Developing a Platoon-Wide Eco-Cooperative Adaptive Cruise Control (CACC) System

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Ziran Wang (王子然), *Guoyuan Wu, Peng Hao,*
Kanok Boriboonsomsin, and Matthew J. Barth

Center for Environmental Research and Technology
University of California, Riverside

Outline

- Introduction and Background
- Platoon-Wide Eco-CACC Protocol
- Preliminary Evaluation and Results
- Conclusions and Future Work

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- **Introduction and Background**
- Platoon-Wide Eco-CACC Protocol
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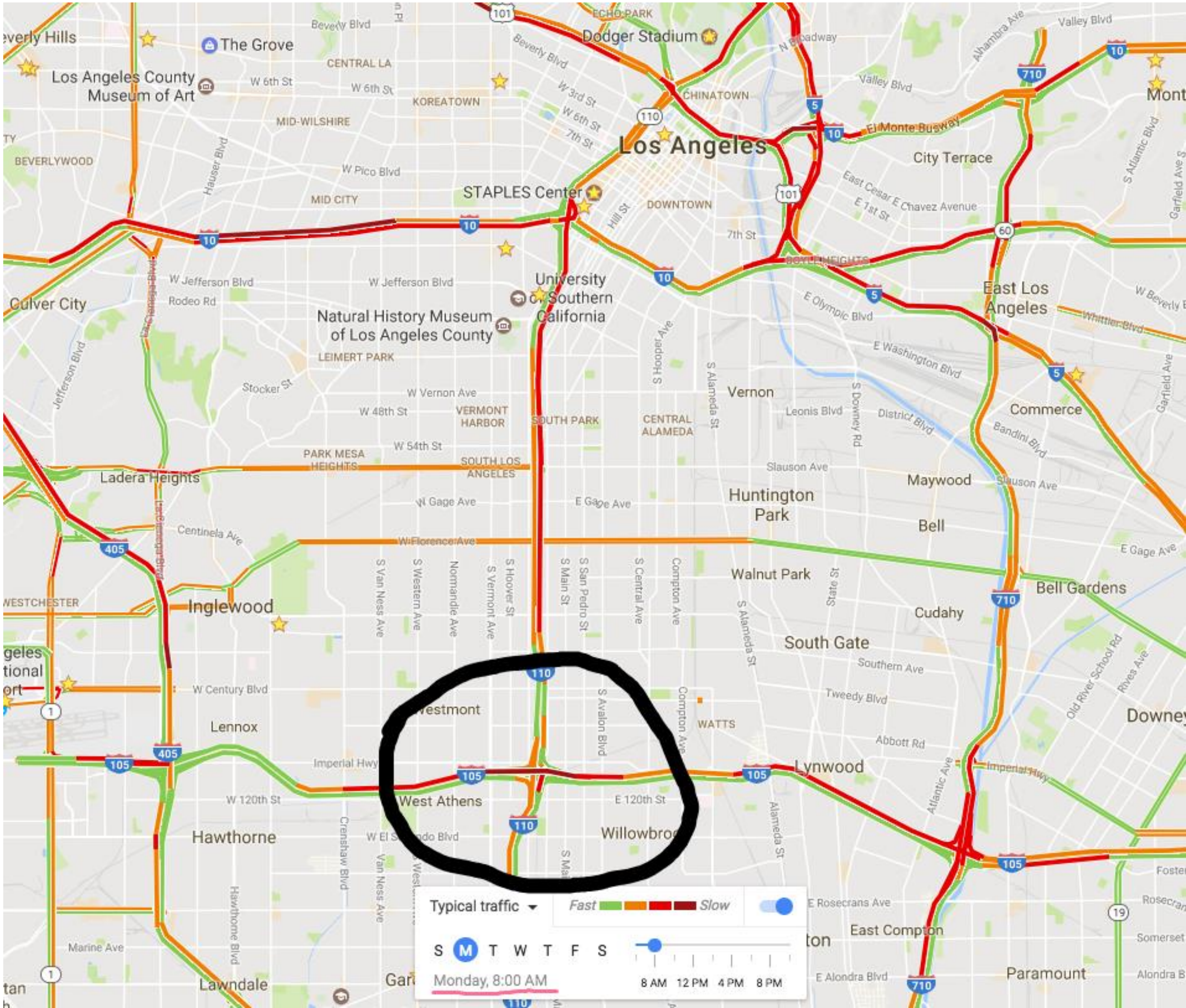
SCCAEPA

105/110 freeway interchange

(Source: Google Map)



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.

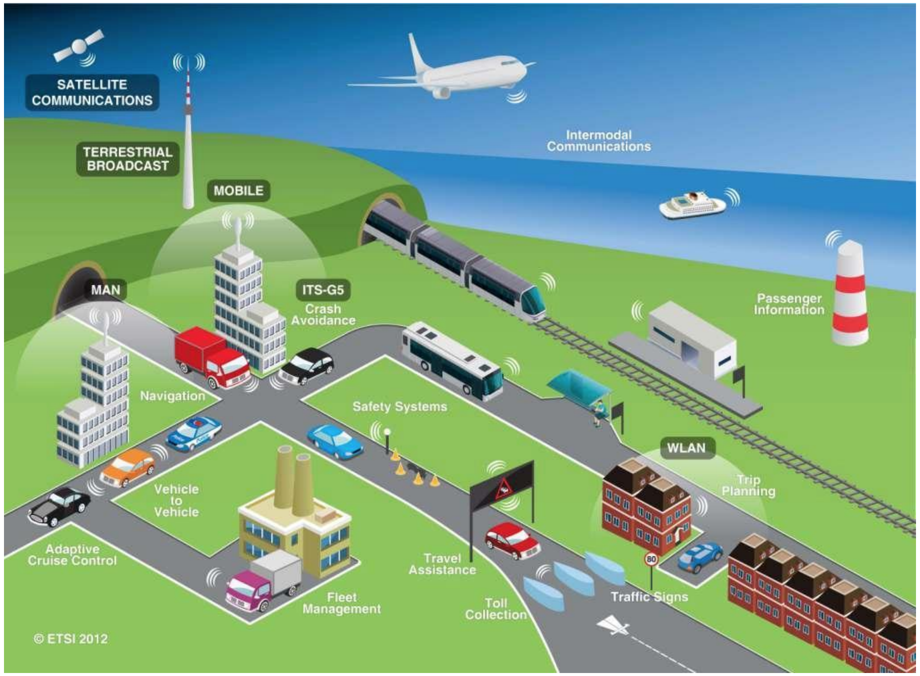
(Source: La La Land)

Motivation of the Research

- **Expand existing transportation infrastructure: costly, and raise negative social and environmental effects**

- **Develop Intelligent Transportation Systems:**

- Improve traffic safety
- Improve traffic mobility
- Improve traffic reliability



(source: ETSI)

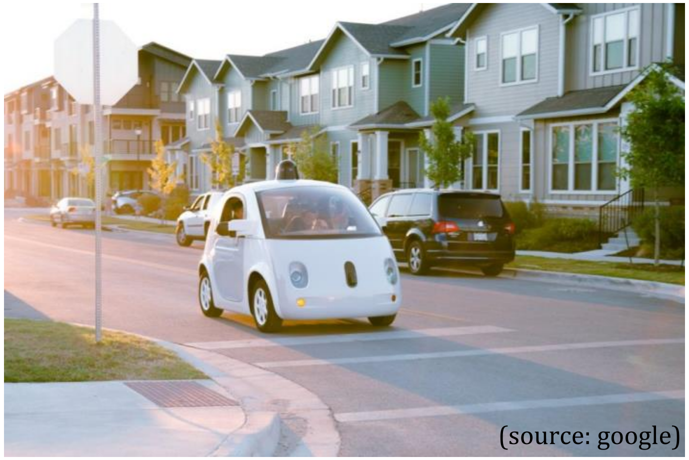
Automated Vehicle Technology

- **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.



(source: google)

(source: google)

- **Level of automation by SAE**

- Level 0: No Automation
- Level 1: Driver Assistance
- Level 2: Partial Automation
- Level 3: Conditional Automation
- Level 4: High Automation
- Level 5: Full Automation

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**

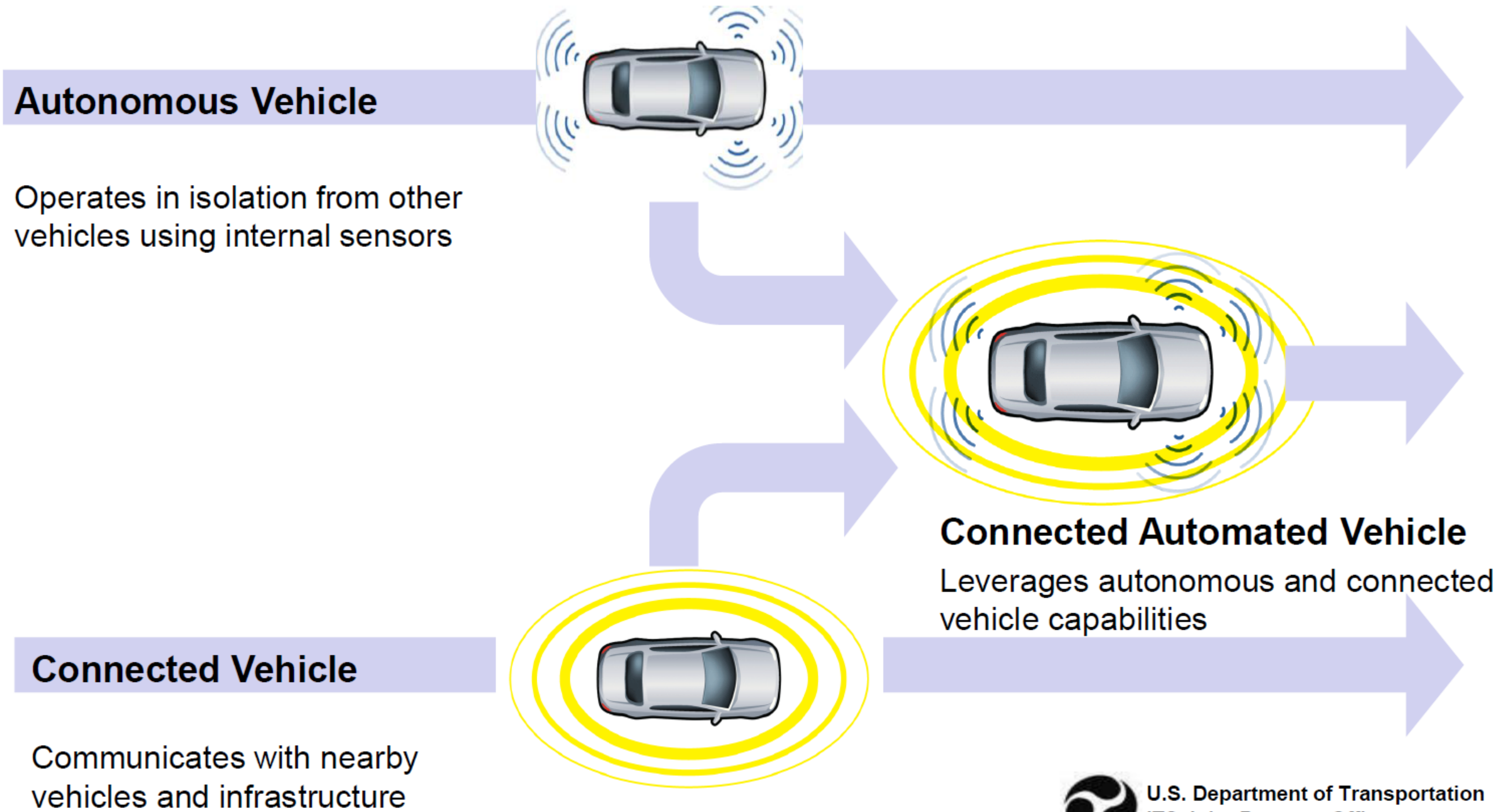
  - **Pros**: In general, partial or full vehicle automation can help **safety**
  - **Cons**: **Mobility and environmental impacts** may remain the same or could even get worse, e.g., adaptive cruise control (ACC) has been shown to have negative traffic mobility impacts

- **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

From CC to ACC to CACC

- **Cruise Control (CC):**

Vehicle maintains a steady speed as set by the driver

↓

- **<u>Adaptive</u> Cruise Control (ACC):**

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

↓

- **<u>Cooperative</u> <u>Adaptive</u> Cruise Control (CACC)**

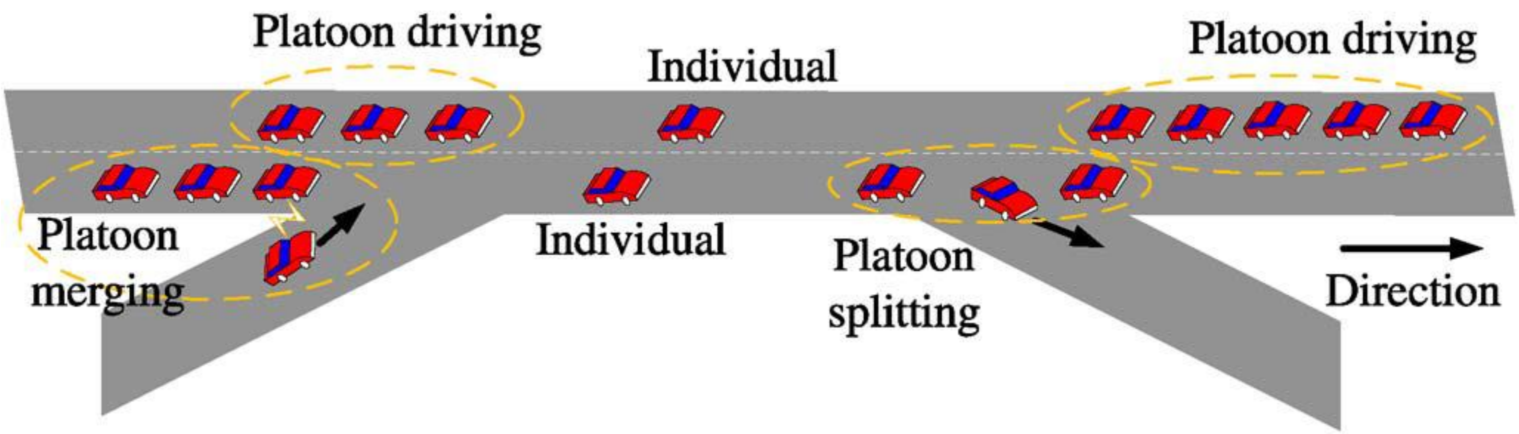
From CC to ACC to CACC

Cruise Control (CC)

Adaptive Cruise Control (ACC)

Cooperative Adaptive Cruise Control (CACC)

- **Take advantage of the Vehicle-to-Vehicle (V2V) and Infrastructure-to-Vehicle (I2V) communication**
- **Form platoons and driven at harmonized speed with smaller time gap**



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

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)


(TechAdvisor, 2013)

Energy Perspective of CACC

- **Much research has studied stability, communicability, safety, mobility, driving comfort, etc.**
- **Little has focused on energy-efficient strategies/maneuvers**
- **Subsequent study of the USDOT's AERIS (Applications for the Environment: Real-Time Information Synthesis) program**

- **Energy efficient can be achieved by**
  - **Congestion mitigation**
  - **Speed management**
  - **Shock wave suppression**

(M. Barth *et al.*, 2008)

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Platoon-Wide Eco-CACC Protocol

- **Different stages of the CACC along freeway**
  - Platoon formation
  - Platoon in-operation
  - Platoon dissolution

- **Different protocols for the involved vehicles**
  - Sequence determination
  - Gap closing and opening
  - Platoon cruising with gap regulation
  - Platoon joining and splitting

- **Assumption: CACC-enabled identical vehicles**

Gap Closing and Opening

- **Gap closing process: a following vehicle tries to catch up with its preceding vehicle from a certain distance**

Accelerate to gain a large speed difference

↓

Cruise at this rather high speed to shorten the gap

↓

Decelerate to the same speed as its preceding vehicle

Gap Closing and Opening

- **Given relative speed ΔV_0 and relative distance ΔD_0 at time $t = 0$, the planned trajectory for the gap closing controller can be determined by solving the following optimization problem**

$$\min \Delta V_{h0} \quad \text{subjects to} \tag{1}$$

$$\Delta V(t) = \begin{cases} \frac{1}{2}(\Delta V_{h0} + \Delta V_0) - \frac{1}{2}(\Delta V_{h0} - \Delta V_0) \cdot \cos(m \cdot t)\,, t \in [0, \frac{\pi}{m}) \\ \Delta V_{h0}, t \in \left[\frac{\pi}{m}, t_1\right) \\ \frac{1}{2}\Delta V_{h0} + \frac{1}{2}\Delta V_{h0} \cdot \cos[n \cdot (t - t_1)]\,, t \in \left[t_1, t_1 + \frac{\pi}{n}\right) \end{cases} \tag{2}$$

$$\frac{\pi}{2m}(\Delta V_{h0} + \Delta V_0) + \Delta V_{h0}\left(t_1 - \frac{\pi}{m}\right) + \frac{\pi}{2n}\Delta V_{h0} = \Delta D_0 \tag{3}$$

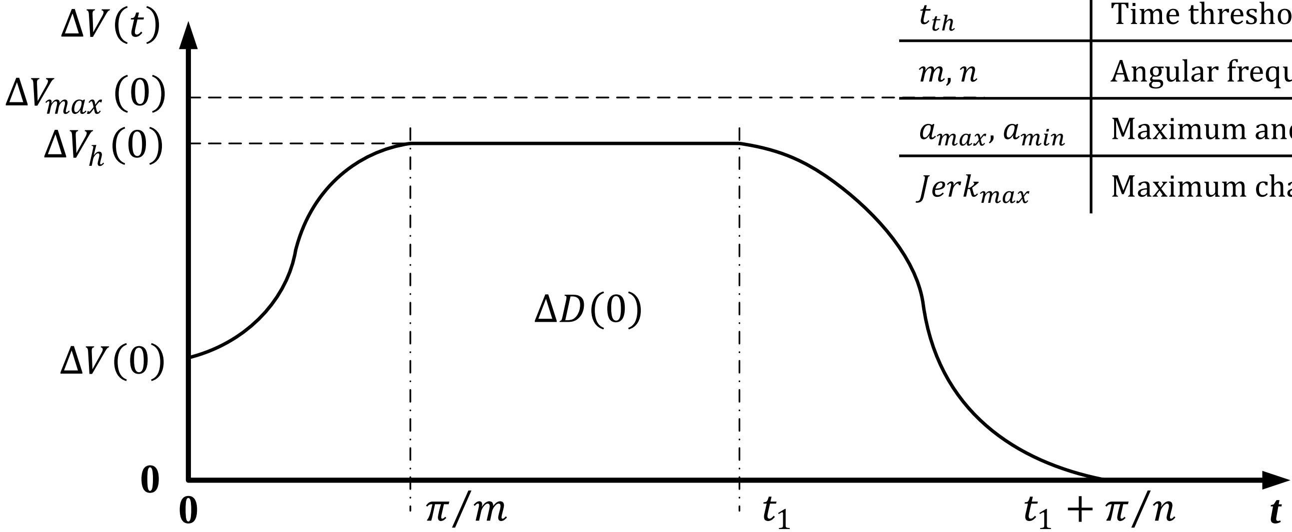
$$\Delta V_0 \leq \Delta V_{h0} \leq \Delta V_{max,0} \text{ and } t_1 + \frac{\pi}{n} \leq t_{th} \tag{4}$$

$$0 \leq \frac{m}{2}(\Delta V_{h0} - \Delta V_0) \leq a_{max} \text{ and } 0 \leq \frac{n}{2}\Delta V_{h0} \leq |a_{min}| \tag{5}$$

$$\frac{m^2}{2}(\Delta V_{h0} - \Delta V_0) \leq Jerk_{max} \text{ and } \frac{n^2}{2}\Delta V_{h0} \leq Jerk_{max} \tag{6}$$

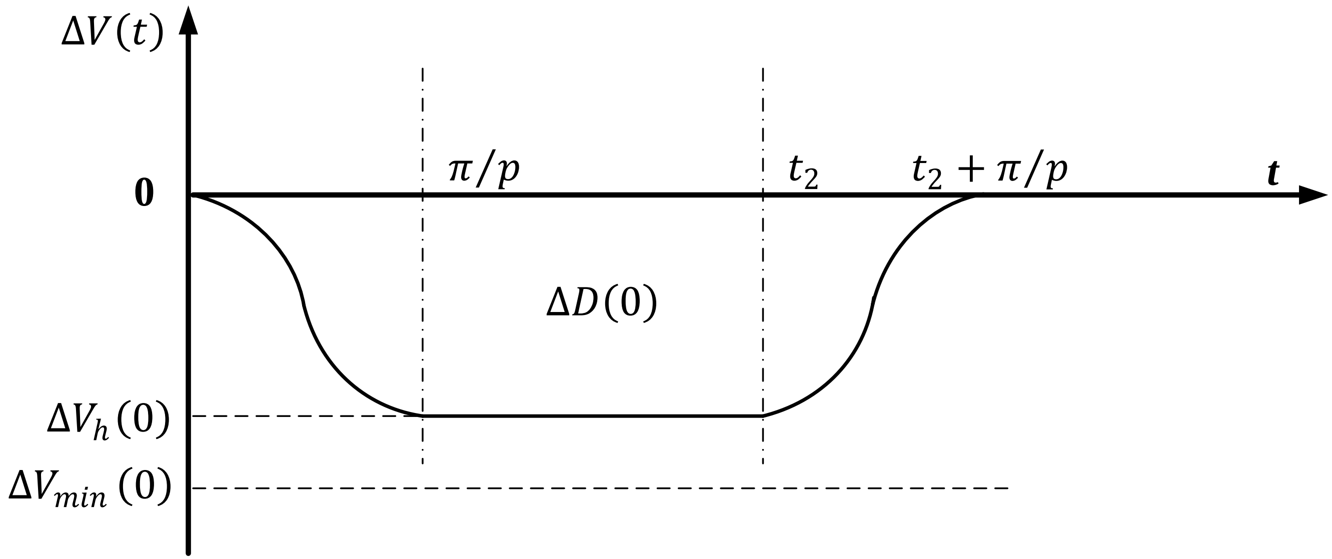
Gap Closing and Opening

Variable	Meaning
ΔD_0	Difference between the initial gap and the desired gap of two consecutive vehicles
ΔV	Speed difference between two consecutive vehicles
ΔV_0	Initial speed difference
ΔV_h	Optimal speed difference peak calculated at time $t = 0$
$\Delta V_{max,0}$	Largest speed difference (at time $t = 0$) constrained by the speed limit posted on the roadway
t_{th}	Time threshold to complete the gap closing maneuver
m, n	Angular frequencies of trigonometric functions
a_{max}, a_{min}	Maximum and minimum acceleration ($\pm$ 2.5 m/s^2)
$Jerk_{max}$	Maximum change rate of acceleration in time (10 m/s^3)



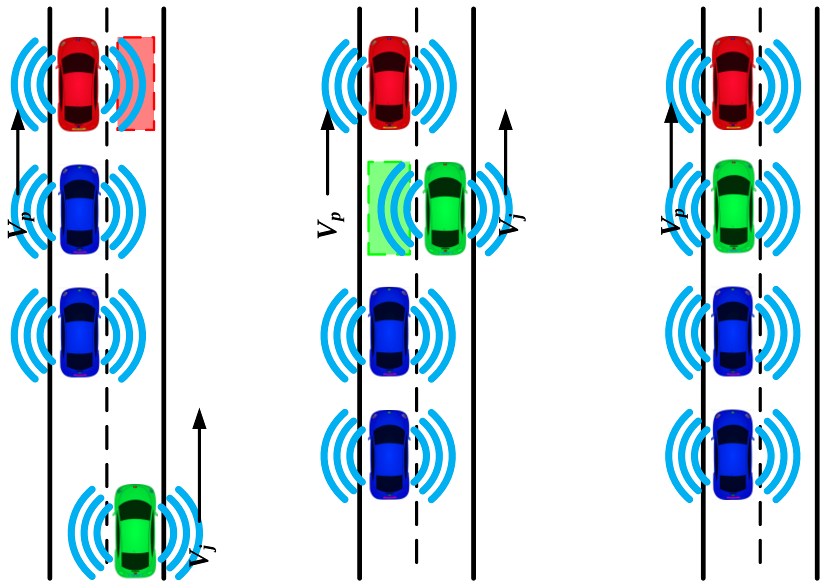
Gap Closing and Opening

- **Similar to the energy-efficient trajectory designed for gap closing, gap opening can be formulated with the constraints of another piecewise trigonometric function**



Platoon Joining and Splitting

- **Four different cases for the lane change within the platoon maneuvers:**
  - **Free-agent-to-free-agent lane change**
  - **Free-agent-to-platoon lane change**
  - **Platoon-to-free-agent lane change**
  - **Platoon-to-platoon lane change**



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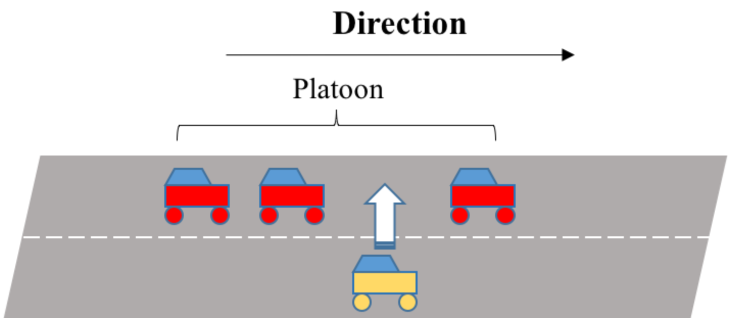
Platoon Joining and Splitting

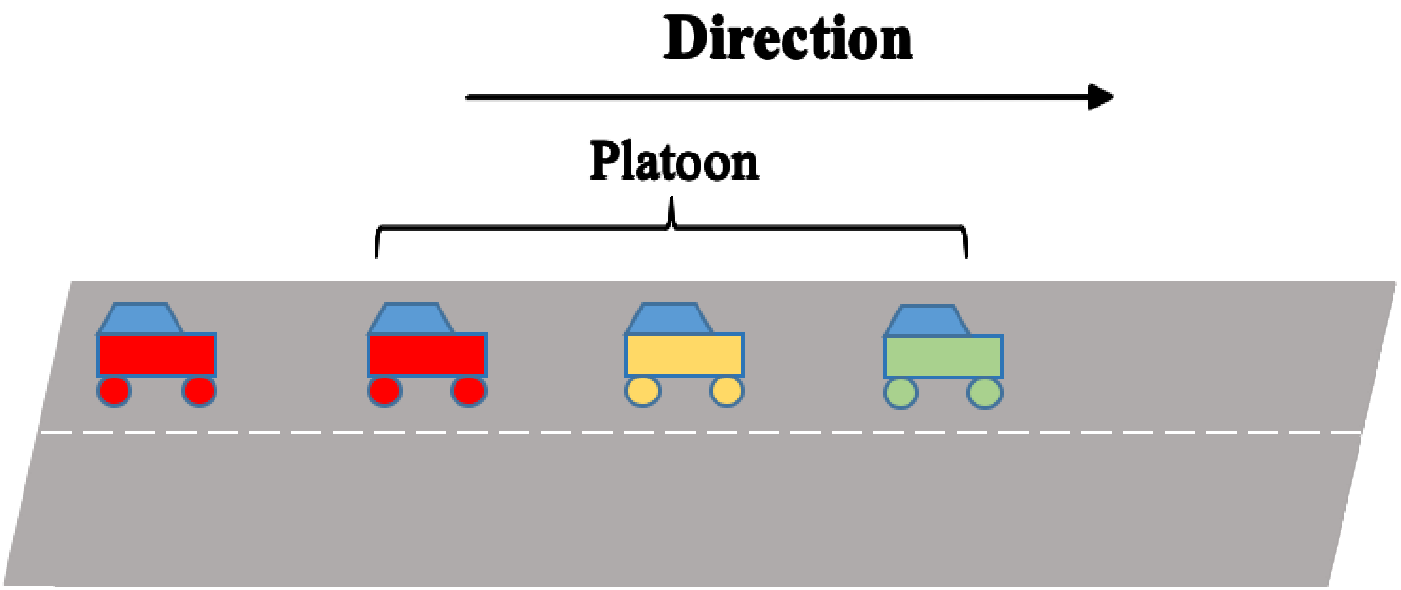
- **Platoon Joining**



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 the proposed gap closing protocol.
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 the proposed gap opening protocol.
5. Vehicle i joins the platoon.

Platoon Joining and Splitting

- **Platoon Joining**



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System Preliminary Evaluation

- **MATLAB/Simulink is used to conduct numerical simulation under two different scenarios**
  - **Platoon formation (gap closing)**
  - **Platoon joining (gap closing and gap opening)**

- **By using Motor Vehicle Emission Simulator (MOVES), results of platoon-wide energy consumption and pollutant emissions are compared with the distributed consensus-based CACC system**

Platoon Formation

- **The following vehicle conduct acceleration and deceleration processes to close the (7.58-0.9=) 6.68 s inter-vehicle time gap**

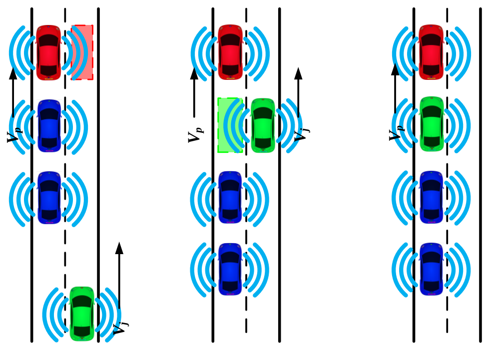
Parameters	Value
Number of Vehicles	2
Length of Vehicles	16.4 feet
Length of Simulation Segment	1 mile
Initial Speed of Vehicles	45 mph
Final Speed of Vehicles	45 mph
Initial Inter-Vehicle Time Gap	7.58 s
Final Inter-Vehicle Time Gap	0.9 s

- **The MOVES model is adopted to perform the multiple scale analysis on the environmental impacts**

	HC (g)	CO (g)	NO_x (g)	CO_2 (g)	Energy (kJ)
Consensus-CACC	0.146	4.68	0.758	684.2	9514.3
Eco-CACC	0.142	4.78	0.747	674.3	9376.6
Improved %	2.74	2.14	1.45	1.45	1.45

Platoon Joining

- **A free-agent vehicle tries to join a three-vehicle platoon**



Parameters	Value
Number of Vehicles	4
Position of Free-Agent Vehicle in Platoon after Joining	2
Length of Vehicles	16.4 feet
Length of Simulation Segment	1 mile
Initial Speed of Free-Agent Vehicle	65 mph
Initial Speed of Platoon Vehicles	45 mph
Final Speed of Platoon Vehicles	45 mph
Initial Inter-Vehicle Time Gap Between Free-Agent Vehicle and Platoon Leading Vehicle	2.7 s
Final Inter-Vehicle Time Gap Between Free-Agent Vehicle and Platoon Leading Vehicle	0.9 s

- **The MOVES model is adopted to perform the multiple scale analysis on the environmental impacts**

	HC (g)	CO (g)	NO_x (g)	CO_2 (g)	Energy (kJ)
Consensus-CACC	0.312	10.14	1.425	1327.8	18462.7
Eco-CACC	0.291	8.42	1.382	1298.9	18061.6
Improved %	6.67	16.96	3.02	2.18	2.17

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Conclusions and Future Work

- Gap-closing and gap-opening controllers have been designed
- Platoon joining and splitting protocols have been developed
- Simulation studies showed the proposed Eco-CACC system may reduce platoon-wide energy consumption by 1.45 % in platoon formation scenario, and by 2.17 % in platoon joining scenario

- Sequence determination of platoon can be further studied
- Other issues (e.g. road grade, communication delay) can be further addressed in the field implementation
- Besides the cyber-space of vehicles, the physical-space of vehicles (vehicle dynamics) can be included in the future

Q & A Time

Thank you very much for the attention!

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