UCR College of Engineering- Center for Environmental Research & Technology

Distributed Consensus-Based Cooperative Adaptive Cruise Control (CACC) Systems

Ziran Wang (王子然)

Ph.D. Candidate
Mechanical Engineering
University of California, Riverside

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Outline

- **Motivation of the Research**
- **Distributed Consensus-Based CACC System**
- **Cluster-Wise Cooperative EAD System**
- **Other Research Topics**

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- **Motivation of the Research**
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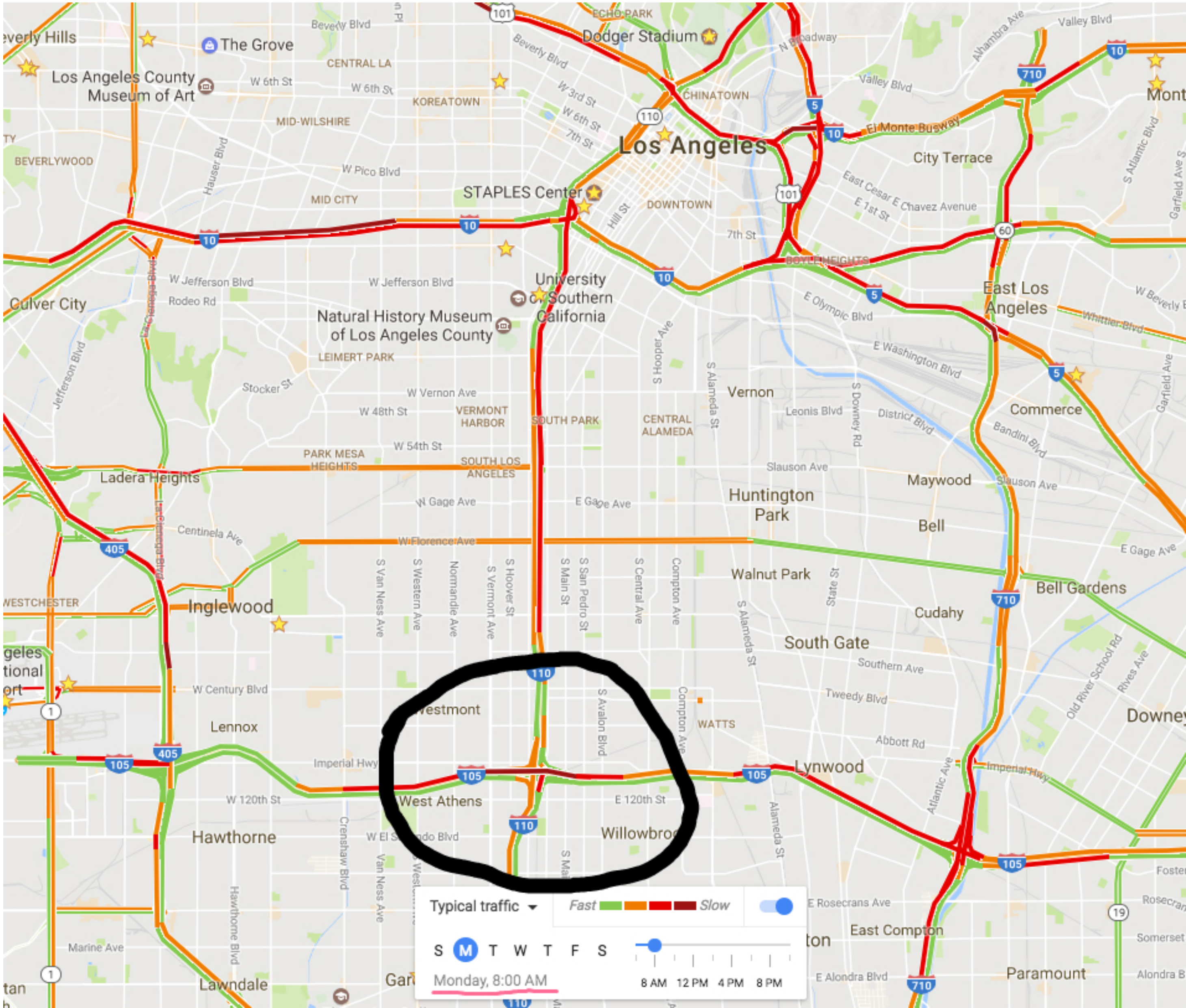


105/110 freeway interchange

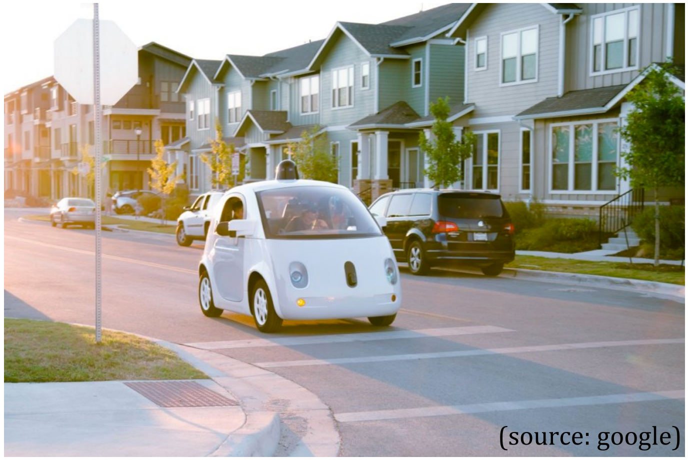
(Source: Google Map)

Wasted Fuel and Wasted Time

- **In 2016, Los Angeles tops the global ranking with 104 hour/commuter spent in traffic congestion**
- **In 2014, 3.1 billion gallons of energy were wasted worldwide due to traffic congestion**
- **In 2013, fuel waste and time lost in traffic congestion cost $124 billion in the U.S.**

(Source: La La Land)

Automated Vehicle Technology



- **Definition of automated vehicles**

At least some aspects of a safety-critical control function (e.g. , steering, acceleration, or braking) occur without direct driver input

- **Sensing techniques**

Radar, Lidar, GPS, odometry, computer vision, etc.

- **Level of automation by NHTSA**

- Level 0: Driver is in complete and sole control
- Level 1: One or more specific control function is involved
- Level 2: Two or more functions work in unison
- Level 3: Driver cede full control under certain conditions
- Level 4: Driver is not expected to control at any time

Connected Vehicle Technology

- **Definition of connected vehicles**

Vehicles that are equipped with Internet access, and usually also with a wireless local area network

- **Communication flow**

- Based primarily on dedicated short-range communications (DSRC)
- Between vehicles (V2V)
- Between vehicles and infrastructure (V2I/I2V)

(source: connectedvehicle.org)

(source: USDOT)

Merging of Connectivity and Automation

- **Automated Vehicles**

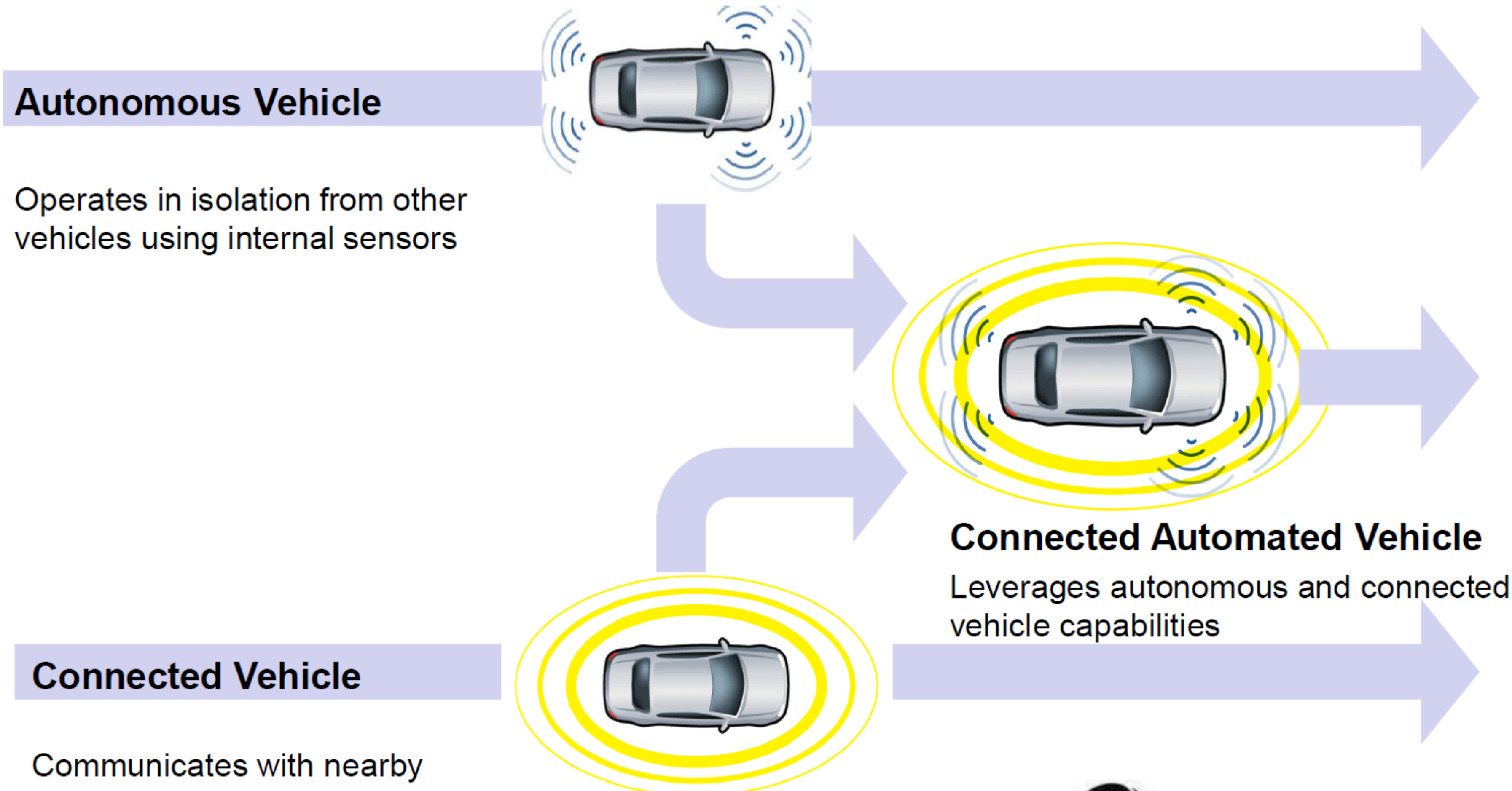
  - **Pros**: In general, partial or full vehicle automation can help **safety**
  - **Cons**: **Mobility and environmental impacts** may remain the same or could even get worse, e.g., adaptive cruise control (ACC) has been shown to have negative traffic mobility impacts

- **Connected Vehicles**

  - **Pros**: Introduction of a significant amount of **information** to support decision making
  - **Cons**: Increase in the driver's cognitive load, thus causing extra **distraction** and system disturbance

- **Therefore, a potentially better solution: Connected + Automated**

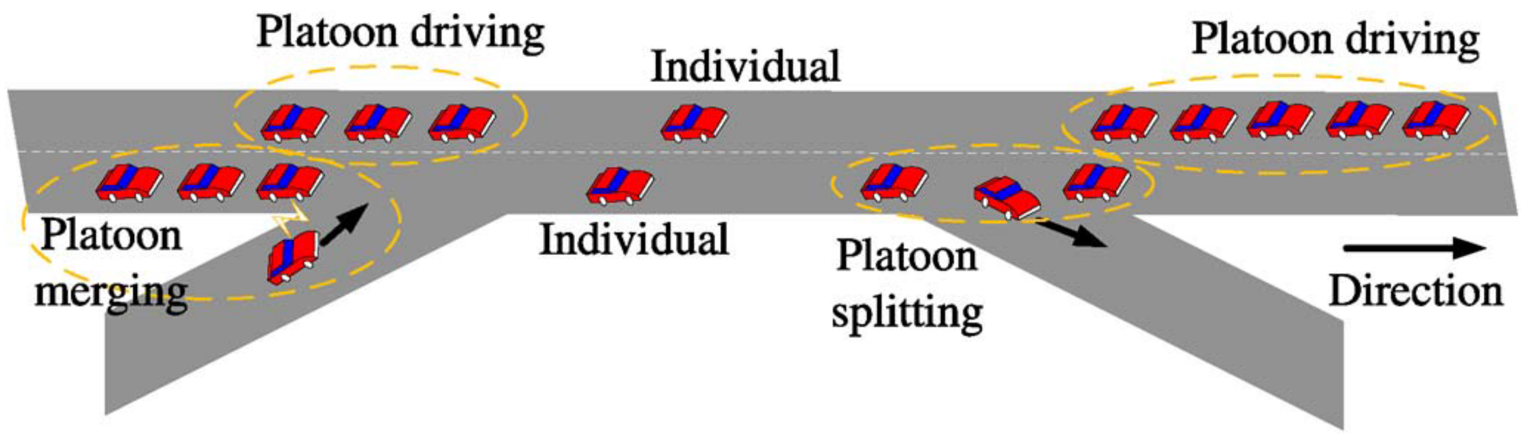
Merging of Connectivity and Automation



U.S. Department of Transportation
ITS Joint Program Office

Cooperative Adaptive Cruise Control (CACC)

- **Take advantage of connected vehicle technology and automated vehicle technology**
- **Form platoons and driven at harmonized speed with smaller time gap**

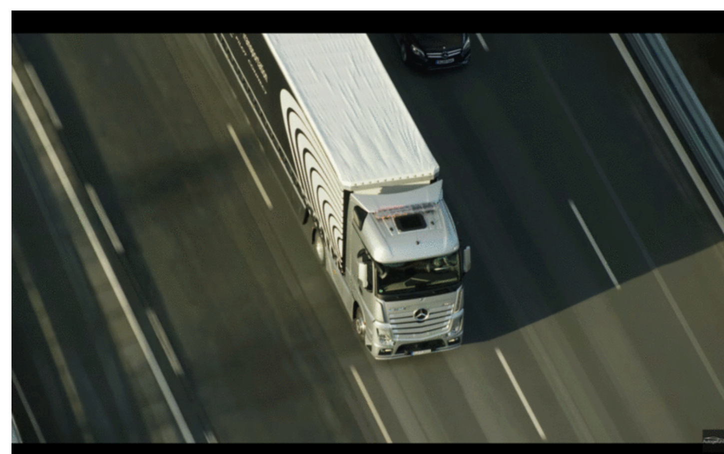


(D. Jia *et al.*, 2016)

Advantages of CACC

- **Safer** than human driving by taking a lot of danger out of the equation
- **Roadway capacity is increased** due to the reduction of inter-vehicle time gap
- **Fuel consumption and pollutant emissions are reduced** due to the mitigation of aerodynamic drag of following vehicles

(S. Oncu *et al.*, 2014)


(source: www.youtube.com/watch?v=LljnfGXos4c)

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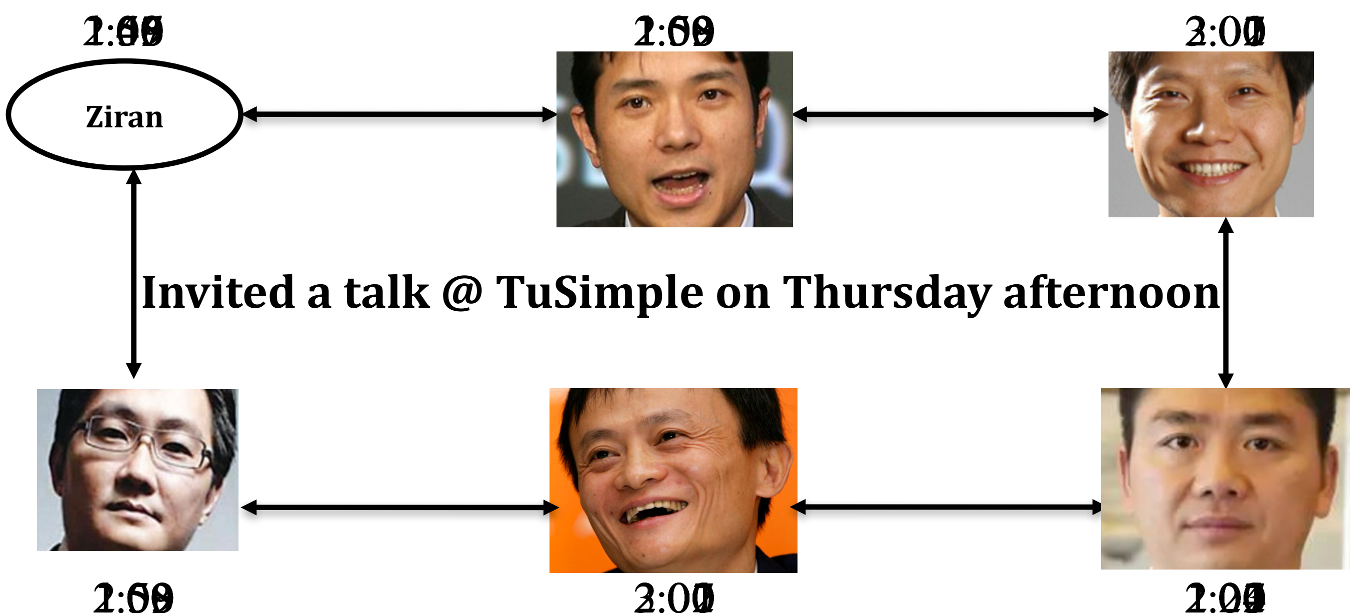
Distributed Consensus Networks

Reach agreement or consensus upon the value of a variable of interest

$$x_i[k+1] = \sum_{j=1}^{n} a_{ij}[k]\, x_j[k], \qquad i = 1, \dots, n$$



$$\frac{1:00 + 1:00 + 2:00 + 2:00 + 3:00 + 3:00}{6} = 2:00$$

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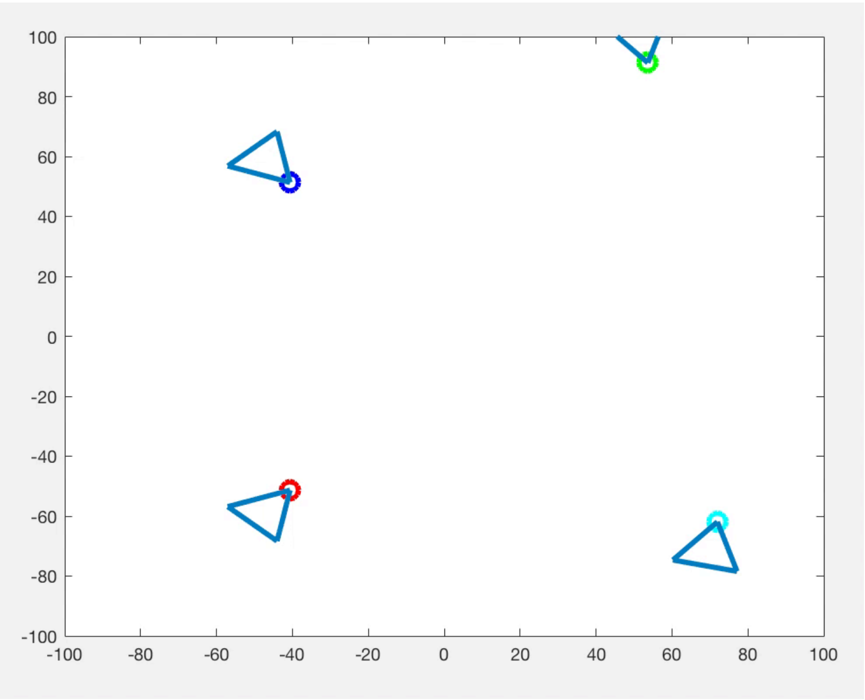
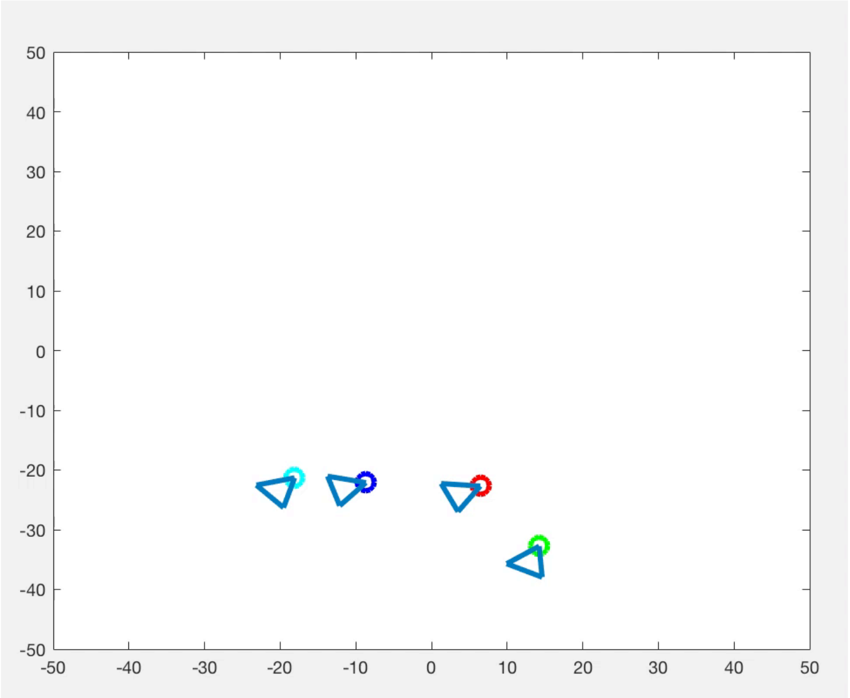
Distributed Consensus Networks



Converge to a desired location

Arrive at their desired locations while preserving the desired formation shape



Distributed Consensus Algorithm for the CACC system

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = -a_{ij}[x_i(t) - x_j\left(t - \tau_{ij}(t)\right) + l_{if} + l_{jr} + \dot{x}_j\left(t - \tau_{ij}(t)\right)\left(t_{ij}^g + \tau_{ij}(t)\right)b_i] \\ \qquad - \gamma a_{ij}\left[\dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right)\right] \end{cases}$$

$$i = 2, \dots, n, j = i - 1$$

$x_i(t)$	Longitudinal position of vehicle ***i*** at time ***t***	t_{ij}^g	Inter-vehicle time gap
$\dot{x}_i(t)$	Longitudinal speed of vehicle ***i*** at time ***t***	l_{if}	Length between GPS antenna to front bumper
$\dot{v}_i(t)$	Longitudinal acceleration of vehicle ***i*** at time ***t***	l_{jr}	Length between GPS antenna to rear bumper
a_{ij}	(i,j)th entry of the adjacency matrix	b_i	Braking factor of vehicle ***i***
$\tau_{ij}(t)$	Communication delay at time ***t***	γ	Tuning parameter

Distributed Consensus Algorithm for the CACC system

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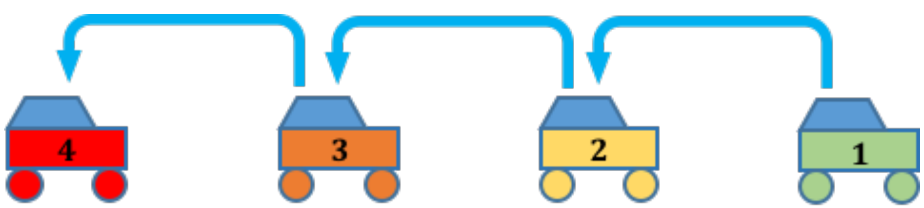
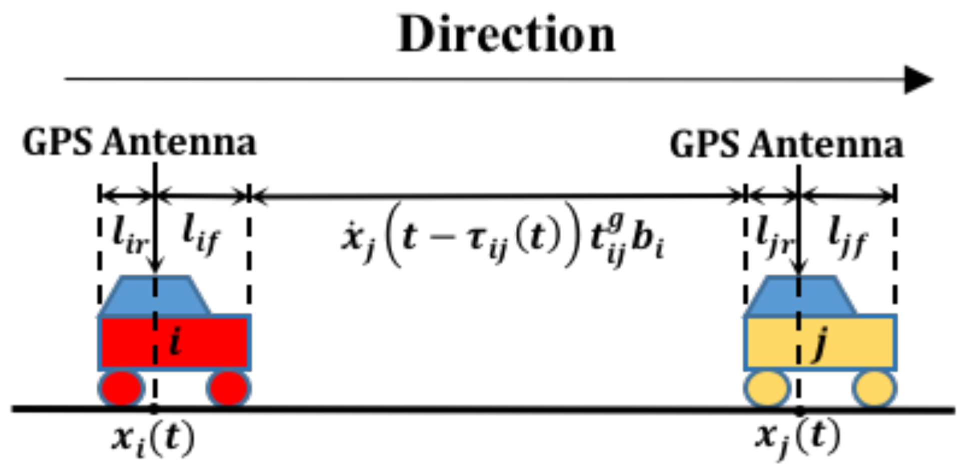
Predecessor following topology





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$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = -a_{ij}\left[x_i(t) - x_j\left(t - \tau_{ij}(t)\right) + l_{if} + l_{jr} + \dot{x}_j\left(t - \tau_{ij}(t)\right)\left(t_{ij}^g + \tau_{ij}(t)\right)b_i\right] \\ \qquad - \gamma a_{ij}\left[\dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right)\right] \end{cases}$$

position consensus

velocity consensus

$$i = 2, \ldots, n, j = i - 1$$

- **Consensus is reached by a platoon of vehicles if**

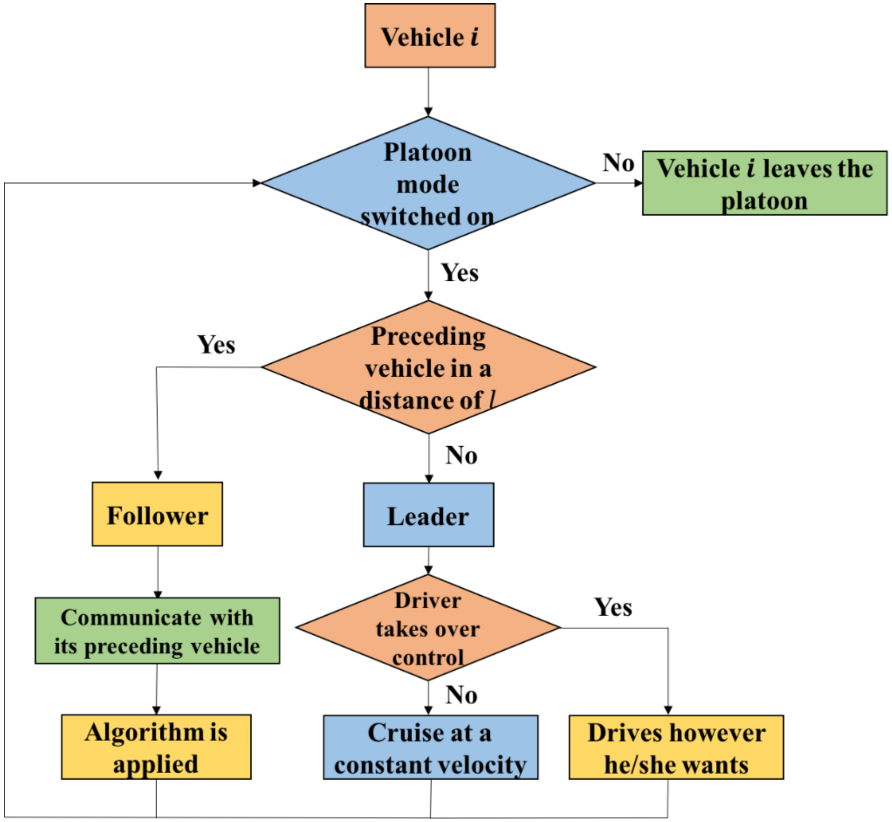
$$\begin{cases} \left\| x_i(t) - x_j\left(t - \tau_{ij}(t)\right) \right\| \to l_{if} + l_{jr} + \dot{x}_j\left(t - \tau_{ij}(t)\right)\left(t_{ij}^g + \tau_{ij}(t)\right) b_i \\ \left\| \dot{x}_i(t) - \dot{x}_j\left(t - \tau_{ij}(t)\right) \right\| \to 0 \end{cases}$$

Distributed Consensus Protocol for the CACC system

- **Assumption**

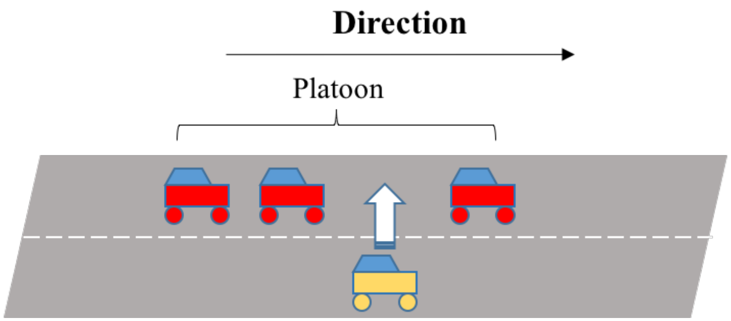
Every vehicle in the system is equipped with appropriate sensors

- **Protocol 1: Normal platoon formation**



Distributed Consensus Protocol for the CACC system

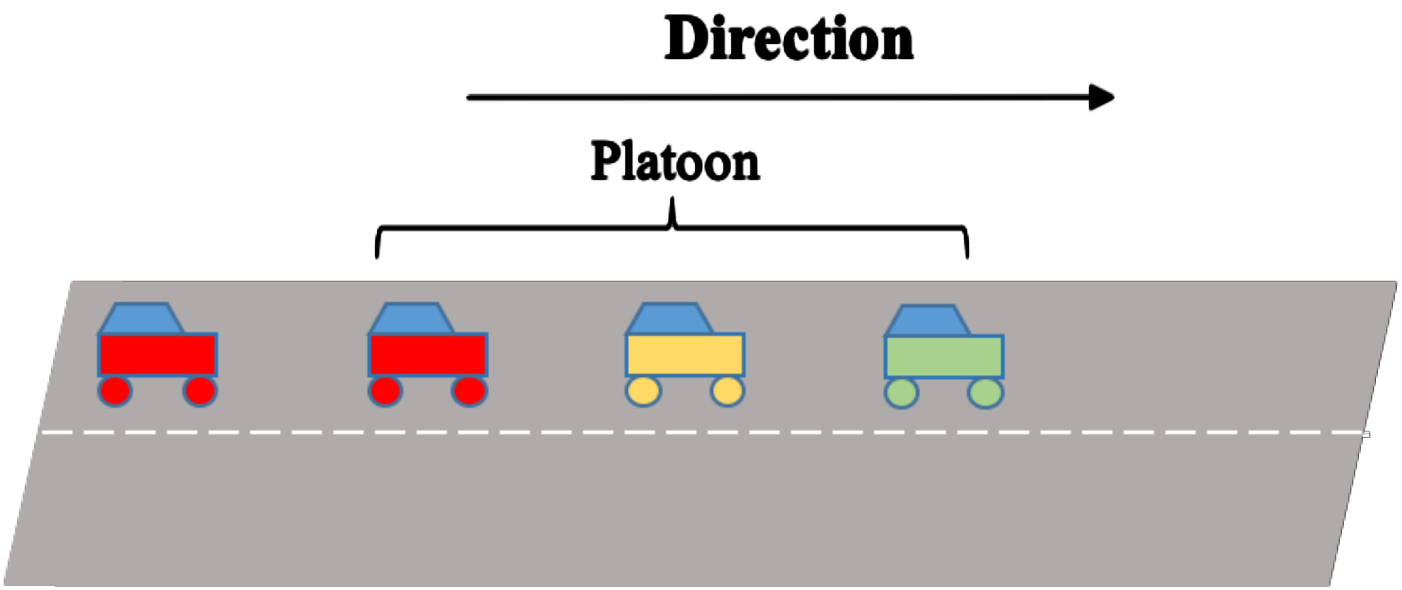
- **Protocol 2: Merging and splitting maneuvers**



1. Vehicle i communicates with the platoon and decides the jth vehicle of the platoon.
2. A “ghost” vehicle with respect to vehicle $j-1$ in the platoon will be created on the lane vehicle i is on.
3. Vehicle i autonomously adjusts its absolute position and velocity with the “ghost” vehicle by distributed consensus algorithm proposed.
4. A “ghost” vehicle with respect to vehicle i is created in front of vehicle $j+1$, and vehicle $j+1$ starts to create a gap for vehicle i by distributed consensus algorithm proposed.
5. Vehicle i merges into the platoon.

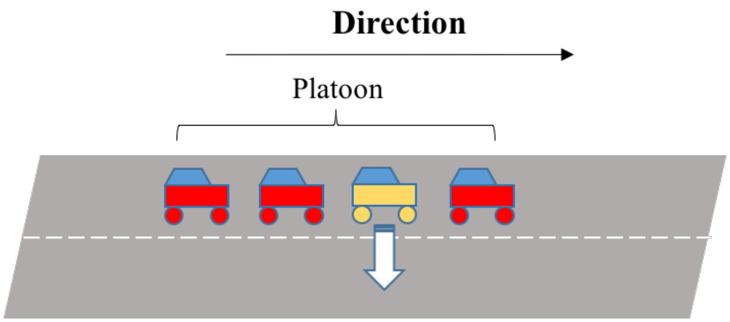
Distributed Consensus Protocol for the CACC system

- **Protocol 2: Merging and splitting maneuvers**



Distributed Consensus Protocol for the CACC system

- **Protocol 2: Merging and splitting maneuvers**



1. After the splitting mode is activated, the driver can take over the lateral control of the vehicle and perform the lane change without adjusting the velocity longitudinally.
2. After vehicle j completes the lane change, vehicle j+1 will sense that its preceding vehicle changes from vehicle j to vehicle $j-1$, and therefore adjust its velocity to close the gap.
3. A new platoon is formed, where vehicle $j+1$ becomes vehicle j, and vehicle $j+2$ becomes vehicle $j+1$, and so on.

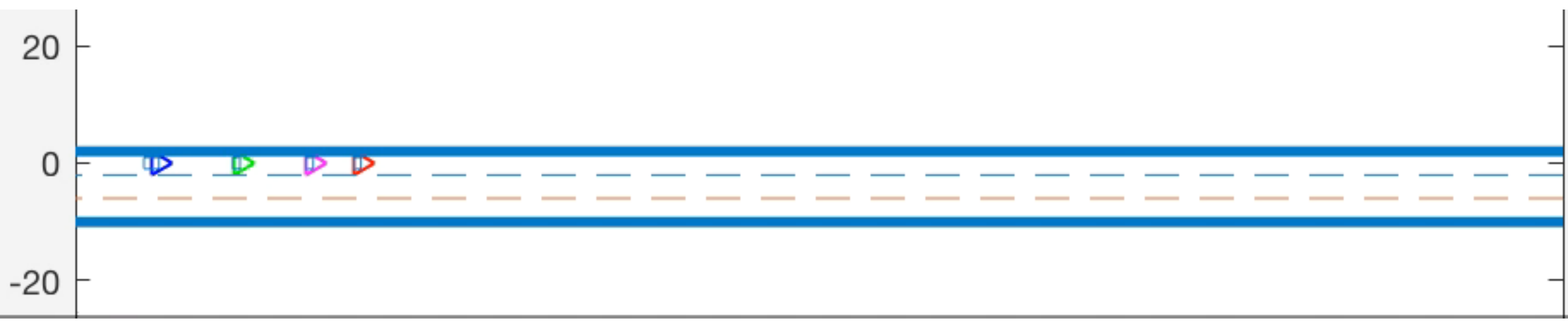
Simulation Study

- **Scenario 1: Normal platoon formation**

TABLE 1: Values of vehicle parameters.

Parameters	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
GPS antenna to front bumper l_{if}	3 m	3 m	3 m	6 m
GPS antenna to rear bumper l_{ir}	2 m	2 m	2 m	4 m
braking factor b_i	1	1	1.1	1.6
initial velocity $\dot{x}_{i0}$	30 m/s	33 m/s	36 m/s	39 m/s
desired velocity $\dot{x}_i$	30 m/s	30 m/s	30 m/s	30 m/s

initial time gap t^g_{ij0}	0.91 s	1.11 s	1.67 s
initial weighted inter-vehicle distance d_{ij0}	30 m	40 m	65 m
desired time gap t^g_{ij}	0.43 s	0.48 s	0.69 s
desired time headway t^h_{ij}	0.6 s	0.64 s	0.86 s
desired weighted inter-vehicle distance d_{ij}	13 m	14.3 m	20.8 m
desired unweighted inter-vehicle distance d_{ij}/b_i	13 m	13 m	13 m



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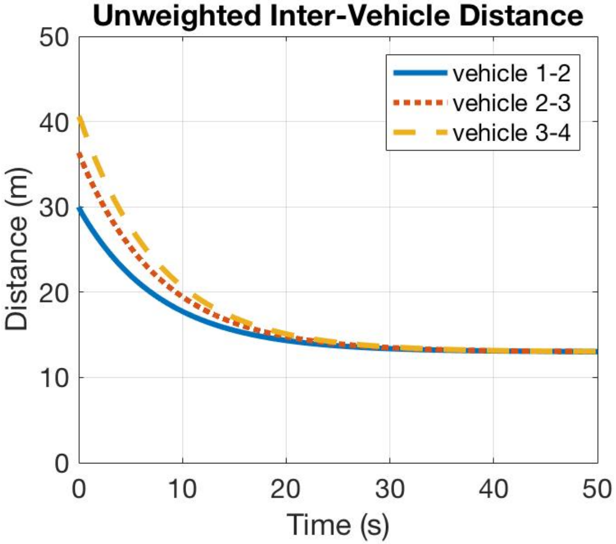
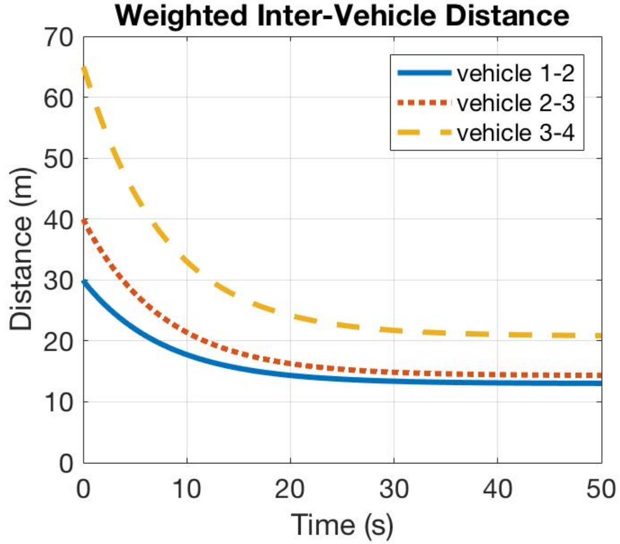
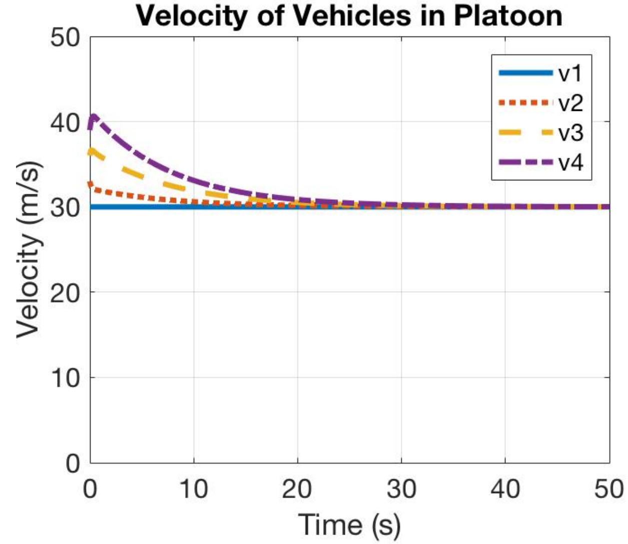
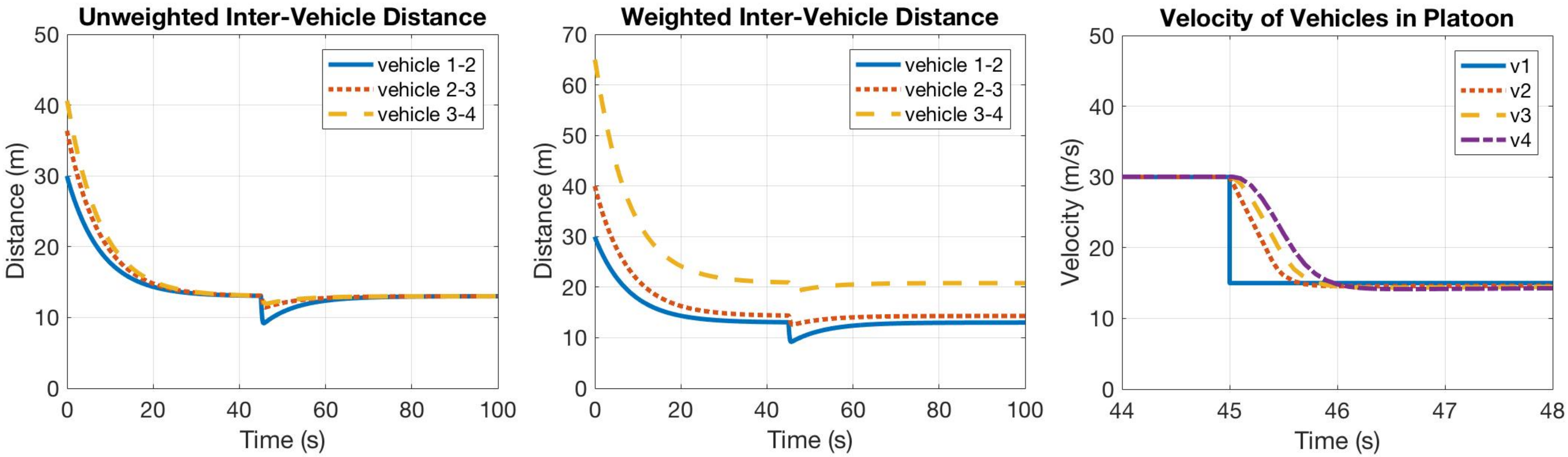


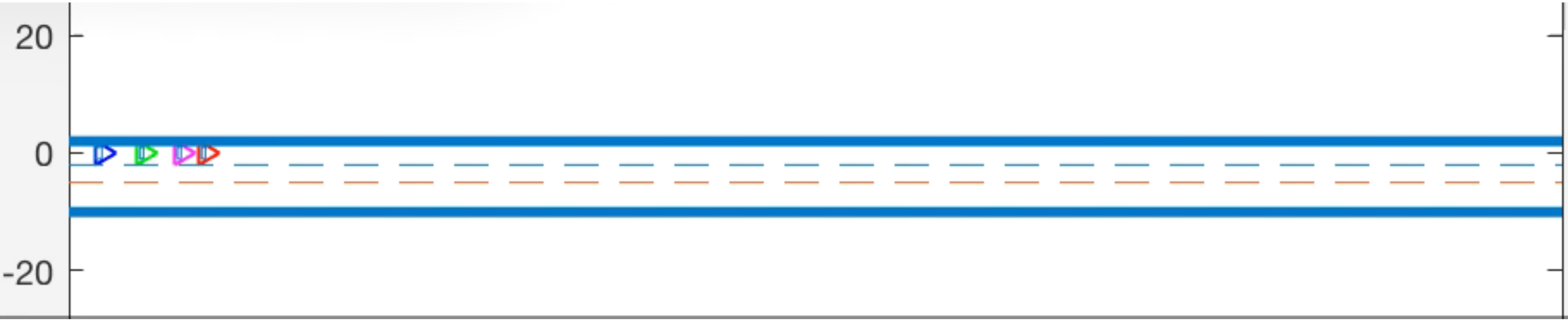




Simulation Study

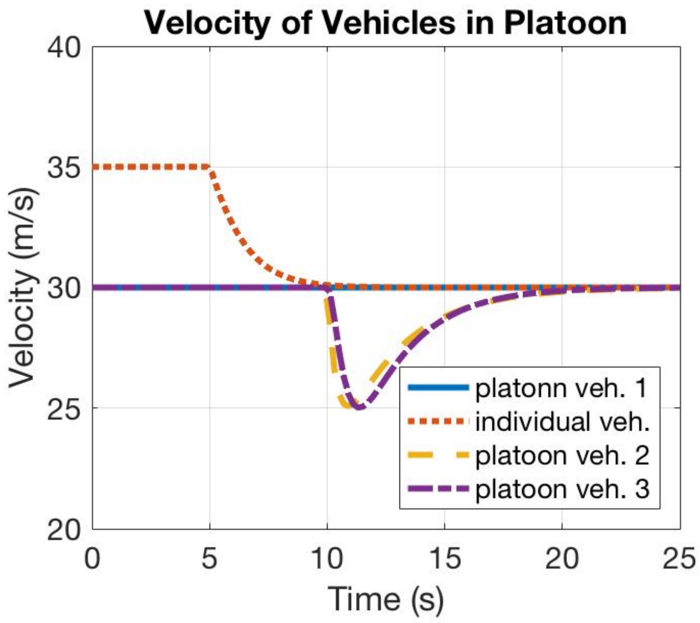
- **Scenario 2: Platoon restoration from disturbances**

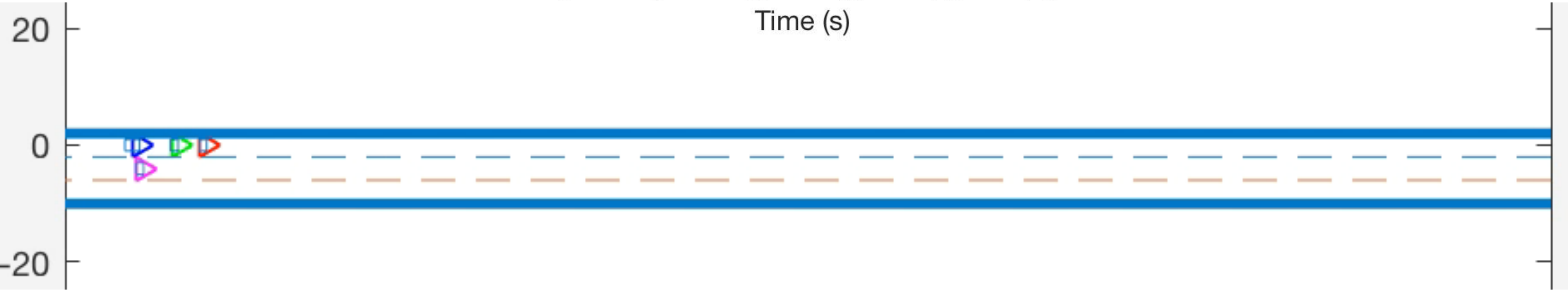




Simulation Study

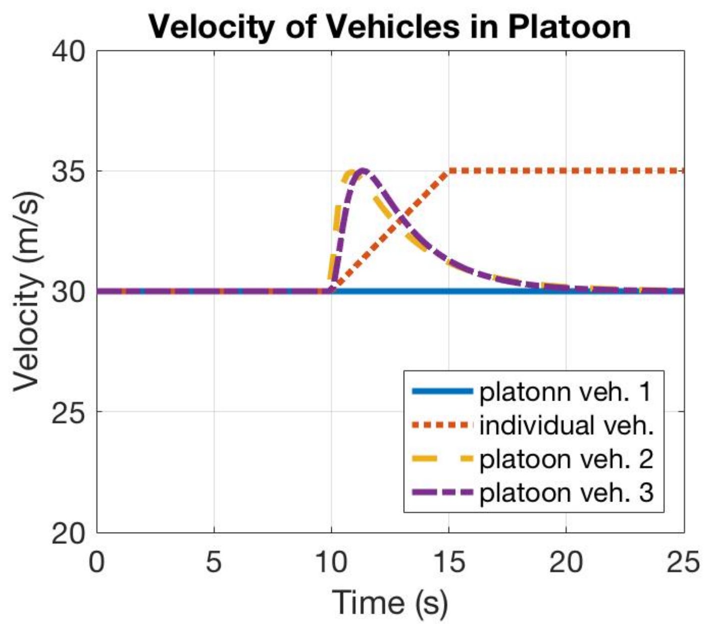
- **Scenario 3: Merging and splitting maneuvers**

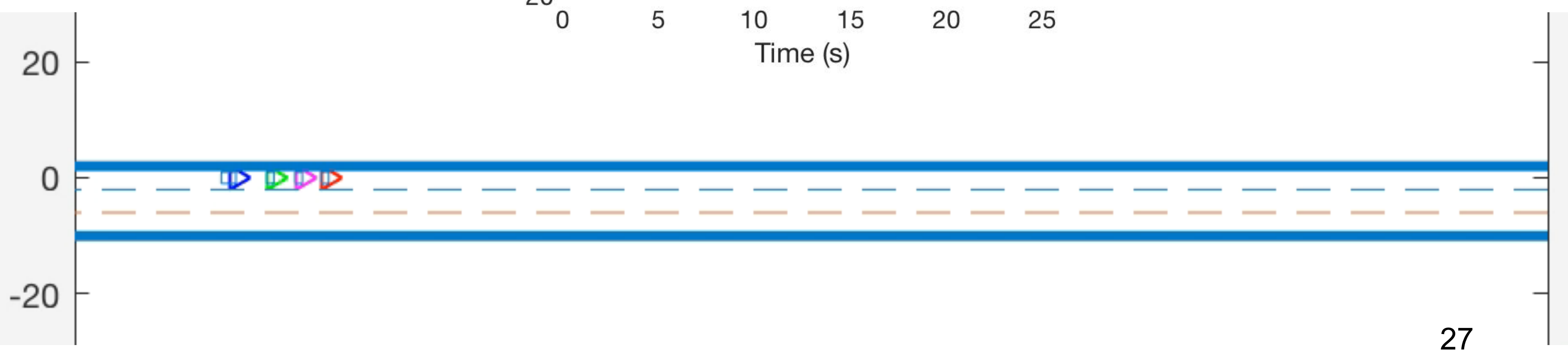




Simulation Study

- **Scenario 3: Merging and splitting maneuvers**





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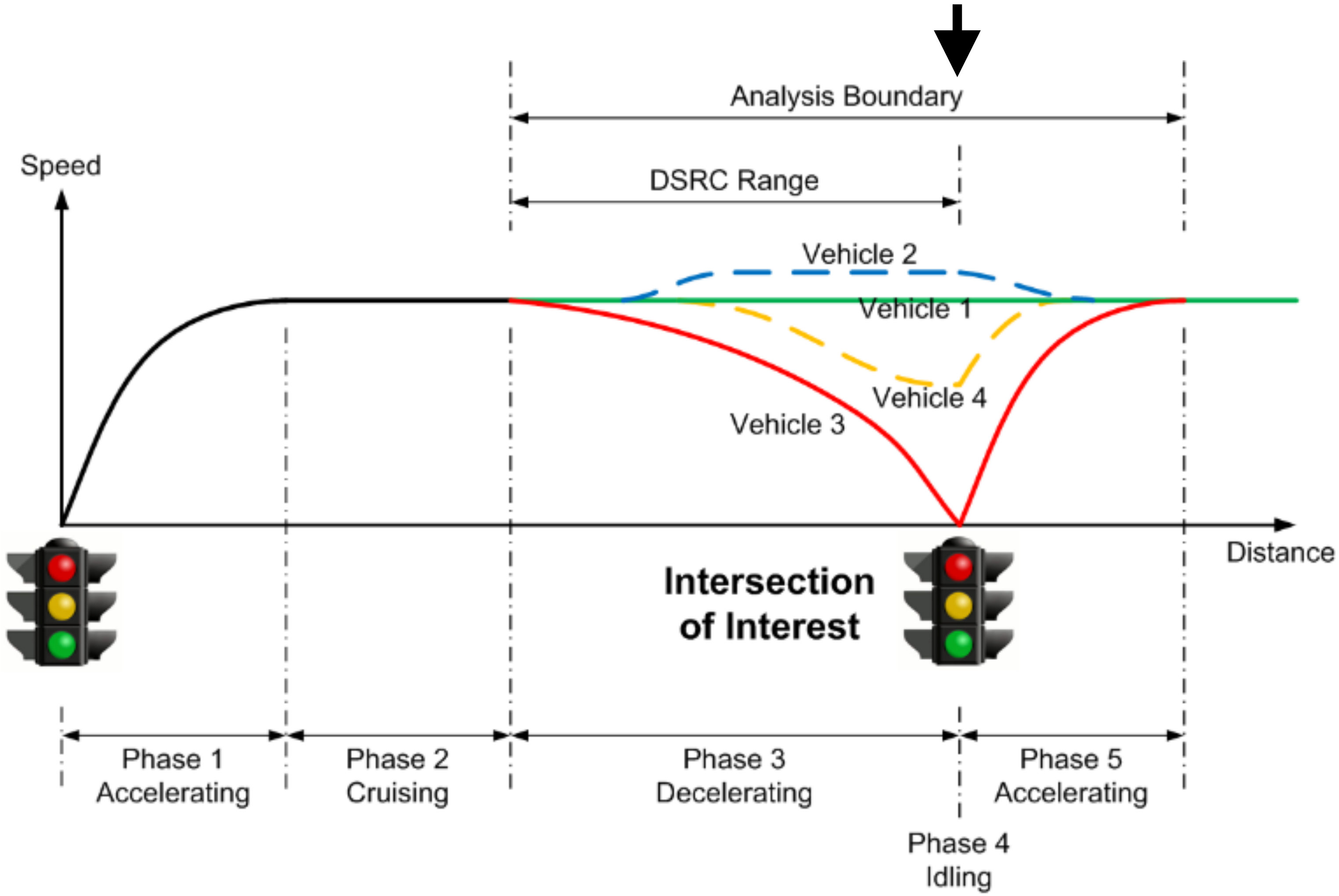
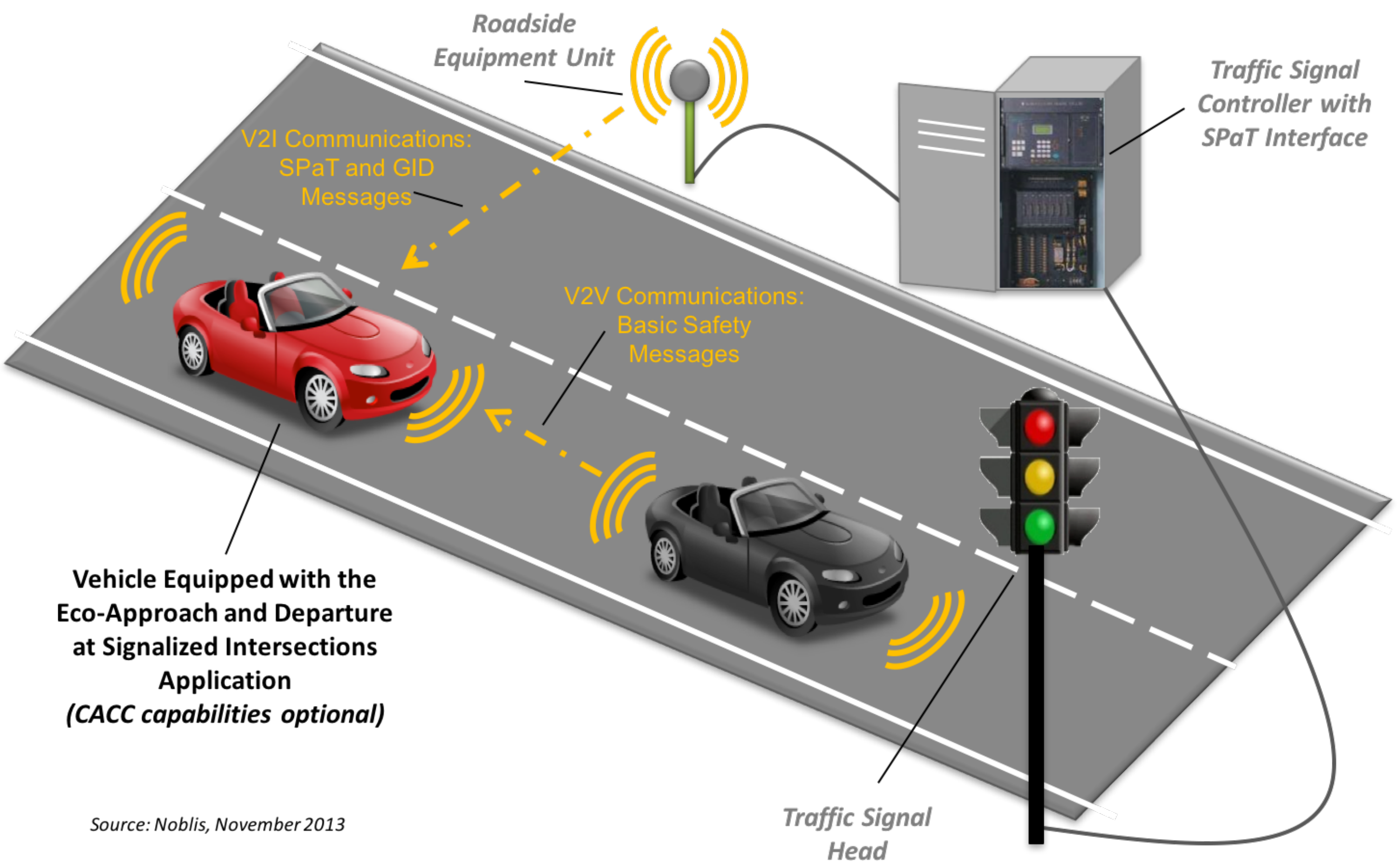
Vehicles Approaching an Intersection

Intersection of interest

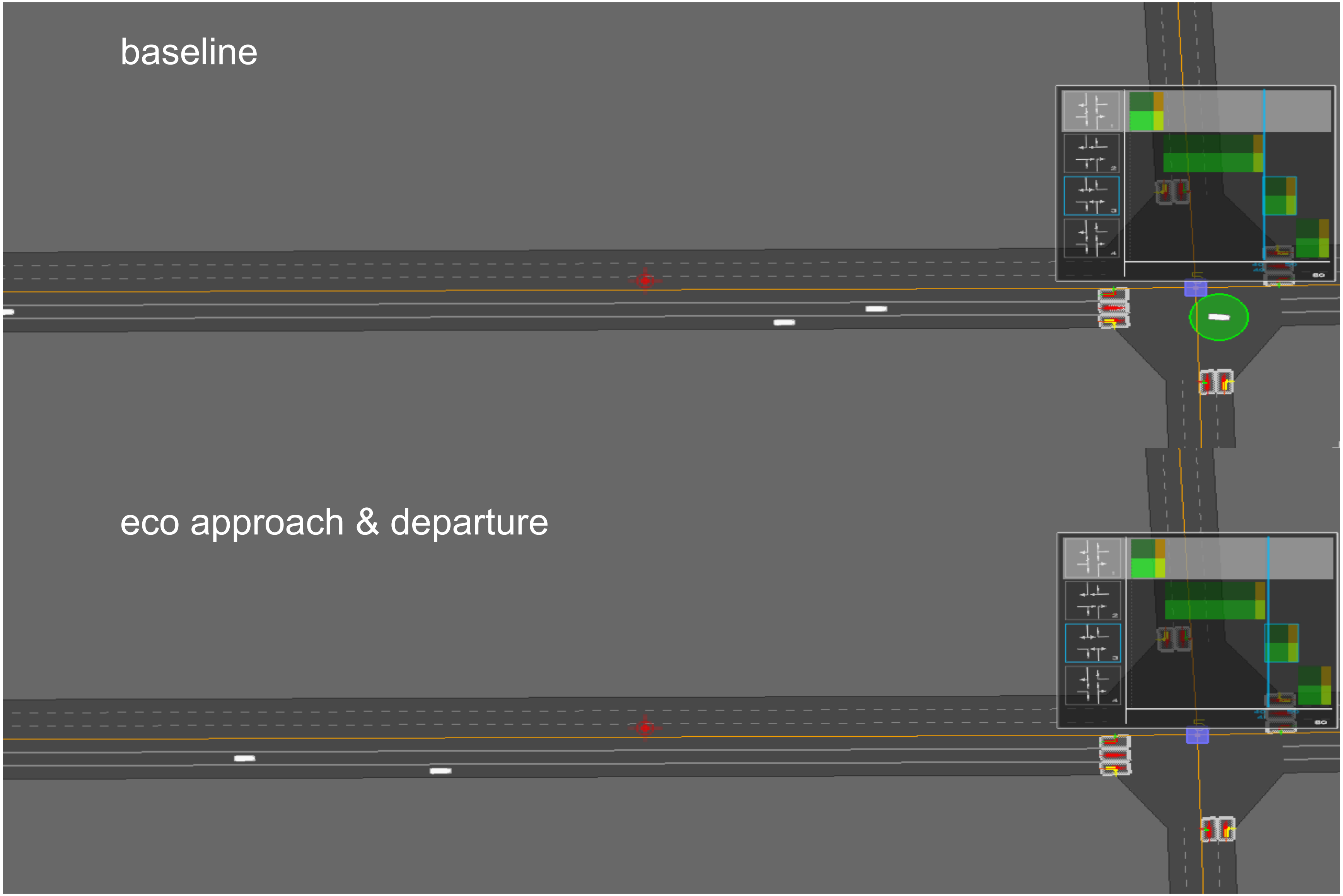


Eco-Approach and Departure (EAD) at Signalized Intersections



Source: Noblis, November 2013

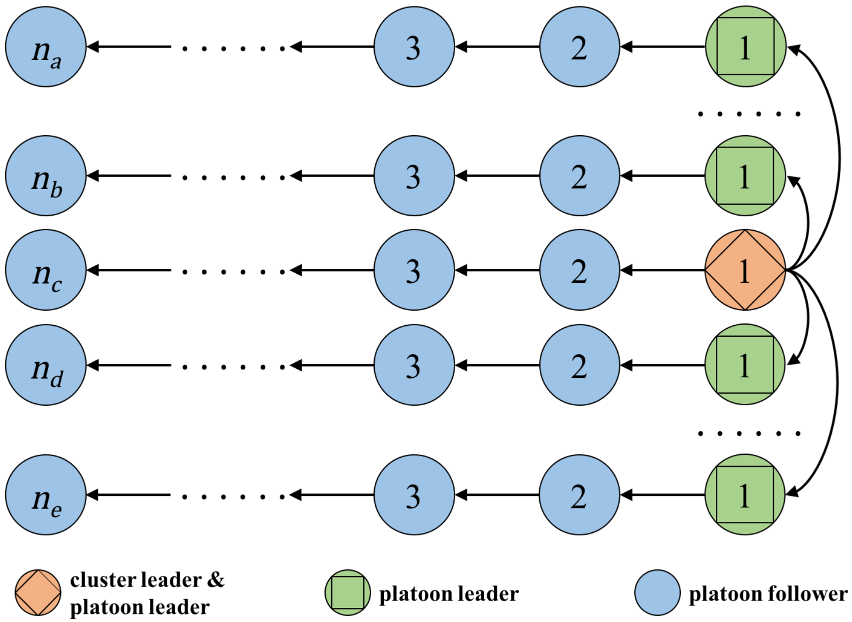
EAD Microscopic Simulation



Cluster-Wise Cooperative EAD at Signalized Intersections

- **Methodology**

1) Initial Vehicle Clustering
2) Intra-Cluster Sequence Optimization
3) Cluster Formation Control
4) Cooperative Eco-Approach and Departure



- **Advantages**

1) Increase traffic flow throughput at a certain arterial segment
2) Decrease the travel time to go through signalized intersections
3) Decrease the total energy consumption and pollutant emissions

Cluster-Wise Cooperative EAD at Signalized Intersections

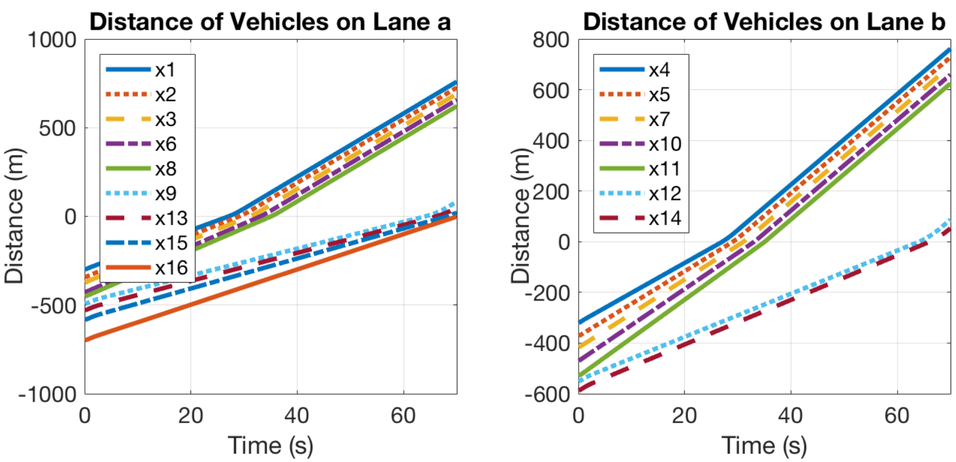
Values of Simulation Parameters

Parameter	***Value***
Number of Cars (N)	16
Number of Lanes (J)	2
Simulation Time Step	0.1 s
Communication Delay (τ_{ij})	60 ms
Roadway Speed Limit (v^{limit})	17.88 m/s
Maximum Acceleration (a_i^{max})	3.5 m/s²
GPS Antenna to Front Bumper (l_{if})	3 m
GPS Antenna to Rear Bumper (l_{jr})	2 m
Braking Factor (b_i)	1
Desired Time Headway (t_{ij}^h) for Ego-EAD	2 s
Desired Time Headway (t_{ij}^h) for Coop-EAD	1 s
Red Window (not allowed to travel through)	27 s
Green Window (allowed to travel through)	8 s
Yellow Window (not allowed to travel through)	2 s

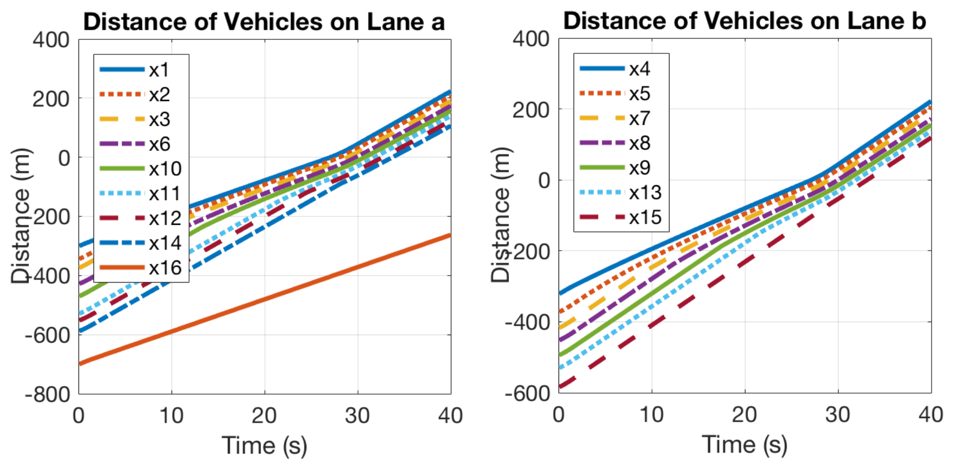
Values of Vehicle Parameters

Vehicle Index	***Lane/Sequence Index***	***Initial Speed***	***Initial Distance to Intersection***
1	a/1	13.41 m/s²	300 m
2	a/2	14.32 m/s²	344 m
3	a/3	14.42 m/s²	374 m
4	b/1	14.10 m/s²	321 m
5	b/2	12.39 m/s²	372 m
6	a/4	13.09 m/s²	428 m
7	b/3	13.12 m/s²	417 m
8	a/5	12.44 m/s²	452 m
9	a/6	12.77 m/s²	494 m
10	b/4	13.88 m/s²	470 m
11	b/5	13.29 m/s²	529 m
12	b/6	12.67 m/s²	552 m
13	a/7	12.64 m/s²	530 m
14	b/7	13.08 m/s²	588 m
15	a/8	13.22 m/s²	584 m
16	a/9	13.30 m/s²	700 m

Cluster-Wise Cooperative EAD at Signalized Intersections



Vehicle Trajectories of Ego-EAD



Vehicle Trajectories of Coop-EAD

Comparison of Energy Consumption and Pollutant Emissions of Ego-EAD and Coop-EAD

	HC (g/s)	*CO (g/s)*	*NO_X (g/s)*	*CO_2 (g/s)*	*PM2.5 (g/s)*	*Energy (KJ/s)*
Ego-EAD	0.041	1.161	0.144	159.852	0.011	2222.938
Coop-EAD	0.037	1.398	0.141	142.253	0.009	1978.150
Reduction%	10.23	13.25	2.29	11.01	19.91	11.01

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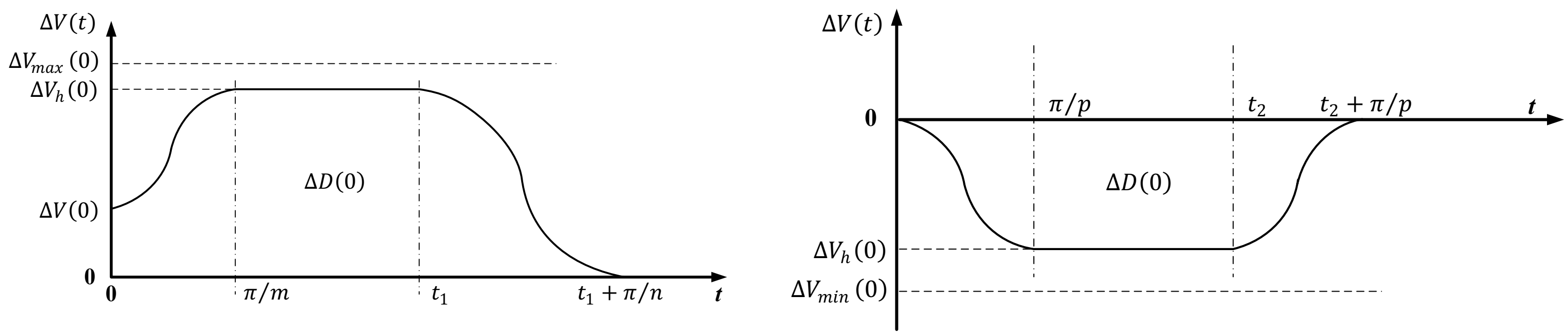
Other Research Topics

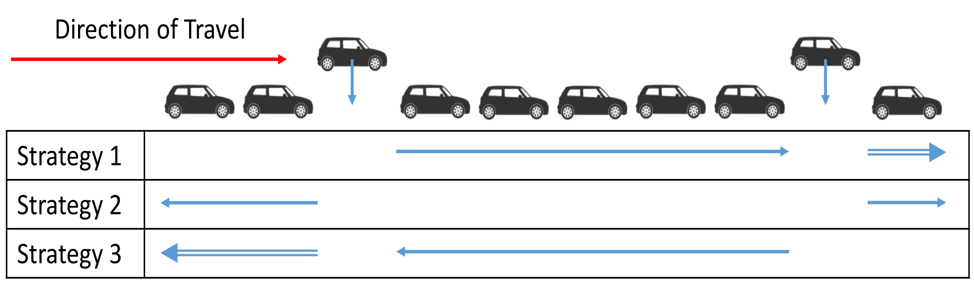
- **Platoon-Wide Eco-CACC System**

Reduce energy consumption at different stages of the CACC operation



- **Intra-Platoon Vehicle Sequence Optimization for Eco-CACC**

Optimize the vehicle sequence when vehicle joins to minimize the total acceleration and deceleration maneuvers



Other Research Topics

- **Connected Eco-Bus: An Innovative Vehicle-Powertrain Eco-Operation System for Efficient Plug-In Hybrid Electric Buses**

i. Sponsored by USDOE ARPA-E, cooperating with Oak Ridge National Laboratory and US Hybrid

ii. Adopt Eco-Approach and Departure, Eco-Cruise, Efficiency-Based Powertrain Control and Machine Learning-Based Powertrain Control technology

iii. Achieve 20% transformational fuel efficiency improvements for transit buses

UNIVERSITY OF CALIFORNIA UC RIVERSIDE | CE-CERT

OAK RIDGE National Laboratory

US Hybrid

arpa-e CHANGING WHAT'S POSSIBLE

RTA Riverside Transit Agency

Q & A Time

Thank you very much for the attention!

WeChat

Website