A Review on Cooperative Adaptive Cruise Control (CACC) Systems: Architectures, Controls, and Applications

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University of California, Riverside

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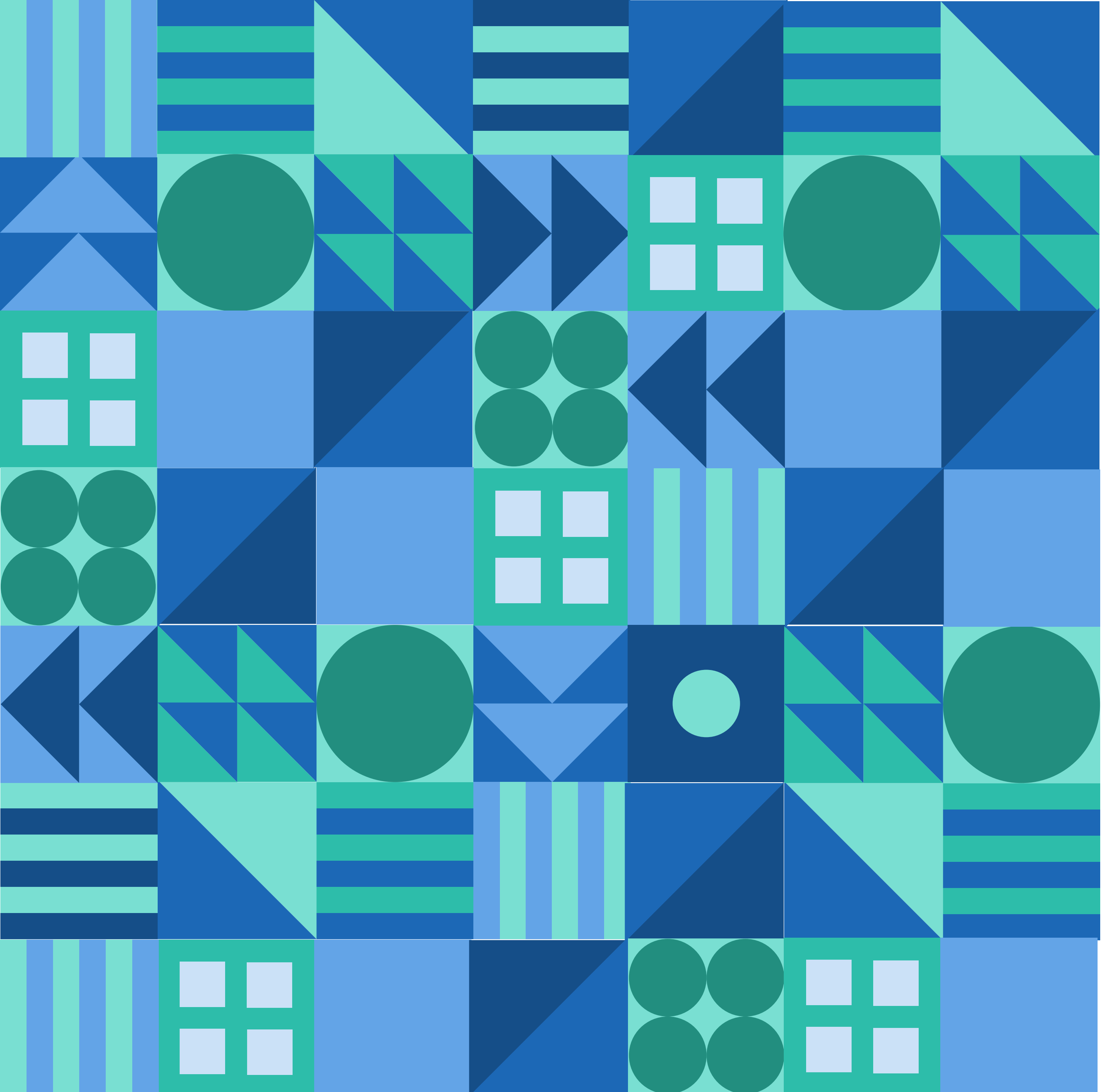
CONTENTS



01

Introduction

01 Introduction – From CC to ACC to CACC

- **Cruise Control (CC):**

Vehicle maintains a steady speed as set by the driver

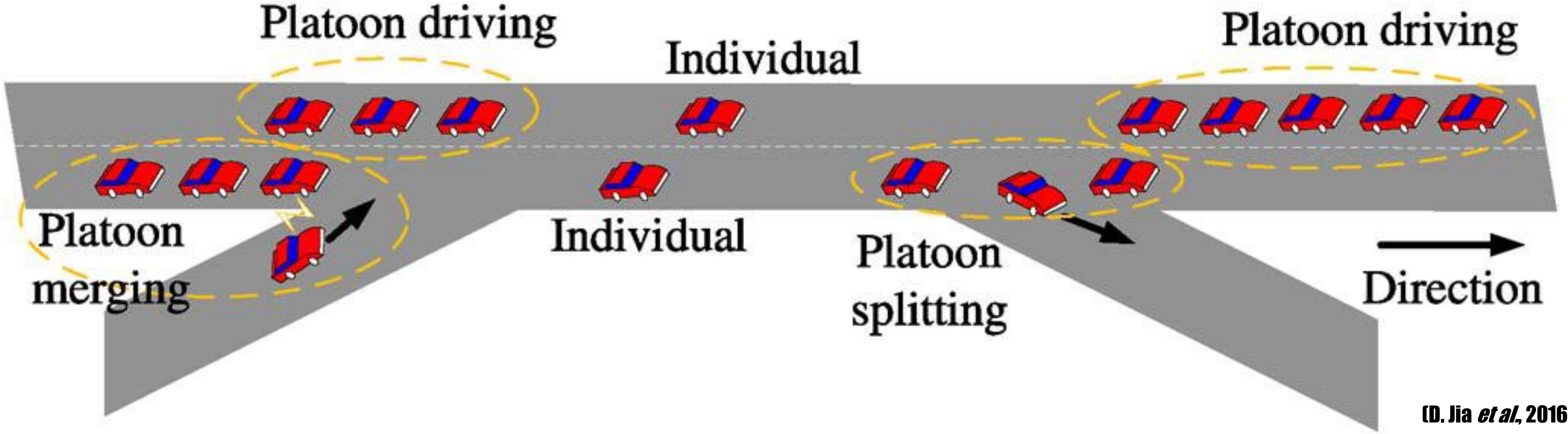
- **Adaptive Cruise Control (ACC):**

Vehicle automatically adjusts speed to maintain a safe distance from vehicle ahead

- **Cooperative Adaptive Cruise Control (CACC)**

01 Introduction – Cooperative Adaptive Cruise Control

- Take advantage of the Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications
- Form platoons/strings and driven at harmonized speed with smaller time gap



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

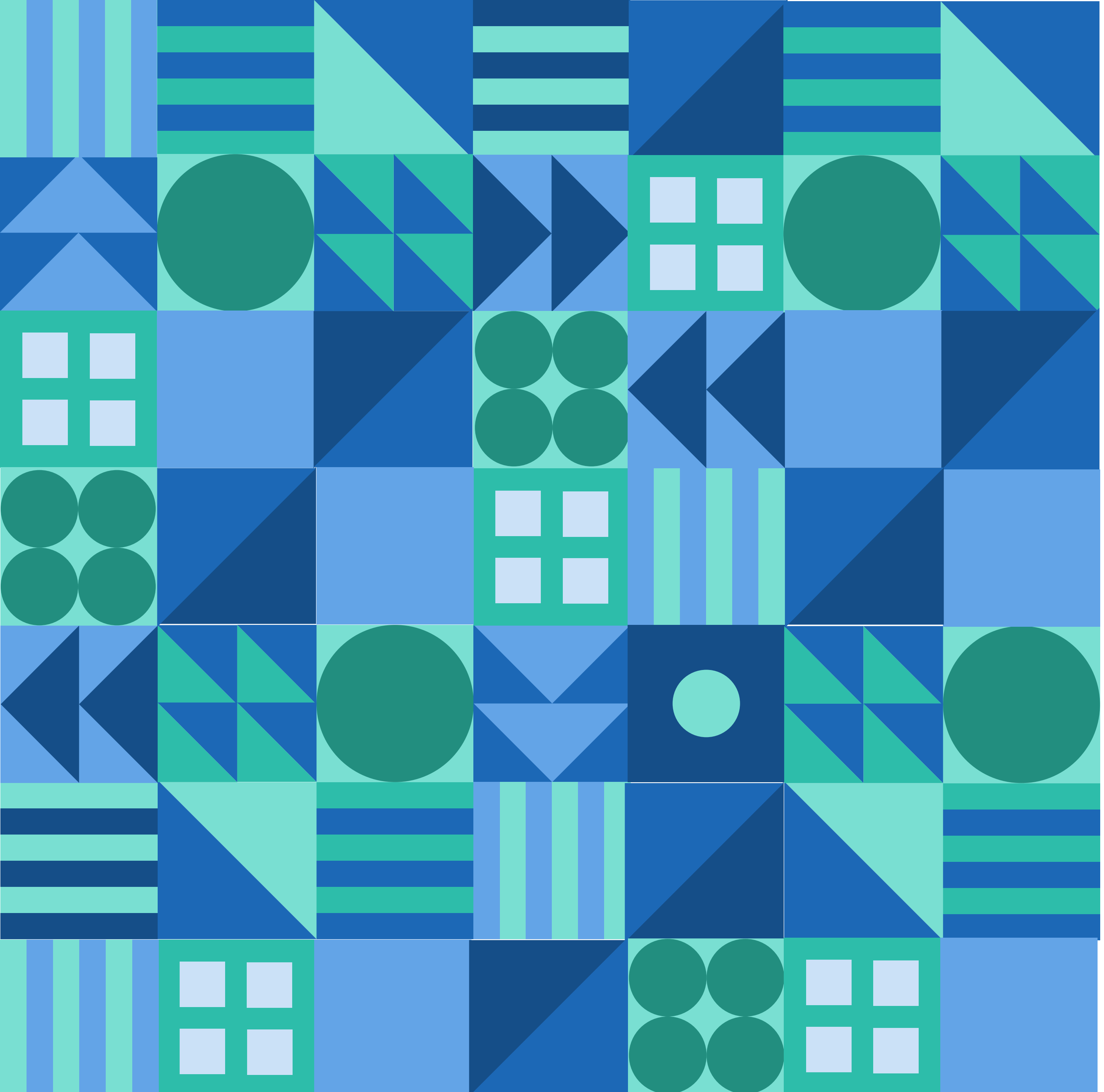
01 Introduction – Cooperative Adaptive Cruise Control

- **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 unnecessary stop and go, and aerodynamic drag of following vehicles


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


(Volvo)


(TechAdvisor, 2013)



02

Architectures

02 Architectures – System Structure

Perception

Two sources: data from wireless safety unit and on-board sensors

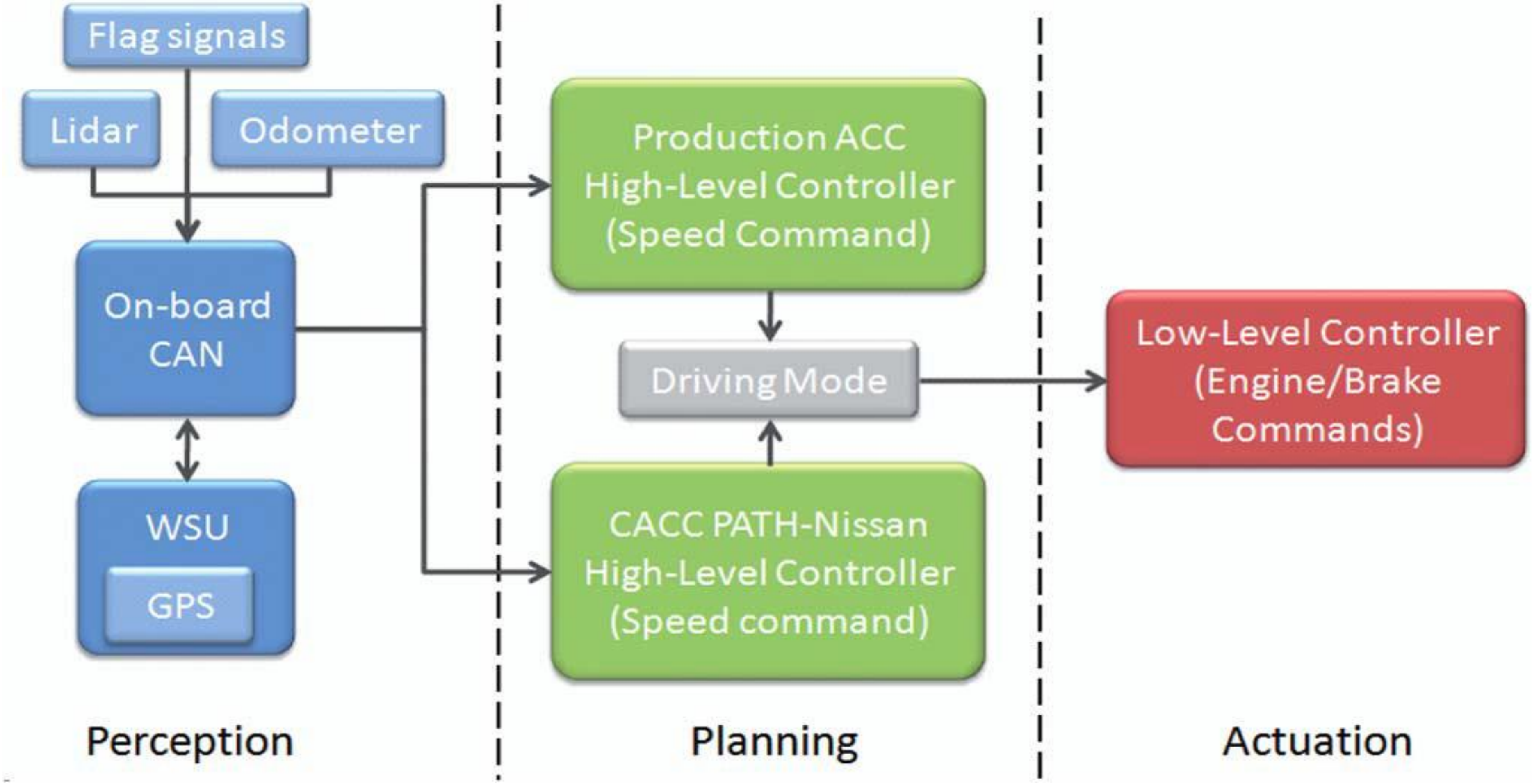
Planning

High-level controller is developed in MATLAB/Simulink and loaded in the vehicle using a dSpace MicroAutoBox

Actuation

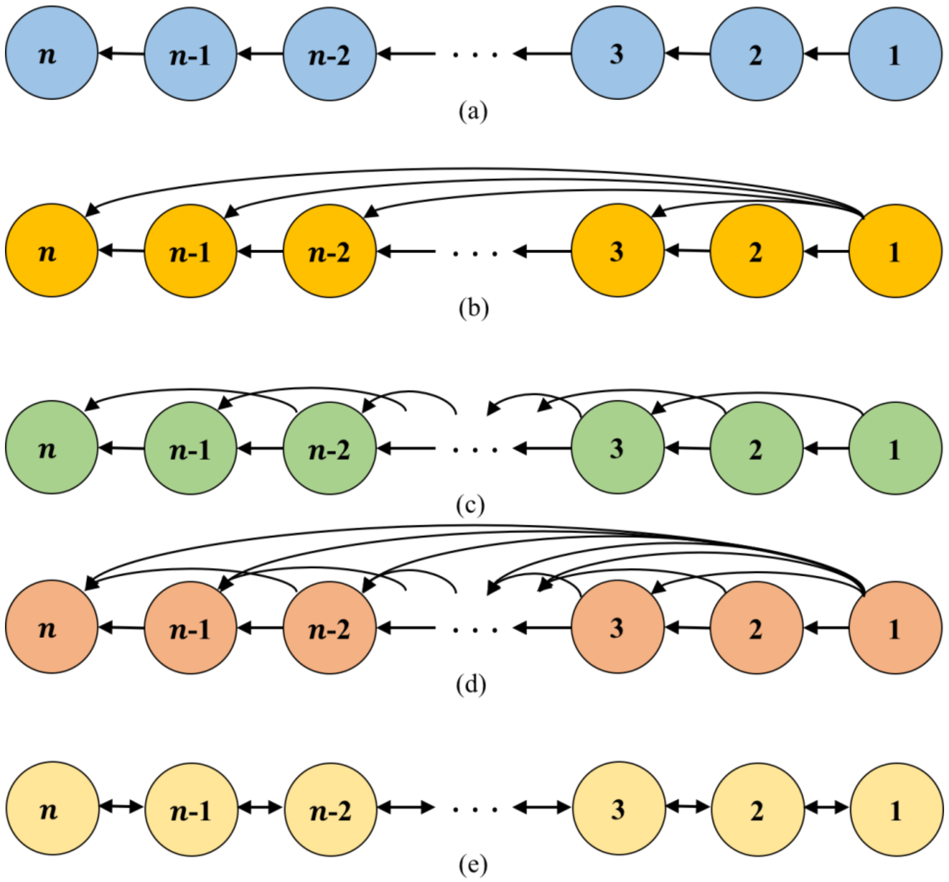
Low level controller converts the target speed commands into throttle and brake actions

02 Architectures – System Structure



02 Architectures – Communication Flow Topology

Denote how information is transmitted among vehicles in a CACC vehicle string



(a)

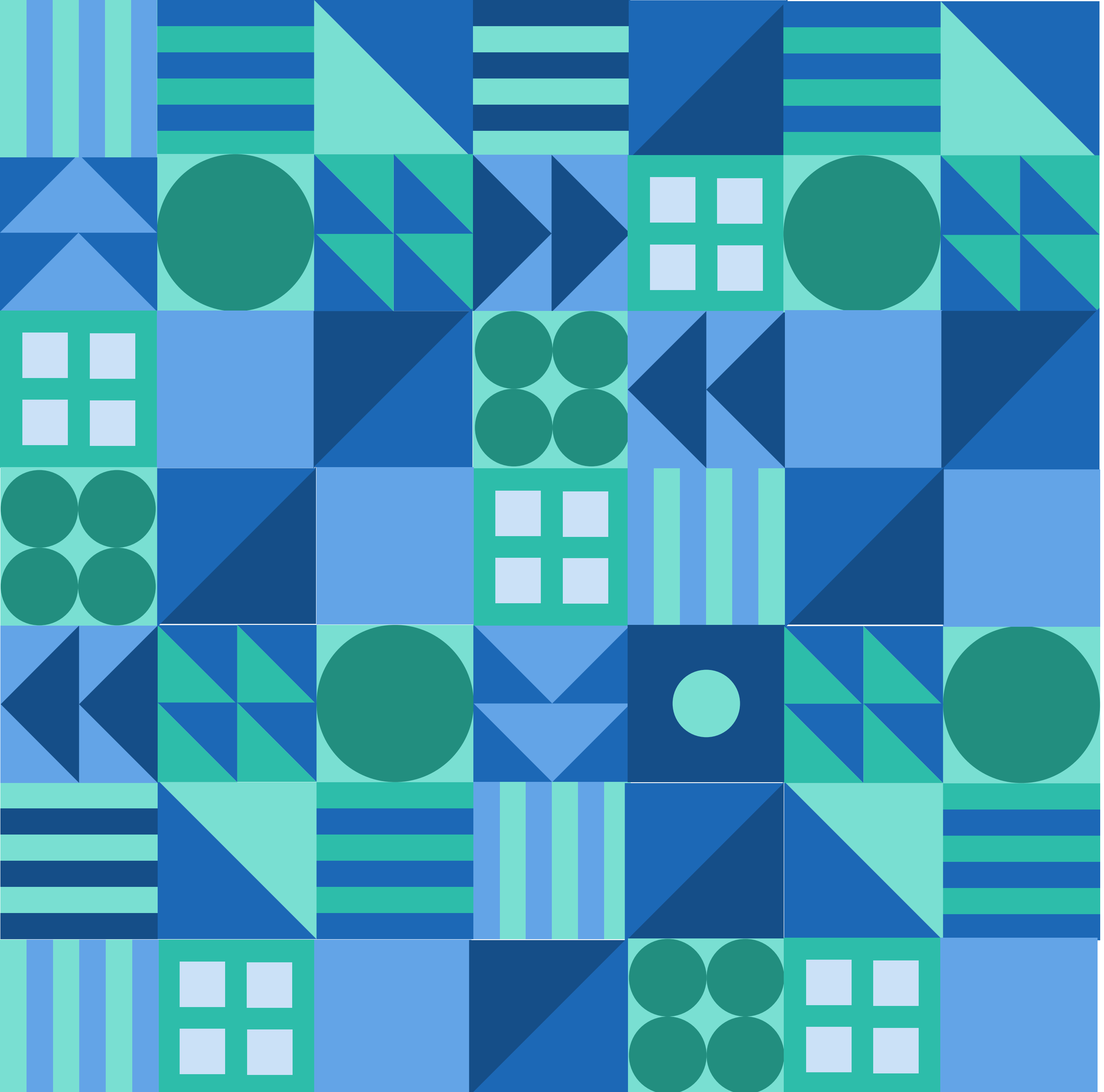
(b)

(c)

(d)

(e)

- **Predecessor-following**
- **Predecessor-leader following**
- **Two predecessor-following**
- **Two predecessor-leader following**
- **Bidirectional**



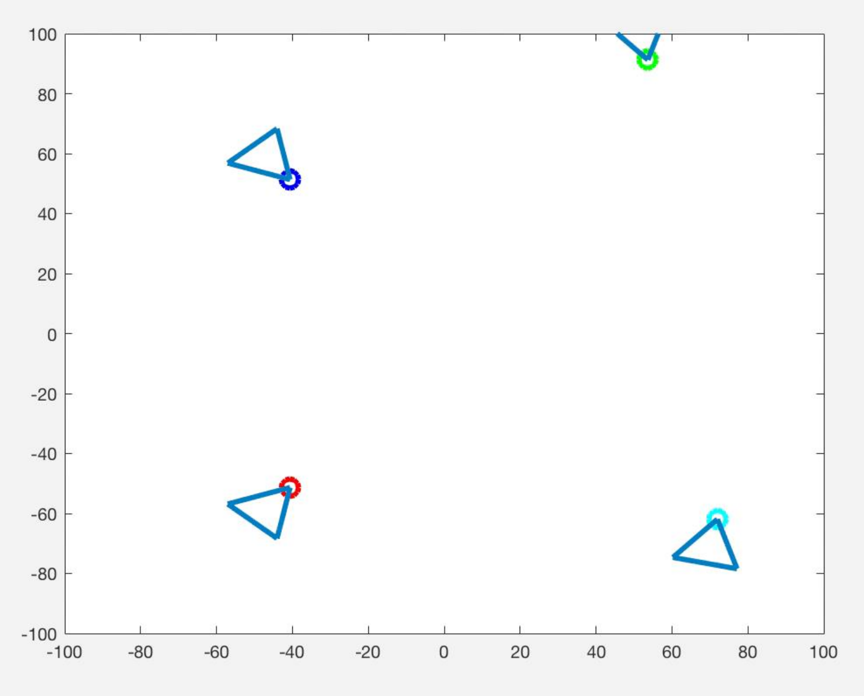
03

Controls

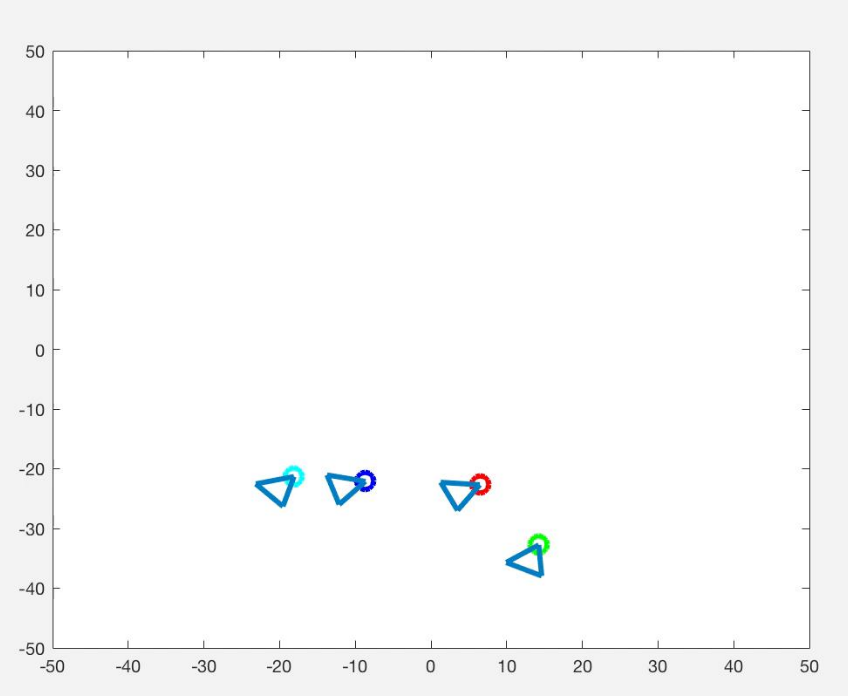
03 Controls – Distributed Control

Consensus Control	Distributed consensus algorithms in the field of multi-agent system are applied to CACC systems
Optimal Control	Optimal controllers for CACC are formulated as structured convex optimization problem with the objective to minimize energy consumption or travel time
Model Predictive Control	A real-time optimization problem is solved to compute optimal acceleration and deceleration commands to minimize energy consumption
H-Infinity Control	H-infinity control can deal with modeling uncertainties and external disturbances, thus is widely studied to improve the robustness of CACC system
Sliding Mode Control	Besides uncertainties and external disturbances, sliding mode control is also widely used to address string stability issue

03 Controls – Distributed Consensus Control



Converge to a desired location



Arrive at their desired locations while preserving the desired formation shape

03 Controls – Distributed Consensus Control

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

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

$x_i(t)$	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

03 Controls – Distributed Consensus Control

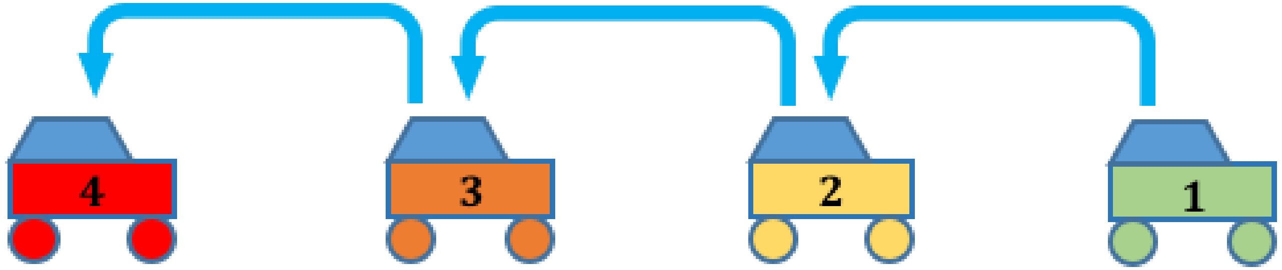
$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = -a_{ij}\boxed{\left[x_i(t) - x_j\left(t-\tau_{ij}(t)\right) + l_{if} + l_{jr} + \dot{x}_j\left(t-\tau_{ij}(t)\right)\left(t^g_{ij} + \tau_{ij}(t)\right)b_i\right]} \\ \qquad -\gamma a_{ij}\boxed{\left[\dot{x}_i(t) - \dot{x}_j\left(t-\tau_{ij}(t)\right)\right]}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

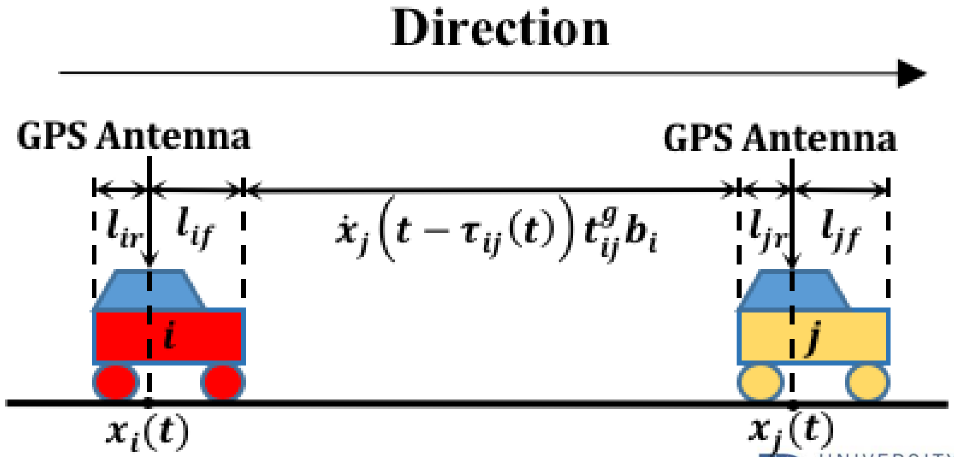
position consensus

velocity consensus

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

Predecessor following topology



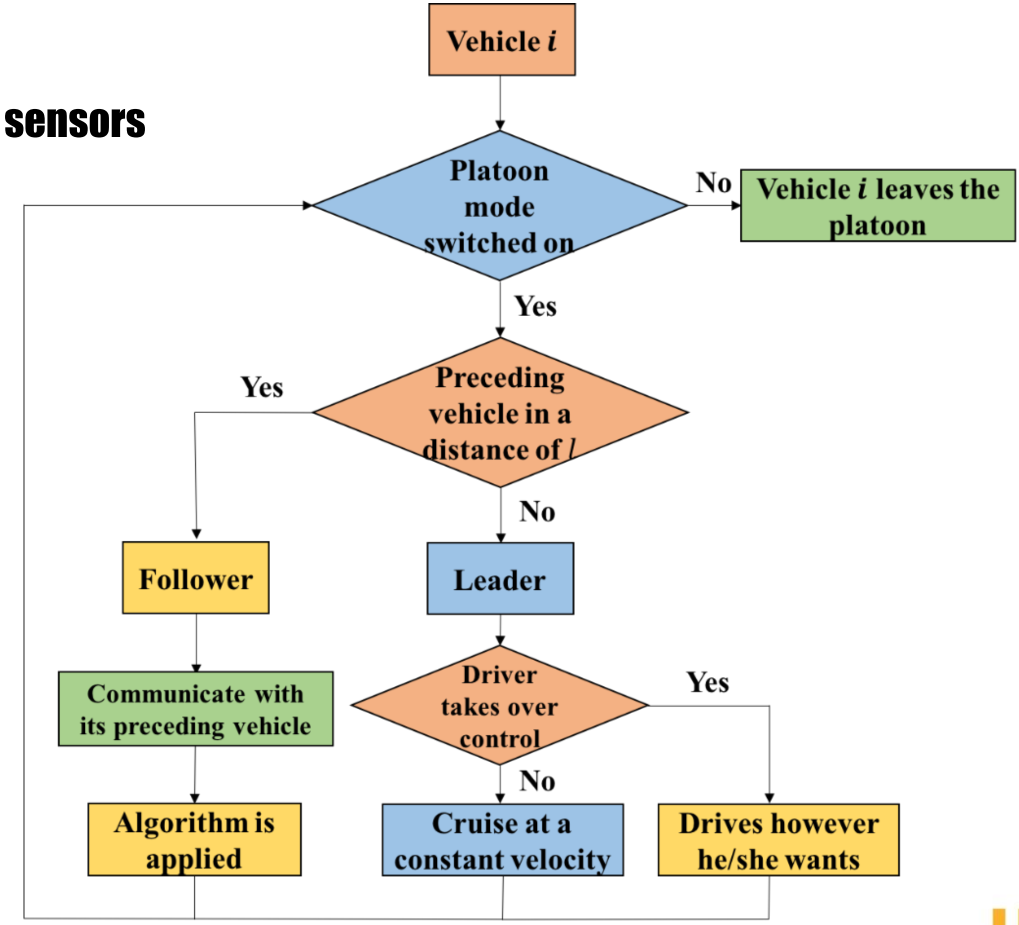


03 Controls – Distributed Consensus Control

- **Assumption**

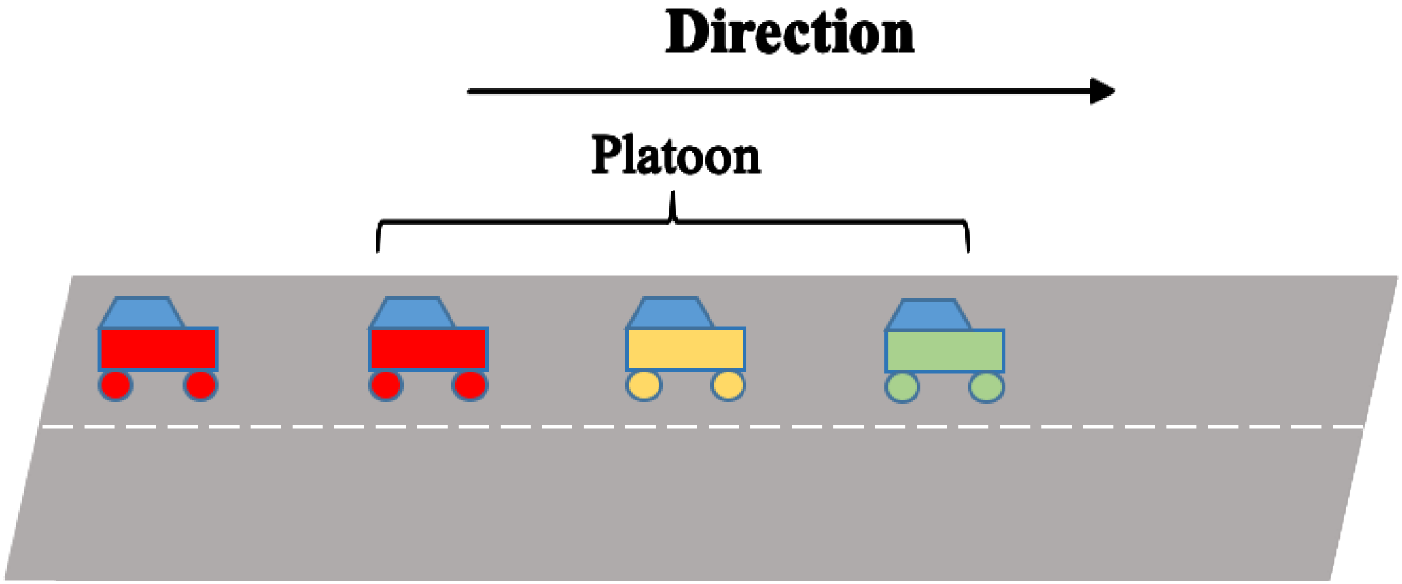
Every vehicle in the system is equipped with appropriate sensors

- **Protocol 1: Normal platoon formation**



03 Controls – Distributed Consensus Control

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



03 Controls – Distributed Consensus Control

- **Scenario 1: Normal platoon formation**

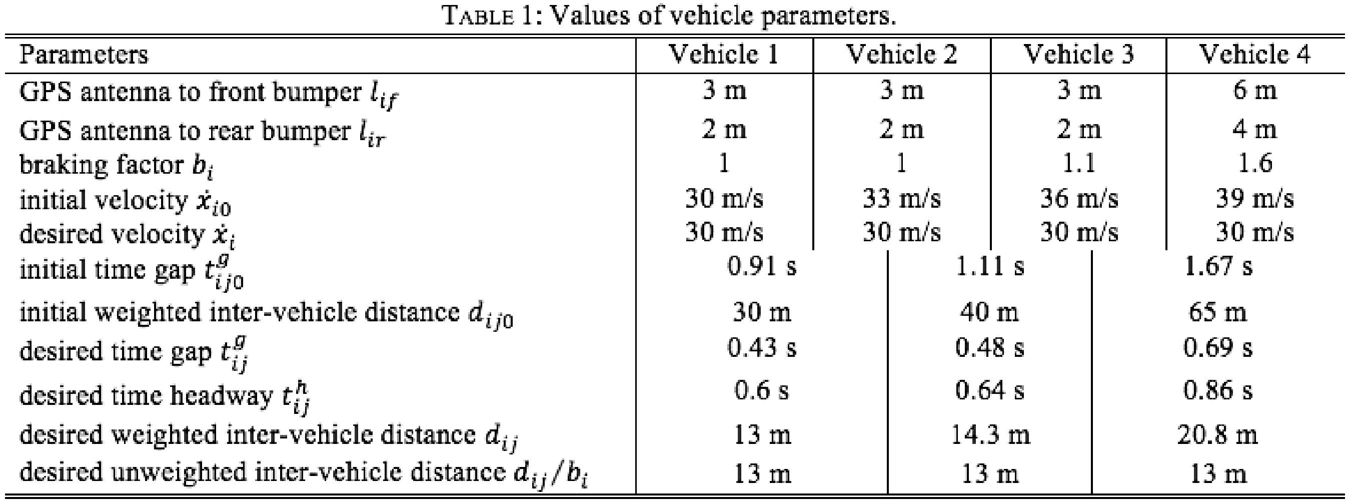
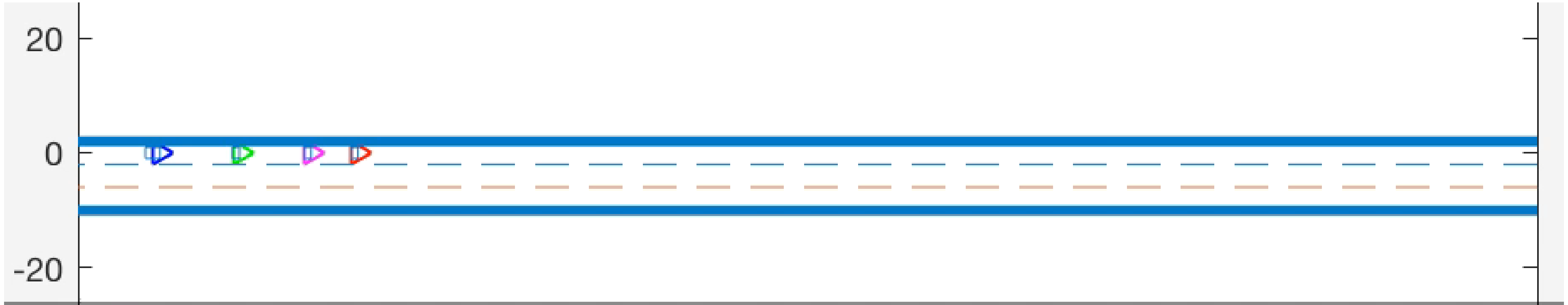


TABLE 1: Values of vehicle parameters.

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



03 Controls – Distributed Consensus Control

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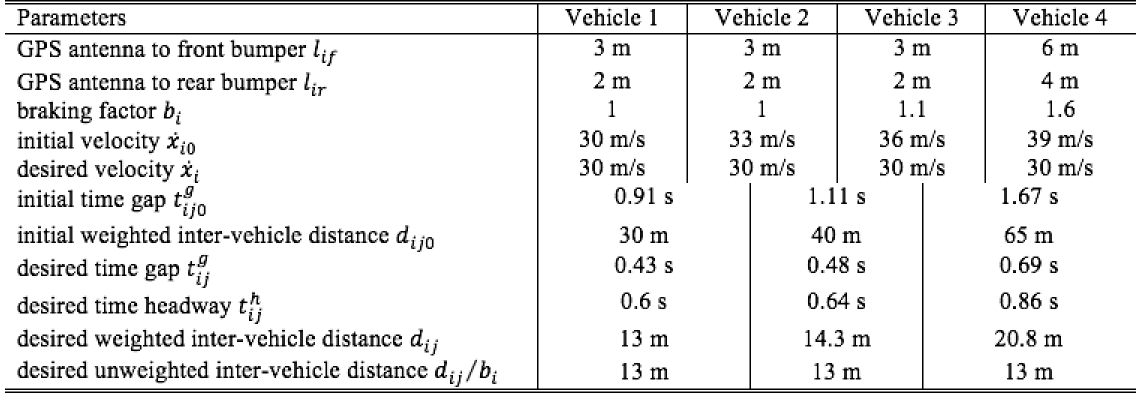

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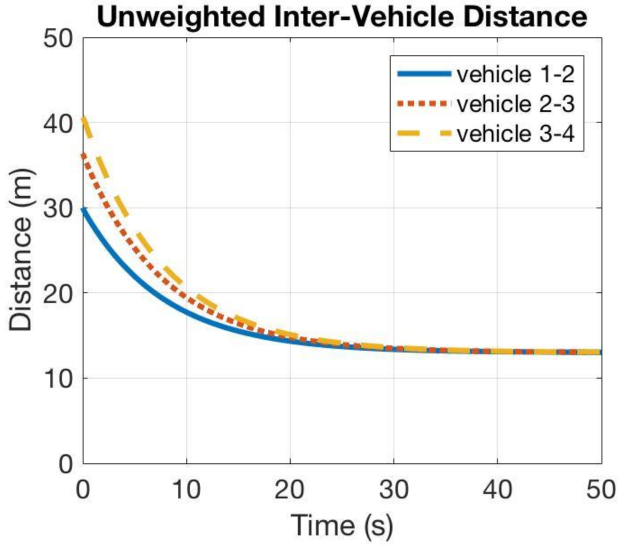

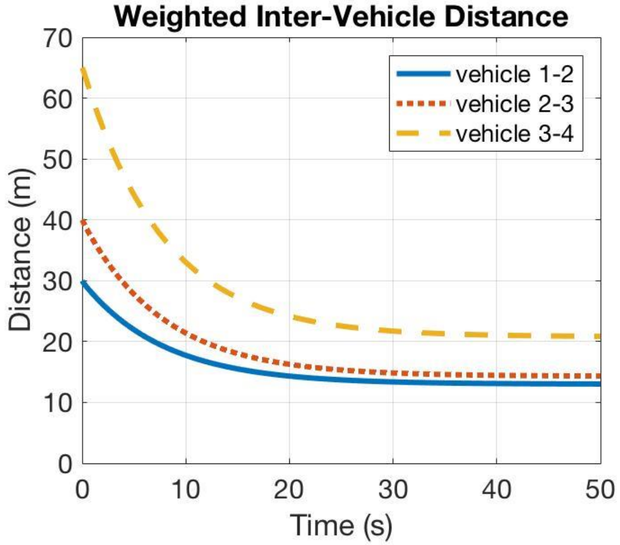

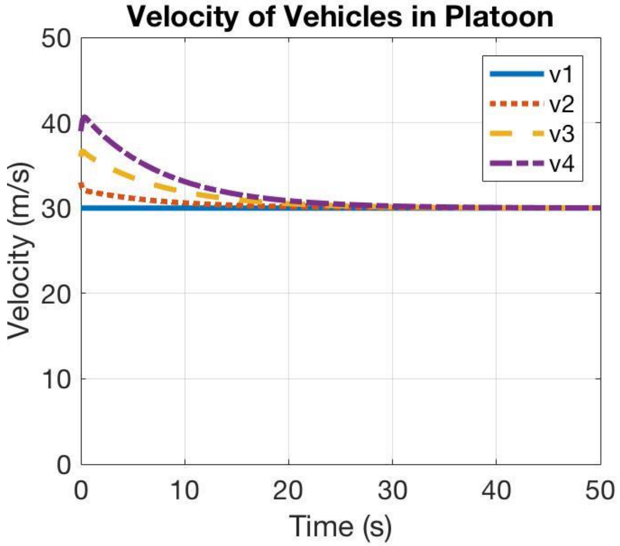

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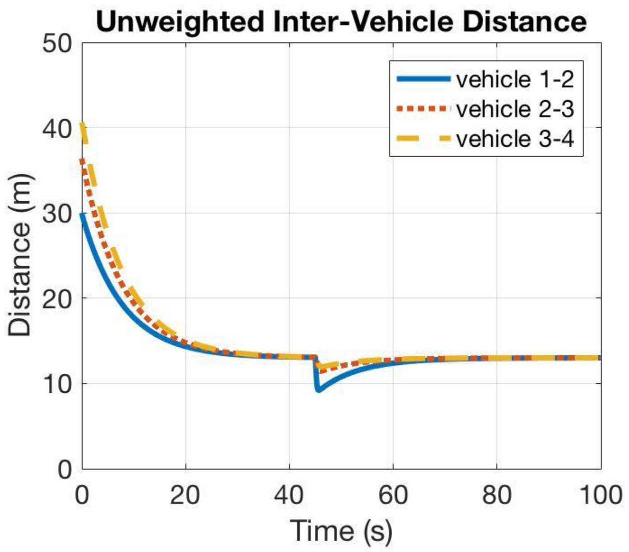
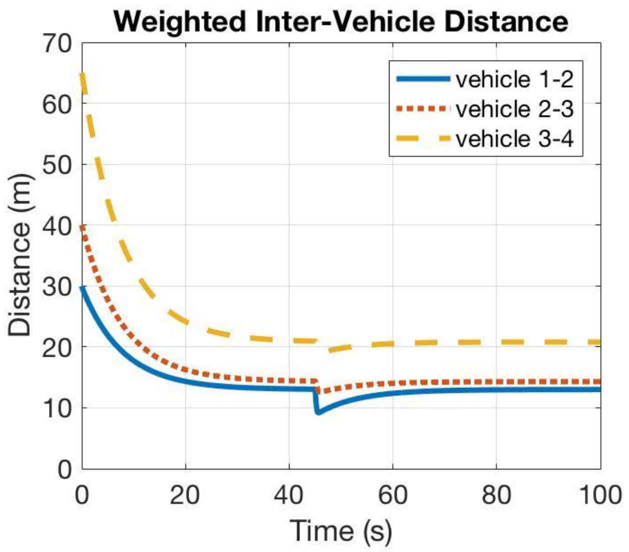
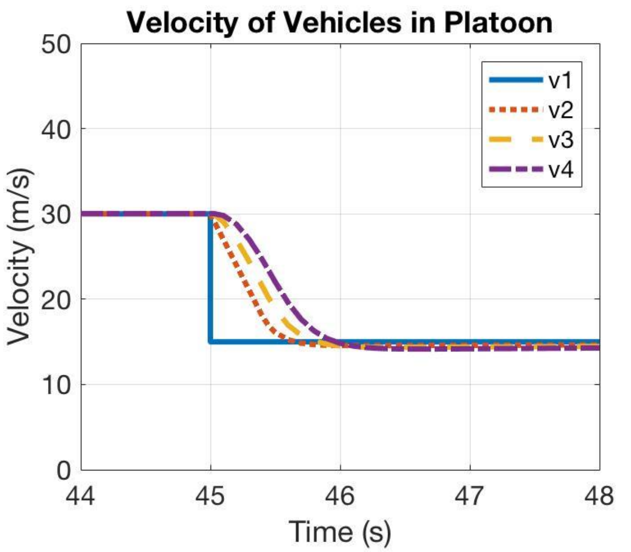
03 Controls – Distributed Consensus Control

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

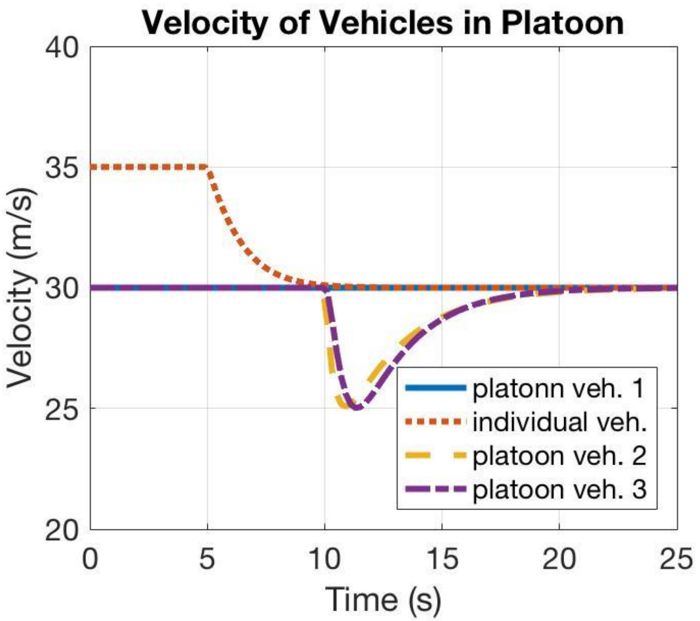


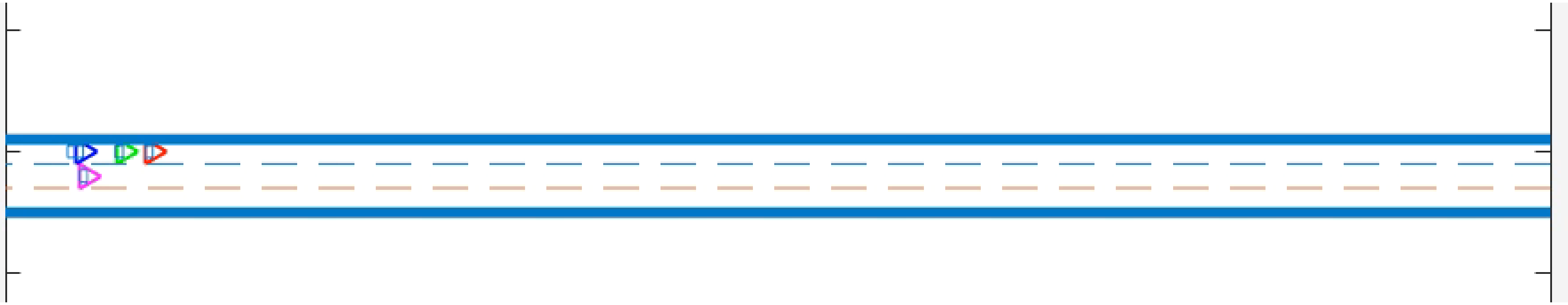




03 Controls – Distributed Consensus Control

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





03 Controls – Distributed Consensus Control

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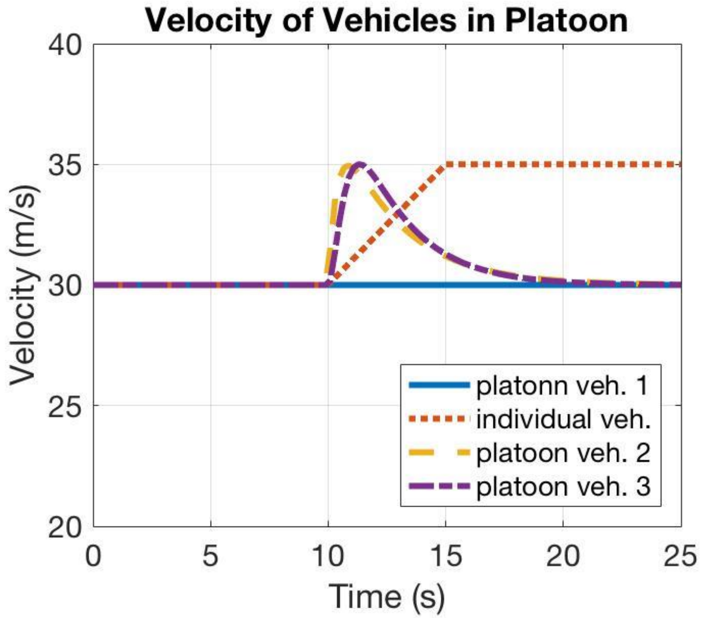

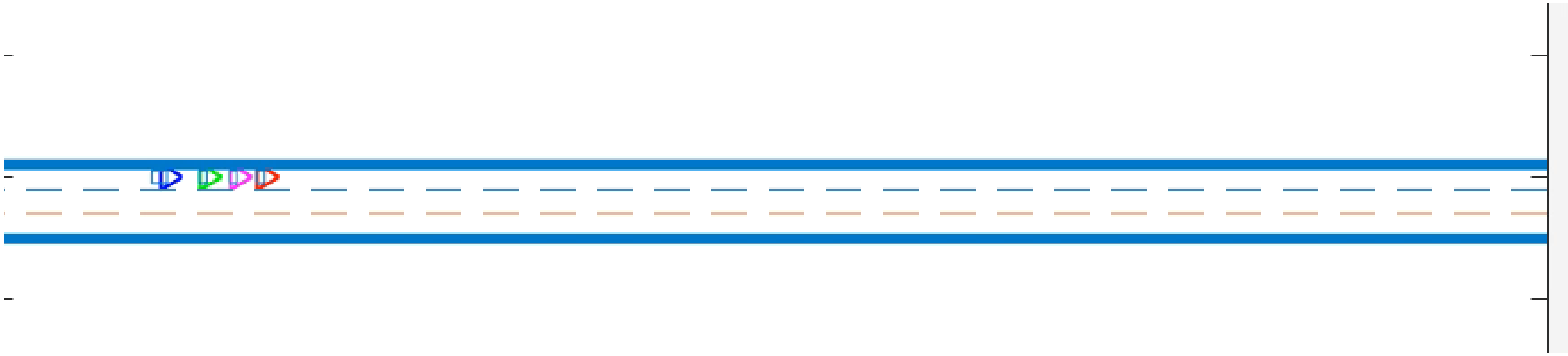

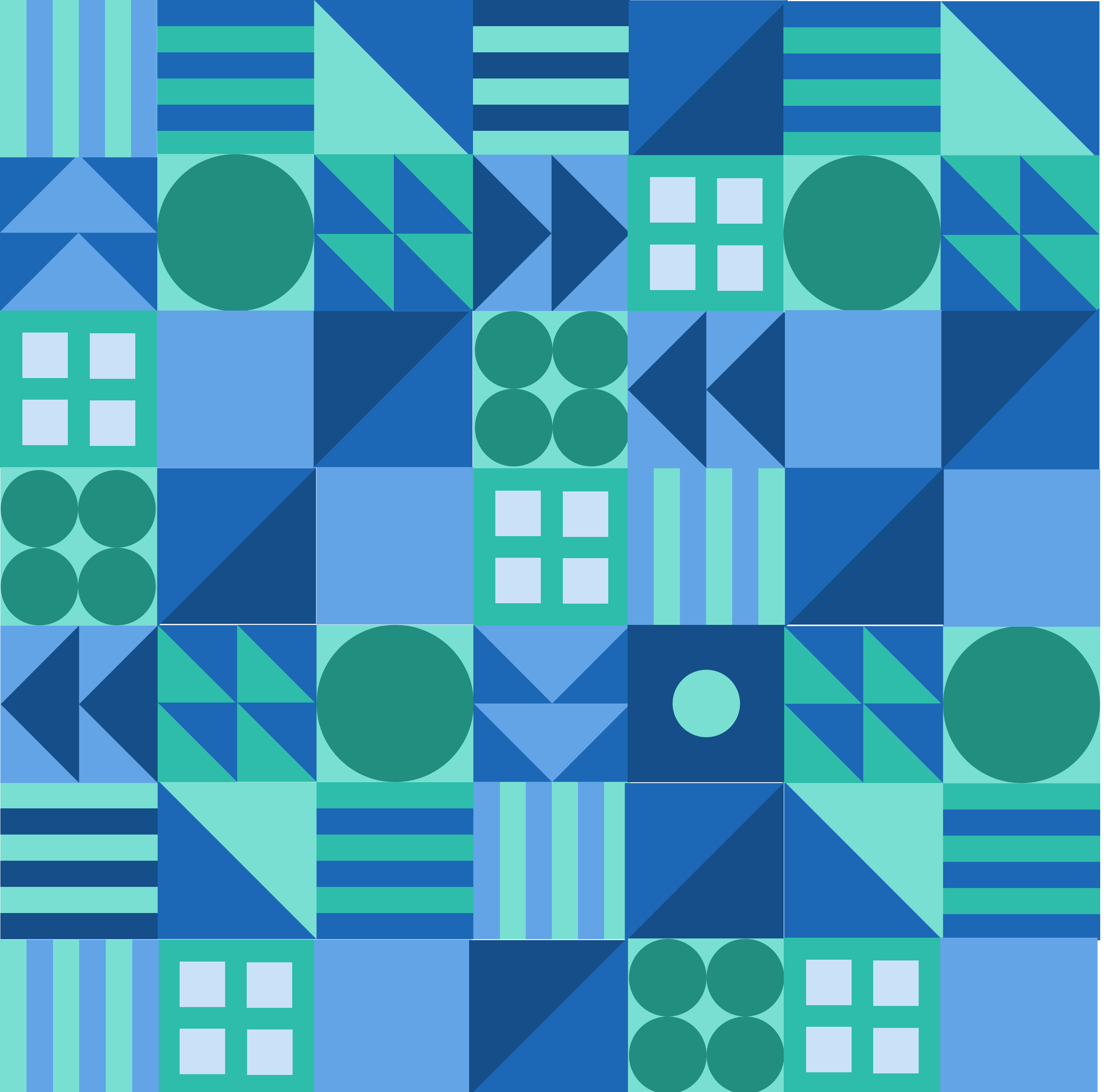

04

Applications

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04 Applications

Vehicle Platooning

Vehicles driven in a form of platoon/string with harmonized speed and constant time headway

Cooperative Eco-Driving

Vehicles collaborate with others to conduct eco-driving maneuvers along signalized corridors

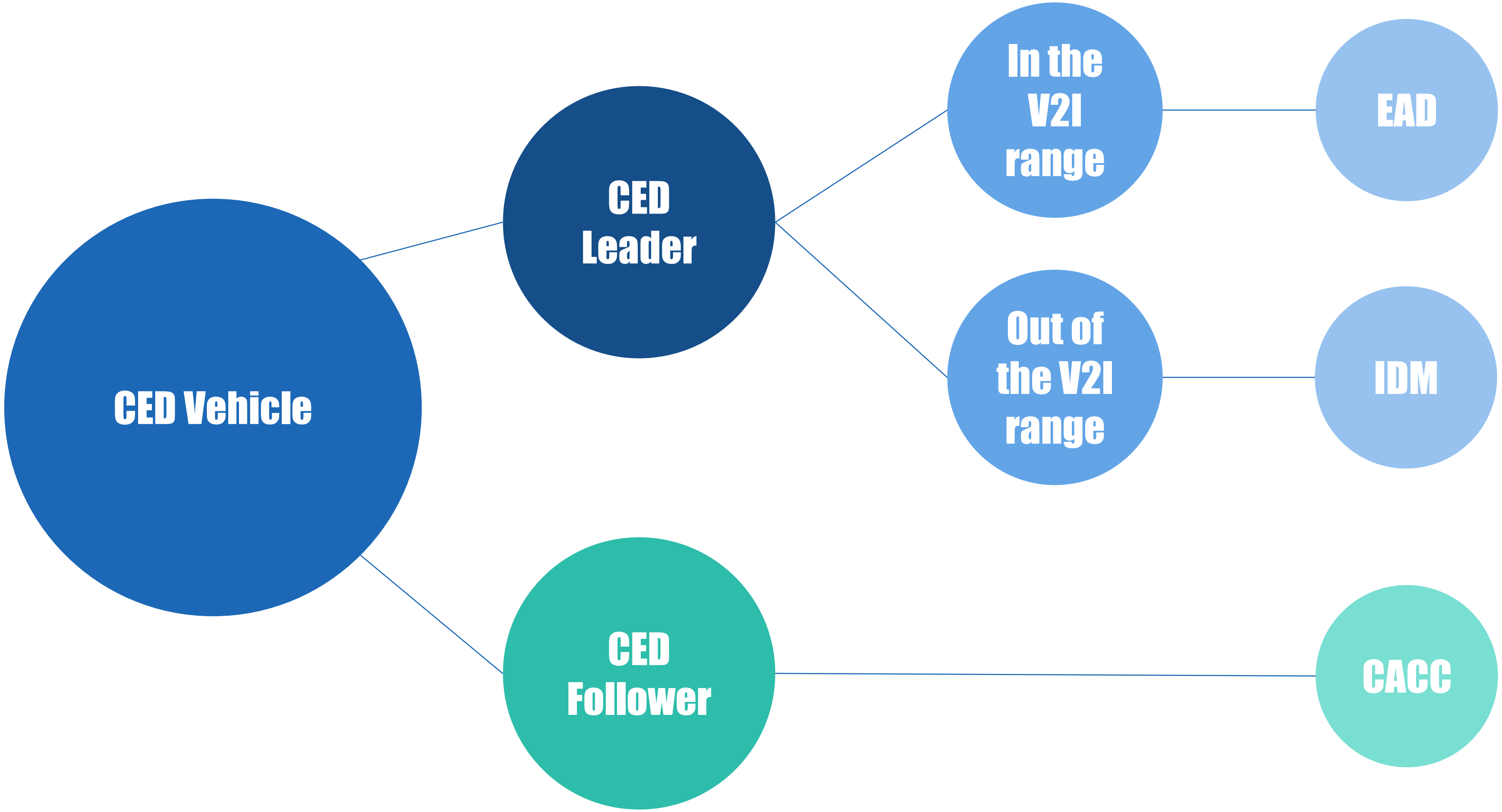
Cooperative Merging

Virtual CACC string can be developed to allow vehicles to merge in a cooperative manner

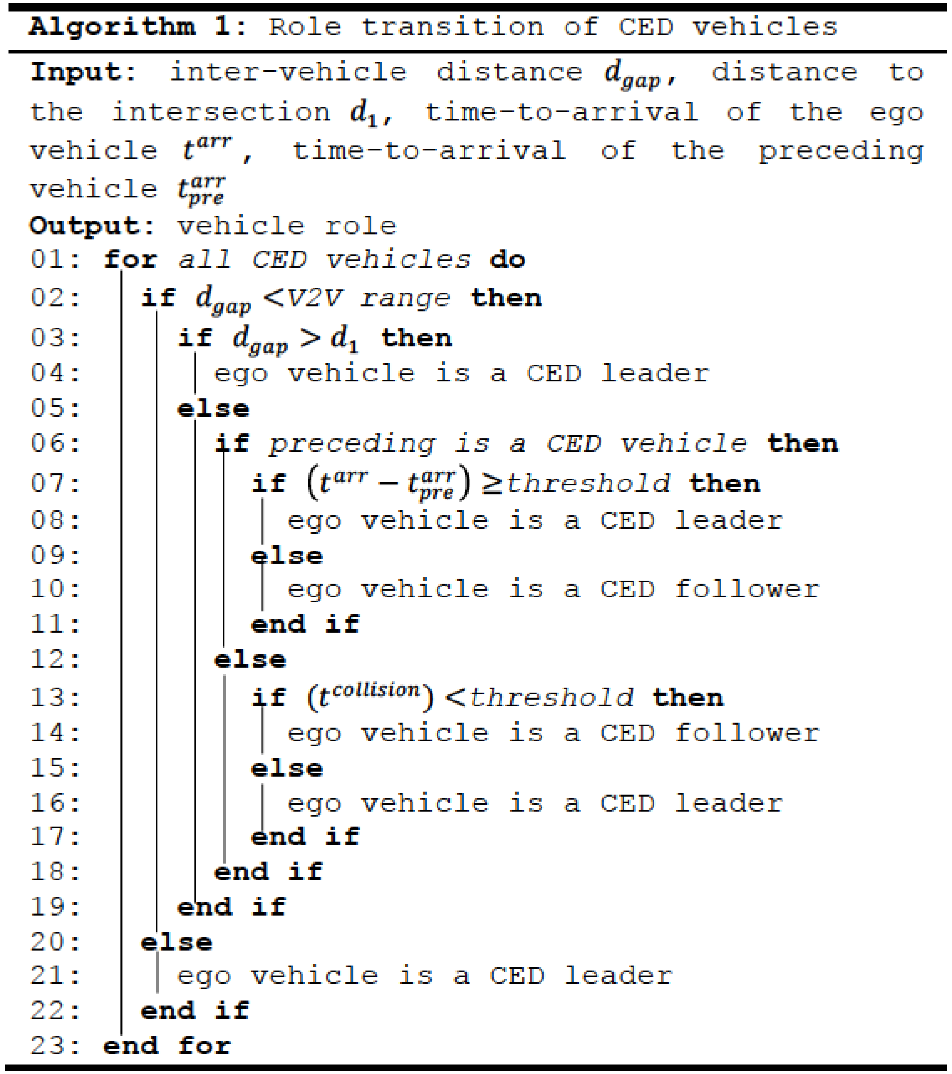
Autonomous Intersection

Collision-free intersection without traffic signal can be designed by CACC technology

04 Applications – Cooperative Eco-Driving



04 Applications – Cooperative Eco-Driving



Algorithm 1: Role transition of CED vehicles

Input: inter-vehicle distance d_{gap}, distance to the intersection d_1, time-to-arrival of the ego vehicle t^{arr}, time-to-arrival of the preceding vehicle t_{pre}^{arr}

Output: vehicle role

```
for all CED vehicles do
    if $d_{gap}$ < V2V range then
        if $d_{gap} > d_1$ then
            ego vehicle is a CED leader
        else
            if preceding is a CED vehicle then
                if $(t^{arr} - t_{pre}^{arr}) \geq threshold$ then
                    ego vehicle is a CED leader
                else
                    ego vehicle is a CED follower
                end if
            else
                if $(t^{collision}) < threshold$ then
                    ego vehicle is a CED follower
                else
                    ego vehicle is a CED leader
                end if
            end if
        end if
    else
        ego vehicle is a CED leader
    end if
end for
```

- **Only CED vehicles are classified into leaders and followers, while conventional vehicles are not**
- **CED leaders conduct eco-driving maneuvers with respect to the traffic signals through V2I communications**
- **CED followers follow the movements of CED leaders through V2V communications**

04 Applications – Cooperative Eco-Driving

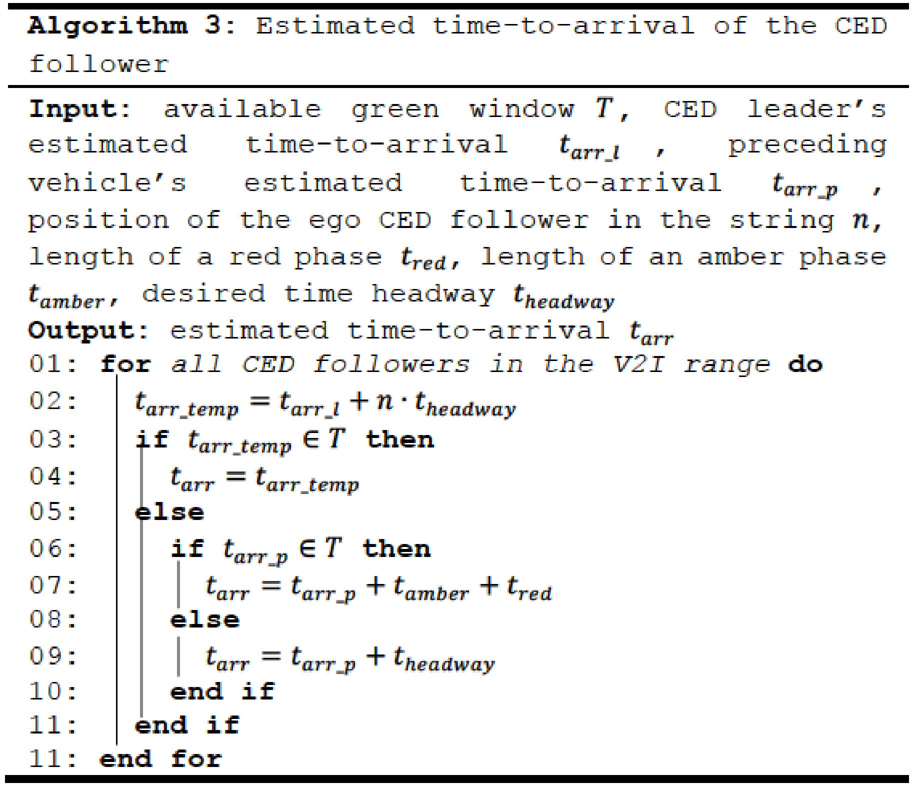
1. The vehicle's longitudinal acceleration is controlled by the proposed distributed consensus algorithm

$$a_{ref} = \beta \cdot \left(d_{gap} - d_{ref}\right) + \gamma \cdot (v_{pre} - v_{ego})$$

$$d_{ref} = min(d_{gap}, d_{safe})$$

$$d_{gap} = v_{ego} \cdot t_{gap}$$

2. The estimated time-to-arrival should be updated all the time, in case the CED follower cannot travel through the intersection during the green phase – in that case, the CED follower changes into CED leader



Algorithm 3: Estimated time-to-arrival of the CED follower

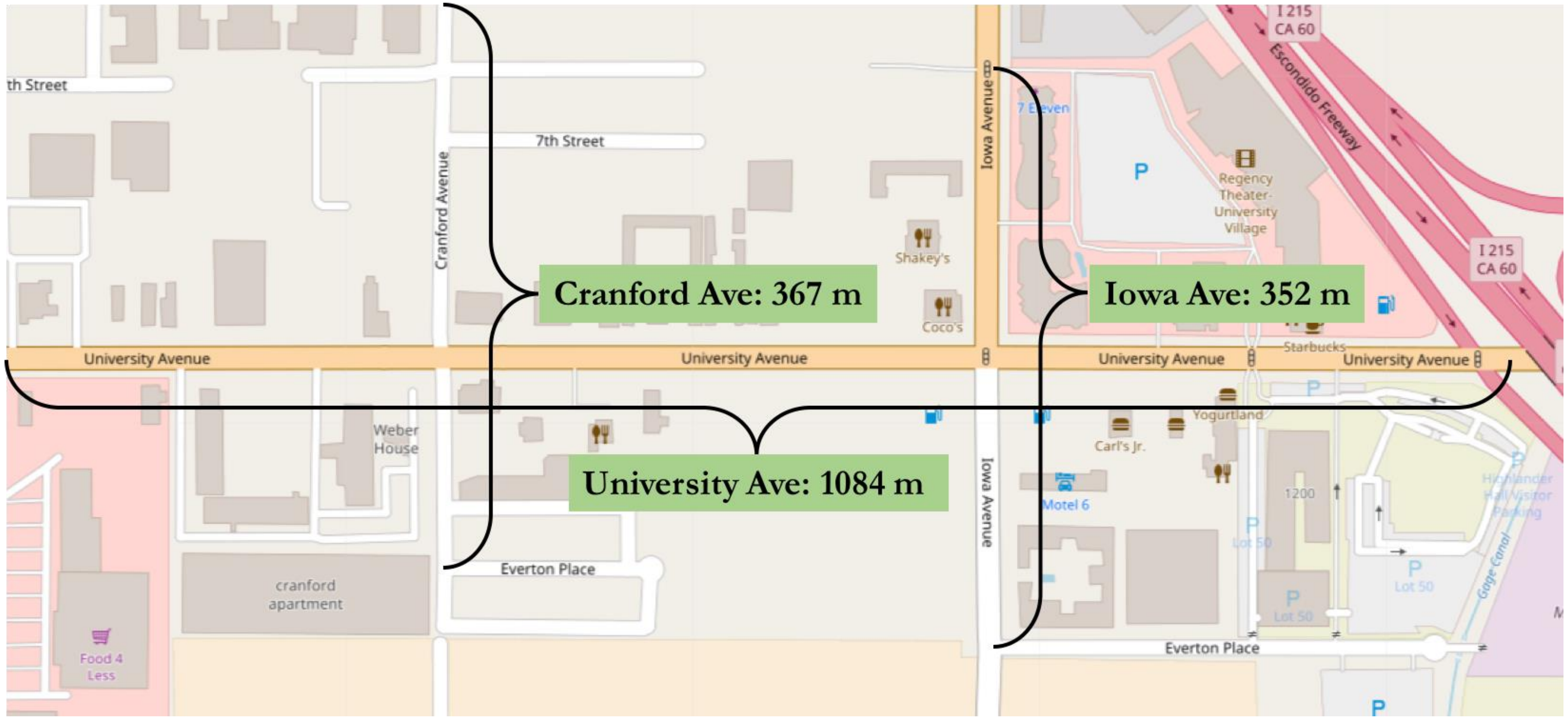
Input: available green window T, CED leader's estimated time-to-arrival t_{arr_l}, preceding vehicle's estimated time-to-arrival t_{arr_p}, position of the ego CED follower in the string n, length of a red phase t_{red}, length of an amber phase t_{amber}, desired time headway $t_{headway}$

Output: estimated time-to-arrival t_{arr}

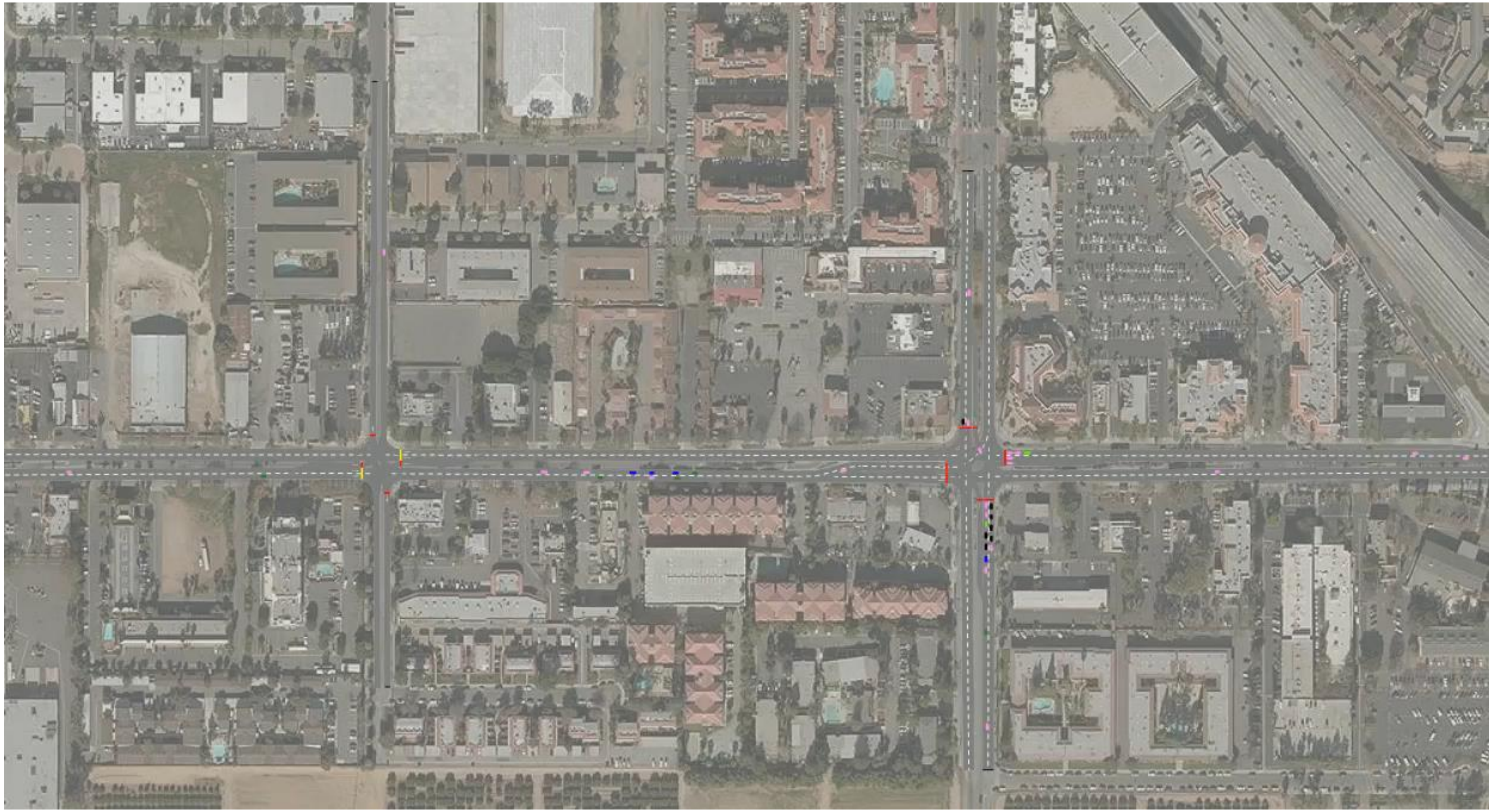
```
for all CED followers in the V2I range do
    $t_{arr\_temp} = t_{arr\_l} + n \cdot t_{headway}$
    if $t_{arr\_temp} \in T$ then
        $t_{arr} = t_{arr\_temp}$
    else
        if $t_{arr\_p} \in T$ then
            $t_{arr} = t_{arr\_p} + t_{amber} + t_{red}$
        else
            $t_{arr} = t_{arr\_p} + t_{headway}$
        end if
    end if
end for
```

04 Applications – Cooperative Eco-Driving

The simulation study is conducted based on the University Avenue corridor in Riverside, CA



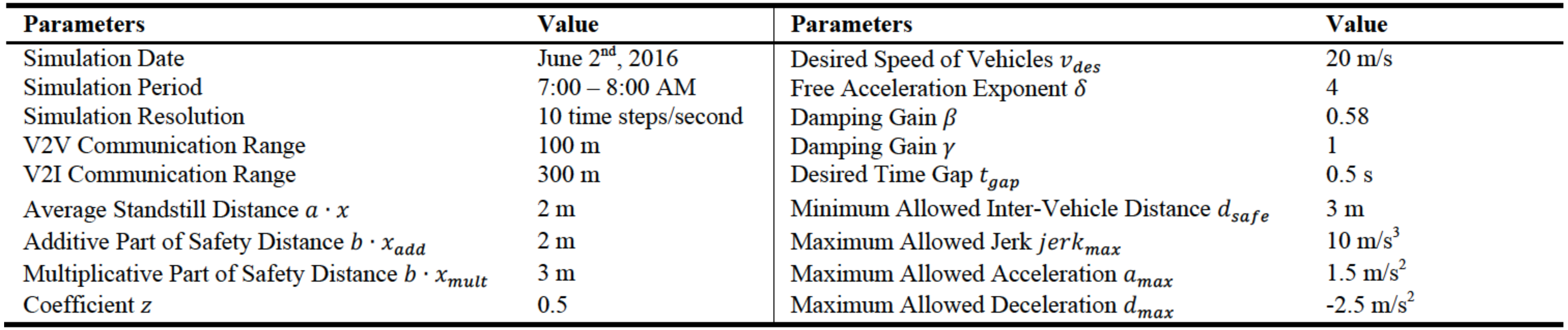
04 Applications – Cooperative Eco-Driving



04 Applications – Cooperative Eco-Driving

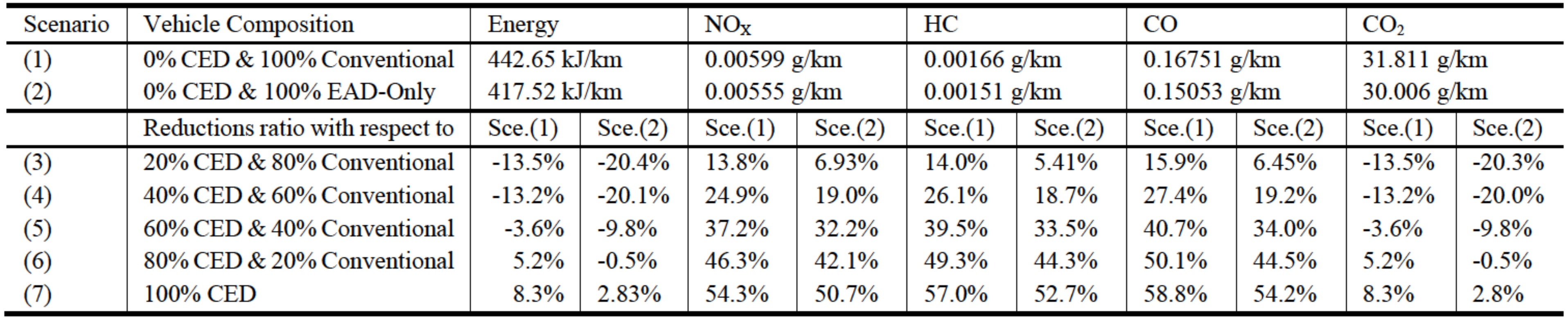
Simulation setup and energy results

TABLE IV. PARAMETERS OF THE SIMULATION TRAFFIC NETWORK AND VEHICLES



Parameters	Value	Parameters	Value
Simulation Date	June 2nd, 2016	Desired Speed of Vehicles v_{des}	20 m/s
Simulation Period	7:00 – 8:00 AM	Free Acceleration Exponent δ	4
Simulation Resolution	10 time steps/second	Damping Gain β	0.58
V2V Communication Range	100 m	Damping Gain γ	1
V2I Communication Range	300 m	Desired Time Gap t_{gap}	0.5 s
Average Standstill Distance $a \cdot x$	2 m	Minimum Allowed Inter-Vehicle Distance d_{safe}	3 m
Additive Part of Safety Distance $b \cdot x_{add}$	2 m	Maximum Allowed Jerk $jerk_{max}$	10 m/s^3
Multiplicative Part of Safety Distance $b \cdot x_{mult}$	3 m	Maximum Allowed Acceleration a_{max}	1.5 m/s^2
Coefficient z	0.5	Maximum Allowed Deceleration d_{max}	-2.5 m/s^2

TABLE V. SIMULATION RESULTS OF ENERGY CONSUMPTION AND POLLUTANT EMISSIONS

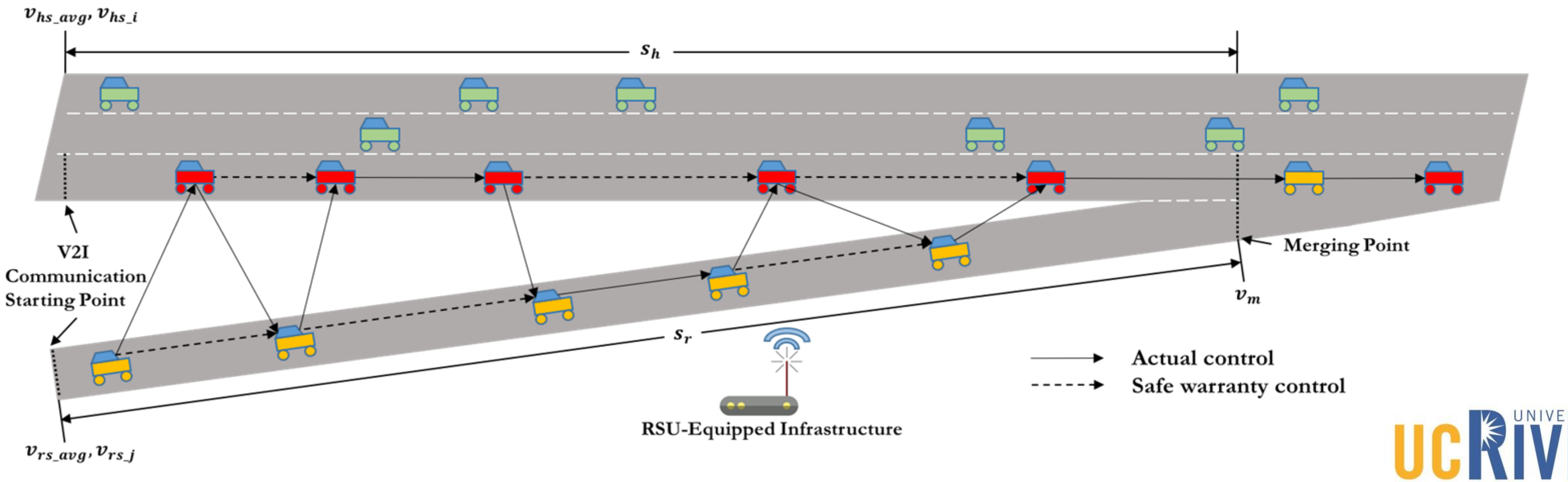


Scenario	Vehicle Composition	Energy		NO_X		HC		CO		CO_2	
(1)	0% CED & 100% Conventional	442.65 kJ/km		0.00599 g/km		0.00166 g/km		0.16751 g/km		31.811 g/km	
(2)	0% CED & 100% EAD-Only	417.52 kJ/km		0.00555 g/km		0.00151 g/km		0.15053 g/km		30.006 g/km	
	Reductions ratio with respect to	Sce.(1)	Sce.(2)	Sce.(1)	Sce.(2)	Sce.(1)	Sce.(2)	Sce.(1)	Sce.(2)	Sce.(1)	Sce.(2)
(3)	20% CED & 80% Conventional	-13.5%	-20.4%	13.8%	6.93%	14.0%	5.41%	15.9%	6.45%	-13.5%	-20.3%
(4)	40% CED & 60% Conventional	-13.2%	-20.1%	24.9%	19.0%	26.1%	18.7%	27.4%	19.2%	-13.2%	-20.0%
(5)	60% CED & 40% Conventional	-3.6%	-9.8%	37.2%	32.2%	39.5%	33.5%	40.7%	34.0%	-3.6%	-9.8%
(6)	80% CED & 20% Conventional	5.2%	-0.5%	46.3%	42.1%	49.3%	44.3%	50.1%	44.5%	5.2%	-0.5%
(7)	100% CED	8.3%	2.83%	54.3%	50.7%	57.0%	52.7%	58.8%	54.2%	8.3%	2.8%

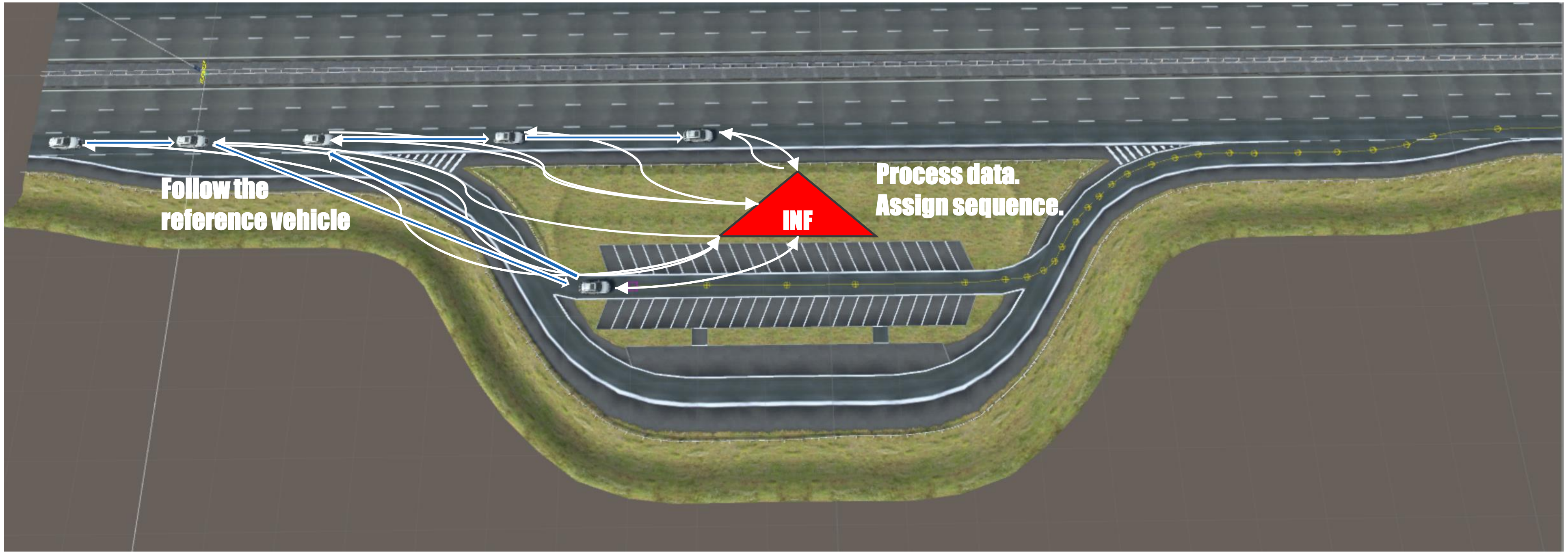
04 Applications – Cooperative Merging

Benefits of *cooperative on-ramp merging system*

- Increase merging *safety* by applying V2X communications
- Increase traffic *mobility* by assigning vehicles into cooperative adaptive cruise control string before merging
- Reduce *energy* consumption by avoiding unnecessary speed changes



04 Applications – Cooperative Merging

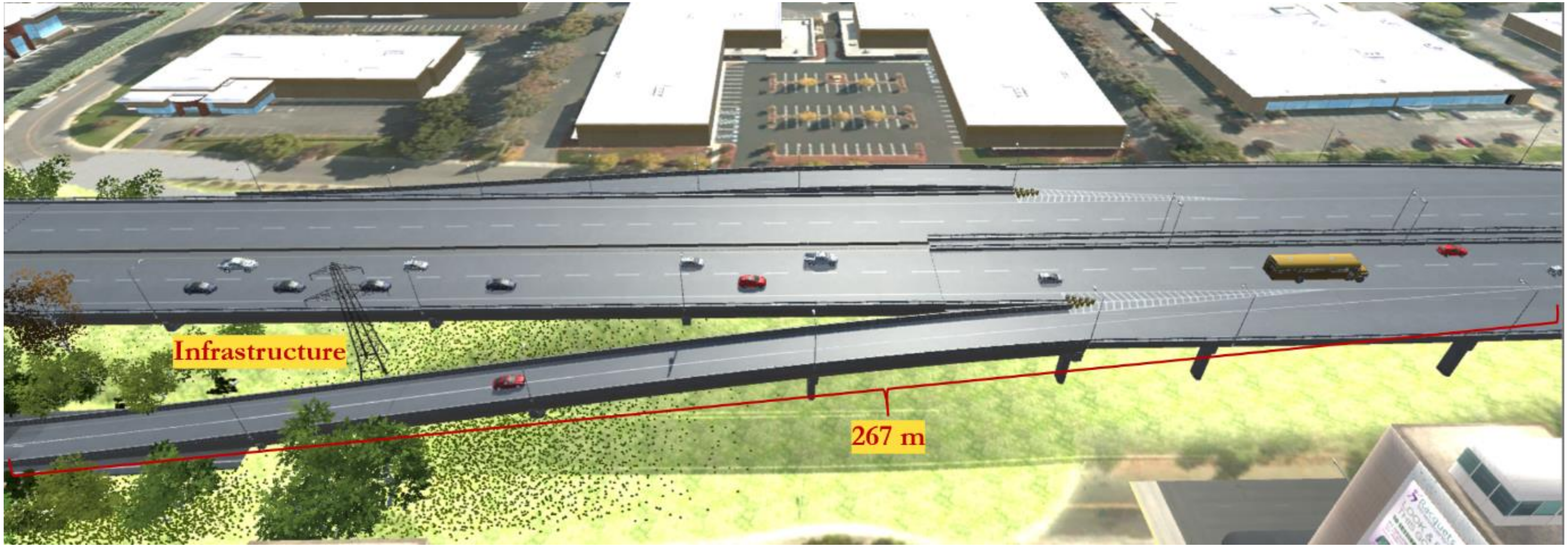


04 Applications – Cooperative Merging

Mountain View, CA modeled in Unity3D environment

04 Applications – Cooperative Merging

Ramp modeled used to conduct simulation



04 Applications – Cooperative Merging

Inspector: ☑ mainCar2 ☐ Static

Tag: Car Layer: Default

Transform

	X	Y	Z
Position	1198.84	27.4777	1093.11
Rotation	0.483	-128.9	-0.02
Scale	1	1	1

Rigidbody

☐ **Car User Control (Script)**

☐ **Spline Move (Script)**

☐ **Car Controller (Script)**

☐ **Adaptive Cruise Control (Scri**

☑ **Cooperative Merging (Script)**

```
UnityEngine.Debug:Log(Object)
Current simulation time is: 0.09999
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.12
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.14
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.16
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.18
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.2
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.22
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Current simulation time is: 0.24
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.26
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.28
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.3
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.32
UnityEngine.Debug:Log(Object)                     1
Current simulation time is: 0.34
UnityEngine.Debug:Log(Object)                     1
```

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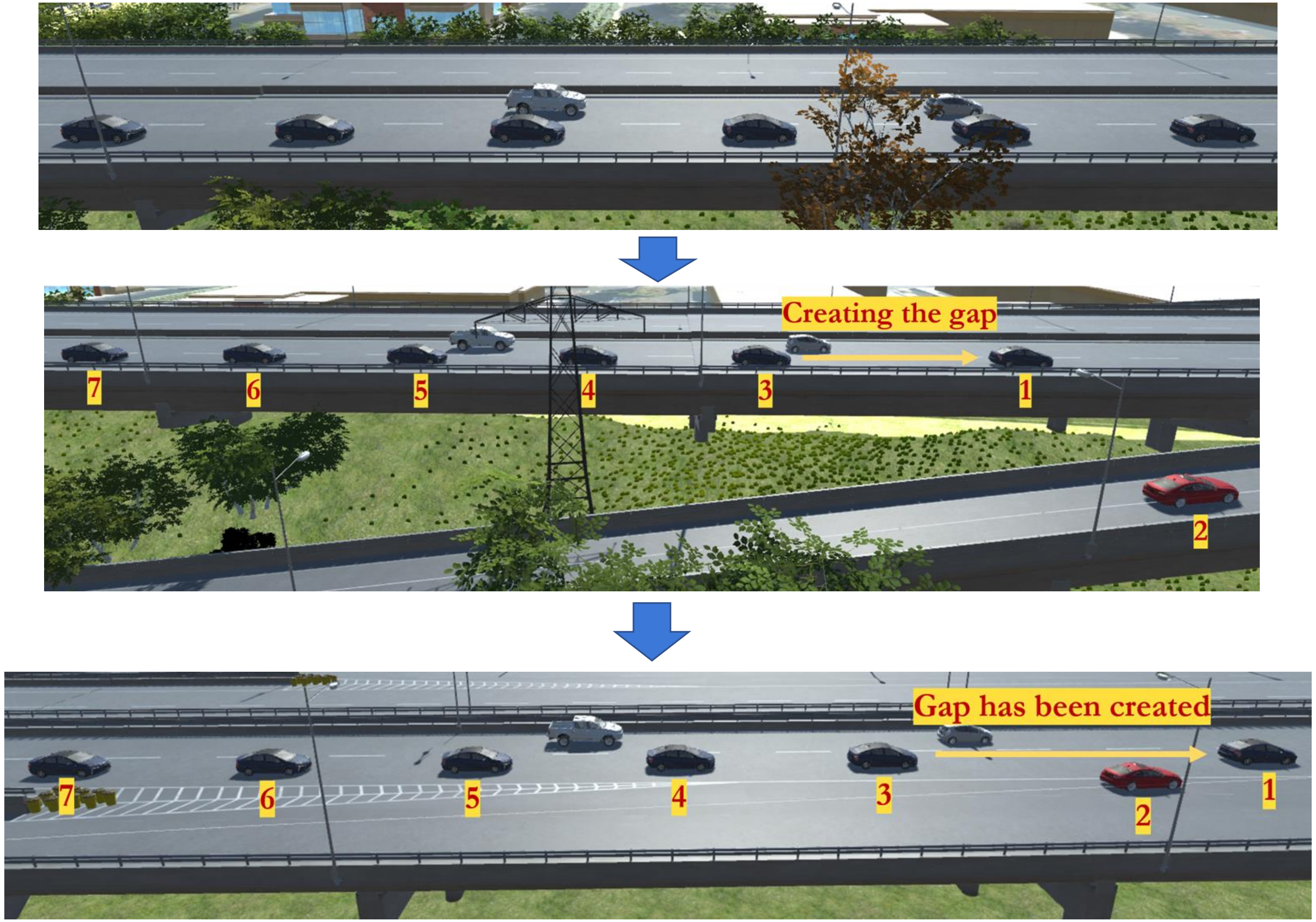
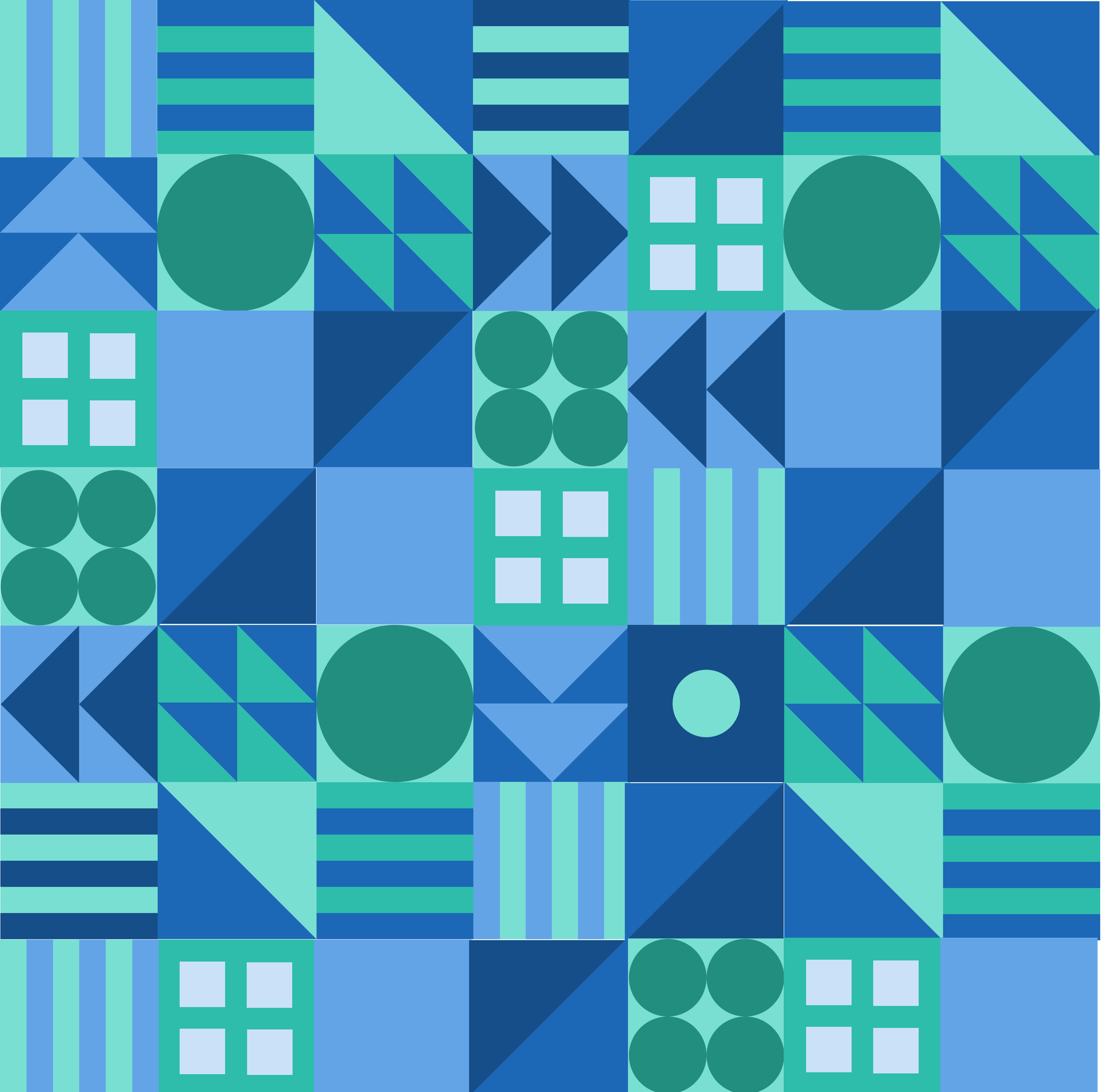
04 Applications – Cooperative Merging



Simulation setting: 1 ramp vehicle, 6 highway vehicles (already formed vehicle string)



05

Discussions

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05 Discussions

The realistic traffic network will introduce highly dynamic environment, including changing information flow topologies, varying workload distribution between different CAVs, and packet loss of V2V communications

Methodologies need to be tested under all kinds of different conditions and environments, and also for a rather long mileage. Since CACC systems often involves several CAVs, it would be difficult to conduct enough tests

Making new policies, updating roadside infrastructure, testing the proposed methods in real traffic cost a lot of money. To achieve a preferred penetration rate of CAVs in the application, the general public also need to spend money to purchase new vehicles

Reliable Architecture

Ready-to-Market Methodology

Reduce the Cost to Implement

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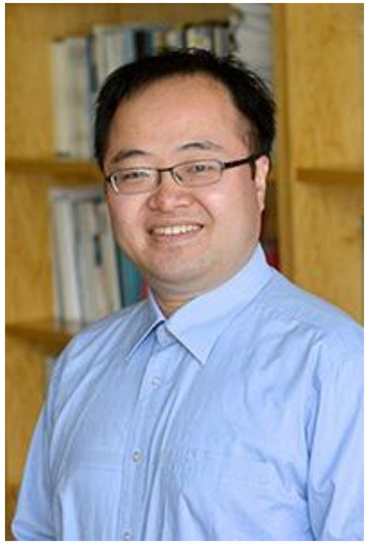

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