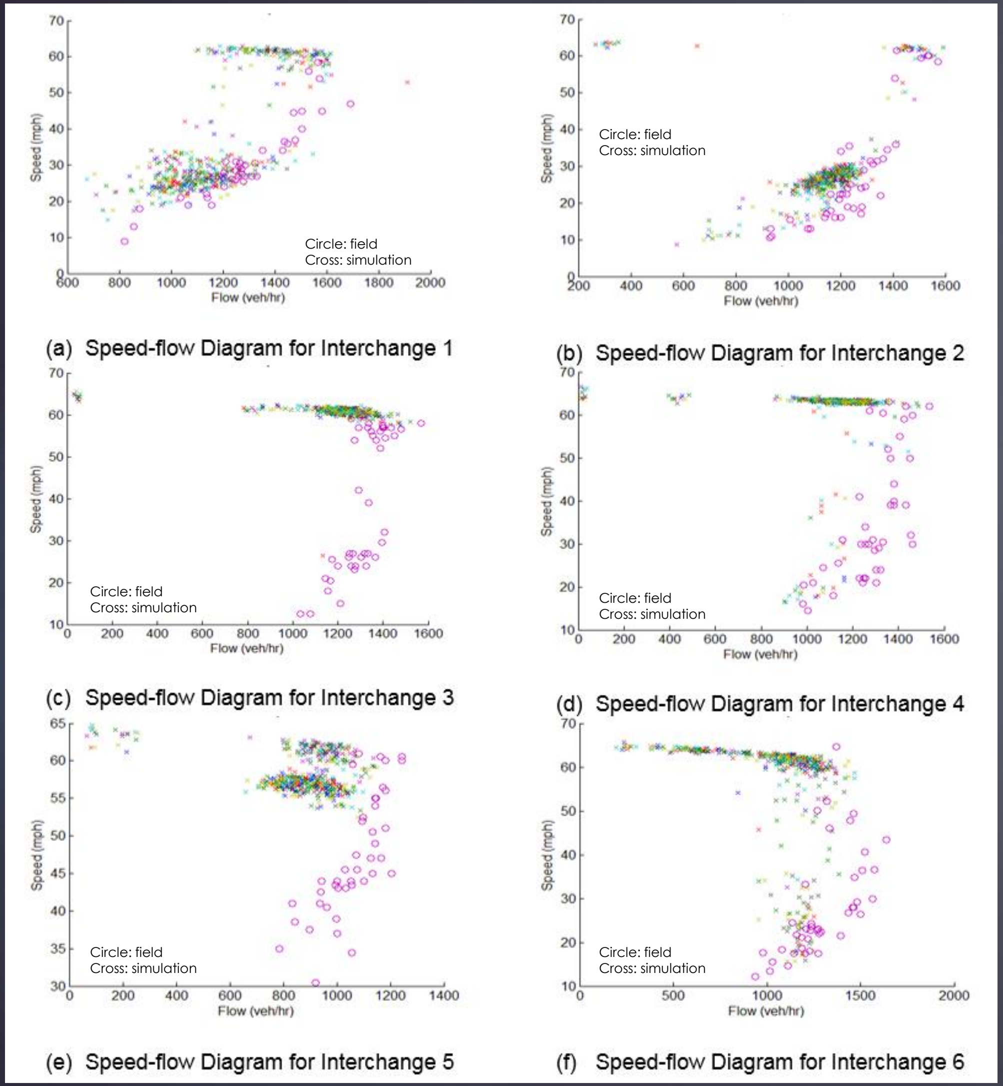
- This wireless communication module is able to provide communication density as well as probability of successfully communication for each individual CACC vehicle
- The managed lane strategies' impact for communication density can be observed

Realistic Large-Scale Network

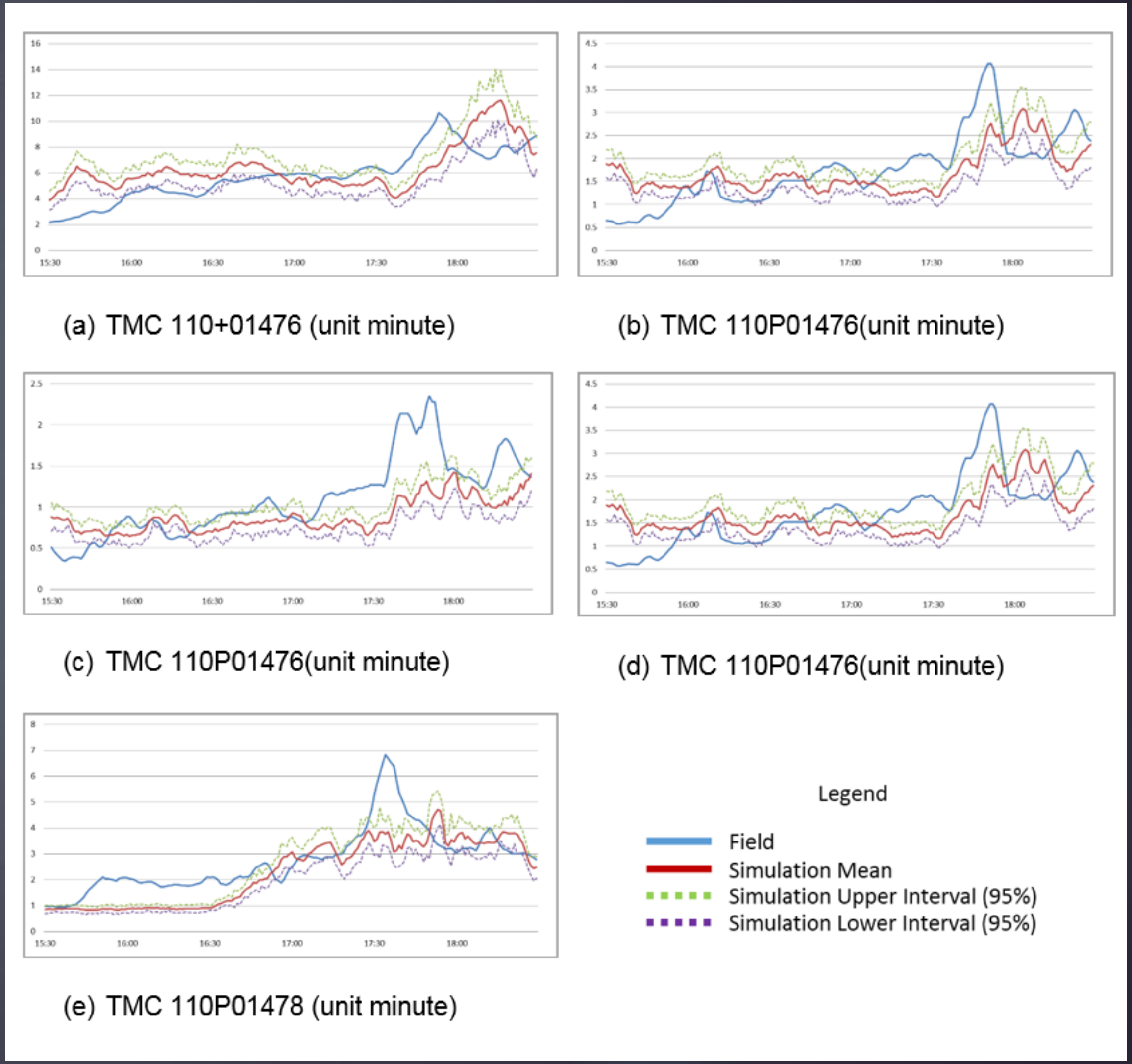


- The I-66 Segment, VA
  - A major commuter corridor out of the beltway of Washington D.C.
  - 14-mile with 4 lanes in each direction
  - With recurring congestion during weekdays
  - HOV lane implemented in the leftmost lane
  - Has 6 interchanges and 2 HOV exclusive exits

I-66 Network Calibration



Speed-flow Diagram (RTMS Data)



Travel Time (INRIX)

Conclusions

Within the proposed simulation network:

- The proposed MOOP control algorithm have been tested numerically. The algorithm offers a good balance and adaptive framework for platoon-wide CACC cooperation
- The DSRC wireless communication module has been integrated to the Driver Model API and tested for its suitability for large-scale traffic simulation
- The effectiveness of certain managed lane strategies of deploying CACC vehicles has been investigated
- The I-66 network has been properly calibrated for CACC evaluation

Future Research

- To integrate the MOOP-CACC algorithm in Vissim Driver Model API
- To conduct CACC evaluation on the I-66 network
- To derive policy recommendations for using managed strategies
- To fine tune the simulation test bed (e.g., distributed computing, more efficient GA solver)

Contributions

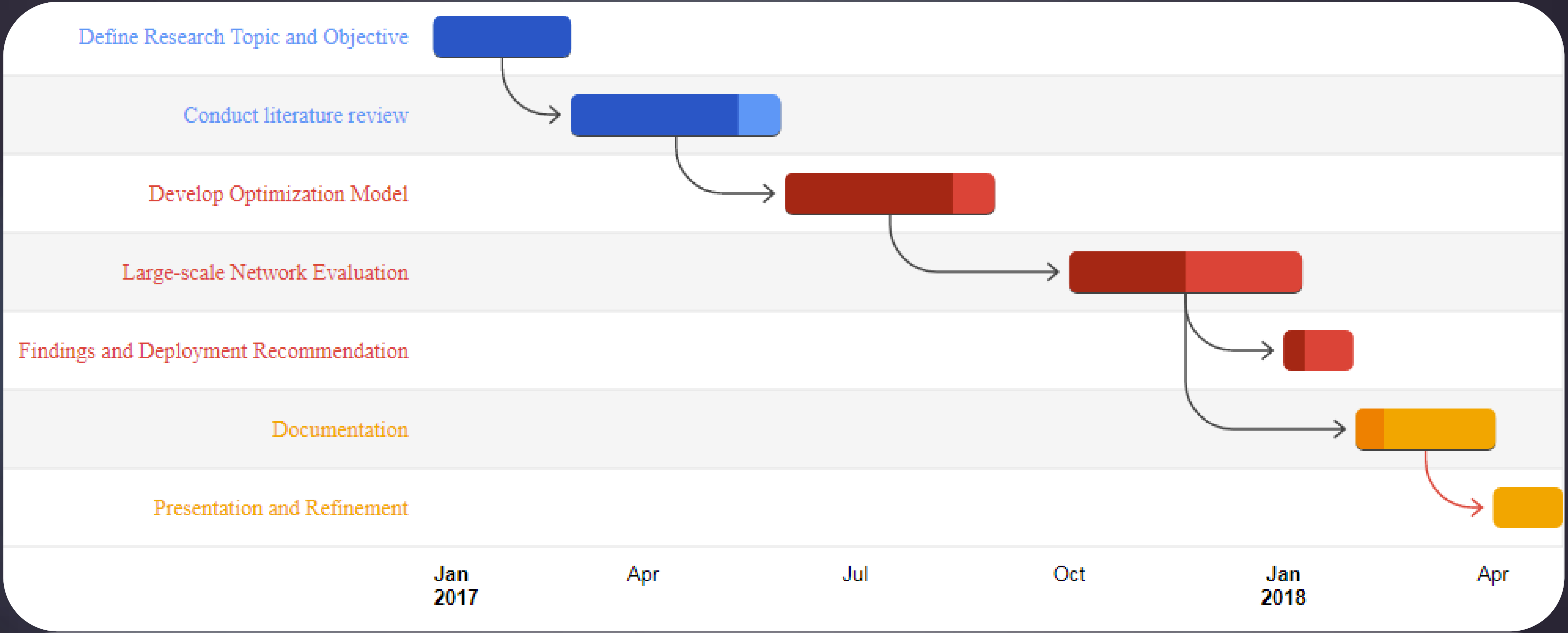
Development of an integrated simulation framework capable of

- Performing true cooperative driving based on multi-objective optimization
- Implementing high-definition longitudinal and lateral movements
- Simulating DSRC communication and its impact in simulation runtime in mixed traffic operation at a large-scale network

Evaluation of deployment of CACC vehicles

- Impact of managed lane strategy at network-level under mixed traffic condition
- Near-term deployment recommendations for stakeholders

Proposed Schedule



Thank you for your time

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