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Distributed Consensus-Based Cooperative Highway On-Ramp Merging Using V2X Communications

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CE-CERT CENTER FOR ENVIRONMENTAL RESEARCH & TECHNOLOGY

UC RIVERSIDE UNIVERSITY OF CALIFORNIA

Content of the Presentation

- Introduction and background
- System architecture and assumptions
- Proposed system methodology
- Simulation study
- Conclusions and future work

Introduction and Background

Wasted Time and Wasted Fuel

- 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


(source: google)


(source: google)

- **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.

Connected Vehicle Technology

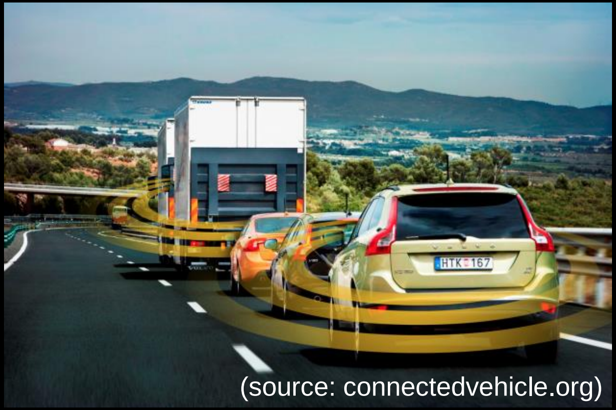
- **Definition of connected vehicles**

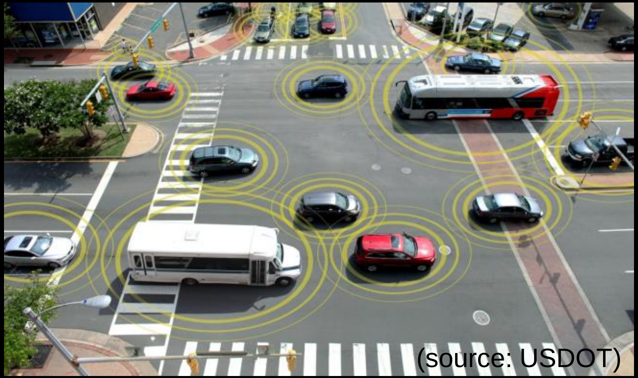
Vehicles that are equipped with Internet access, and usually also with a wireless local area network

- **Communication flow**

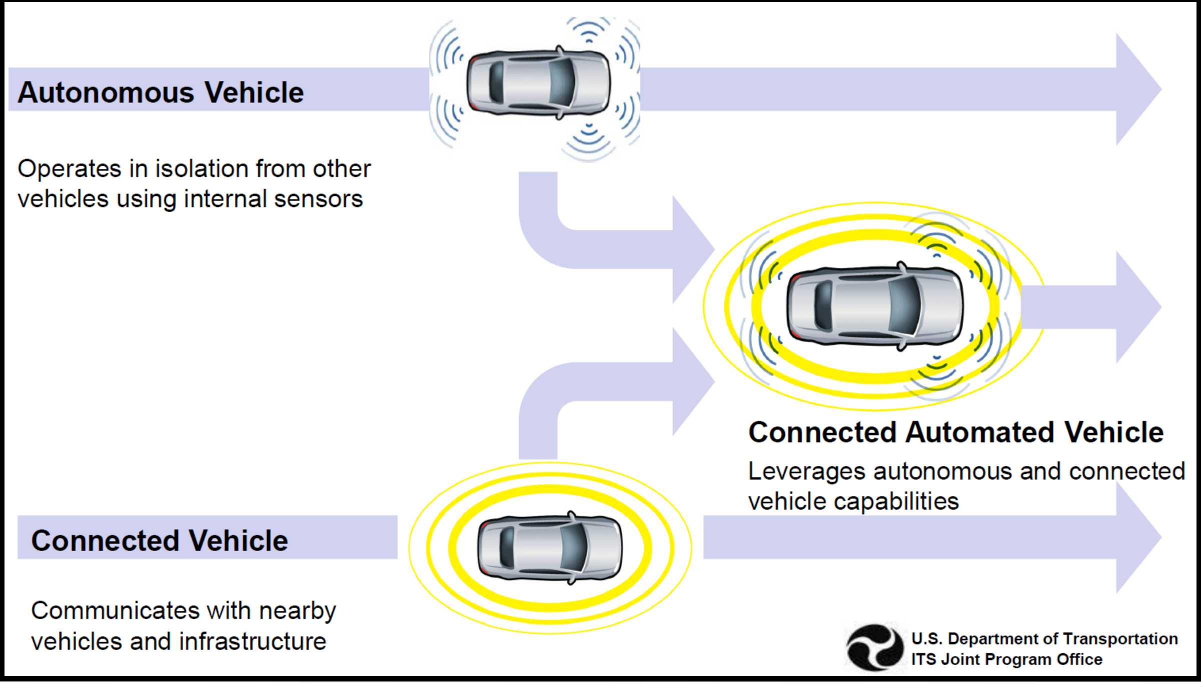
-Based primarily on dedicated short-range communications (DSRC)

-Between vehicles (V2V), or vehicles and infrastructure (V2I/I2V)





Merging of Connectivity and Automation

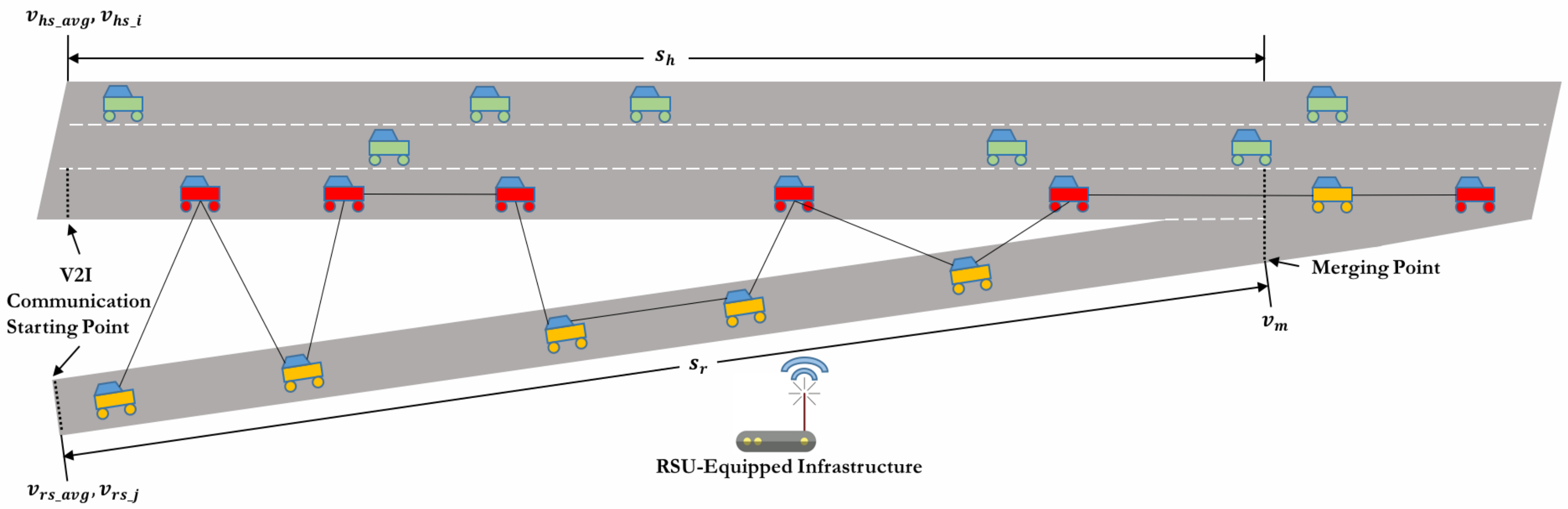


System Architecture and Assumptions

System Assumptions

- All vehicles can get their precise information by equipped sensors
- All vehicles are CAVs with V2V and V2I communications
- Only the longitudinal control is considered in this study

Cooperative Highway On-Ramp Merging System



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Proposed System Methodology

Proposed System Methodology

1. **Vehicle sequencing protocol**

Arrange vehicles with a predefined sequence to merge

2. **Distributed consensus-based cooperative merging protocol**

Propose longitudinal control model for vehicles

Vehicle Sequencing Protocol

Maximum reachable speed of on-ramp vehicles

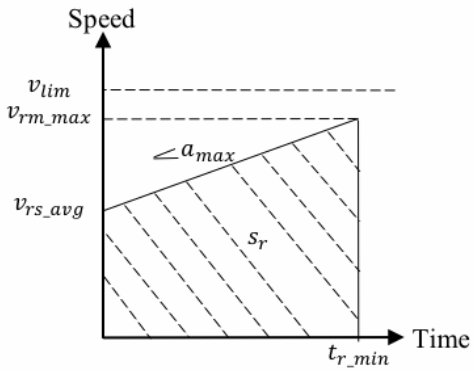
↓

Estimated arrival time

↓

Vehicle sequence identification (SID)

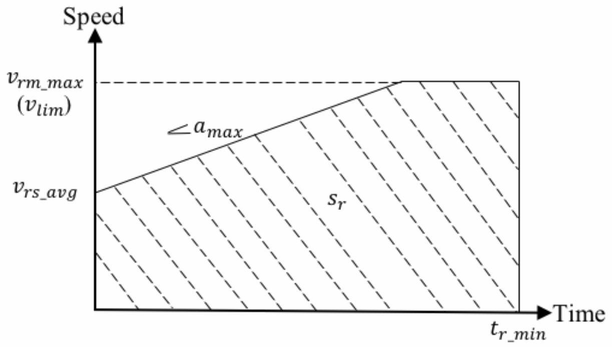
Maximum reachable speed



If on-ramp vehicles cannot accelerate to highway speed limit, the maximum reachable speed of on-ramp vehicles is

$$v_{rm\_max} = \sqrt{{v_{rs\_avg}}^2 + 2a_{max}s_r}$$

Maximum reachable speed



If on-ramp vehicles can accelerate to highway speed limit, the maximum reachable speed of on-ramp vehicles is

$$v_{rm\_max} = v_{lim}$$

Estimated Arrival Time

If $v_{hs\_avg} \leq v_{rm\_max}$**, then** $v_m = v_{hs\_avg}$

$$t_{h\_i} = \frac{s_h}{v_{hs\_i}}$$

$$t_{r\_j} = \frac{2a_{max}s_r + (v_{hs\_avg} - v_{rs\_j})^2}{2a_{max}v_{hs\_avg}}$$

Estimated Arrival Time

If $v_{hs-avg} > v_{rm-max}$**, then** $v_m = v_{rm-max}$

$$t_{h\_i} = \frac{2a_{max}(s_h - s_r) - (v_{hs\_i}{}^2 + v_{rs_{avg}}{}^2) + 2v_{hs\_i}\sqrt{v_{rs\_avg}{}^2 + 2a_{max}s_r}}{2a_{max}\sqrt{v_{rs\_avg}{}^2 + 2a_{max}s_r}}$$

$$t_{r\_j} = \frac{-v_{rs\_j} + \sqrt{v_{rs\_j}{}^2 + 2a_{max}s_r}}{a_{max}}$$

Vehicle Sequence Identification

Estimated arrival time of every vehicle is sent to the infrastructure with V2I communication area

↓

The infrastructure sorts vehicles in the network in order of time

↓

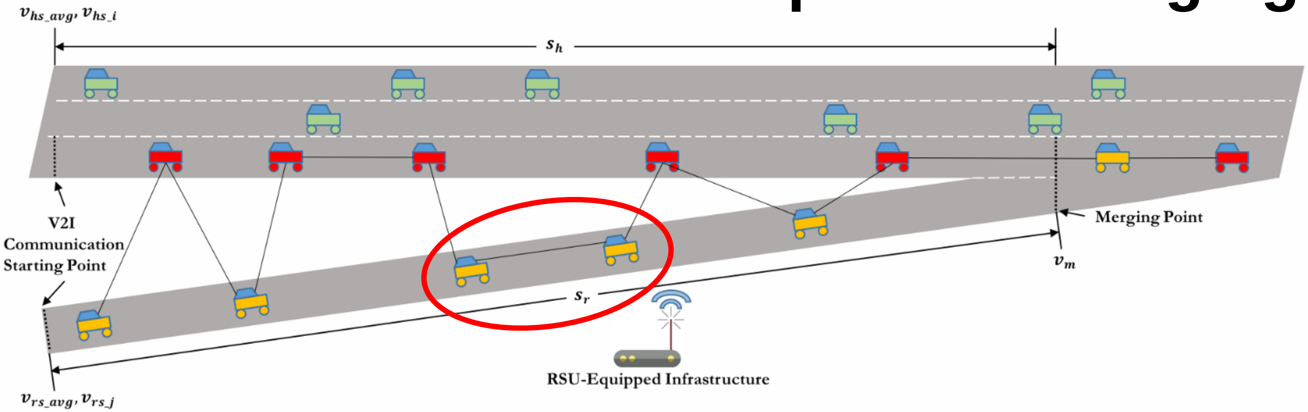
Vehicles are assigned with consecutive SIDs

Distributed Consensus-Based Cooperative Merging Protocol

Input: estimated arrival time and SID of vehicle k (T_k, n_k) and other vehicles in communication range
Output: acceleration of vehicle k

if a vehicle p with SID $(n_p = n_k - 1)$ has its estimated arrival time satisfy $(T_k - t_{head\_V2V} \leq T_p \leq T_k)$
    if vehicle p is on the same lane with vehicle k
        Vehicle p becomes the physical predecessor of vehicle k;
        Acceleration of vehicle k is calculated by ***Algorithm 1***;
    else
        Vehicle p becomes the "ghost" predecessor of vehicle k;
        Acceleration of vehicle k is calculated by ***Algorithm 2***;
    end
else
    Acceleration of vehicle k is calculated by the default car following model;
end

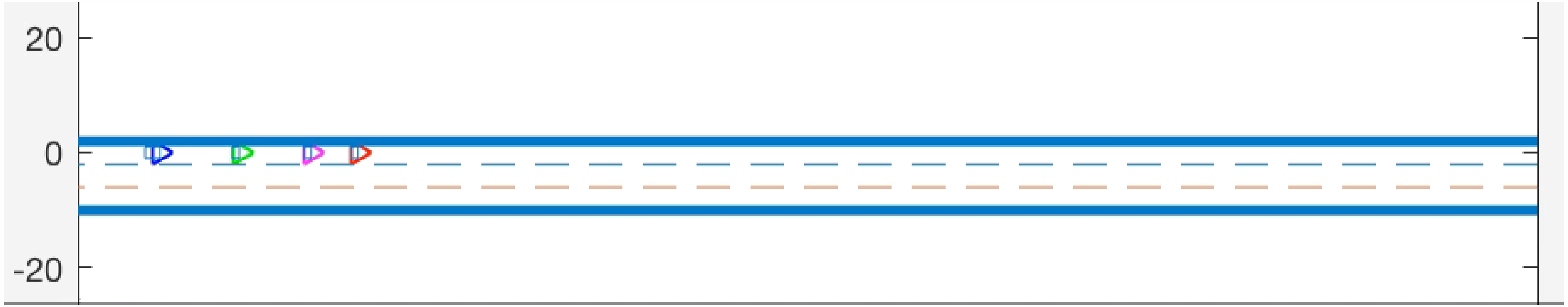
Distributed Consensus-Based Cooperative Merging Protocol



Algorithm 1. Distributed consensus algorithm for **physical** predecessor-follower.

$$a_k = -\delta[(s_k - s_p + s_{head}) + \gamma(v_k - v_p)]$$

Distributed Consensus-Based Cooperative Merging Protocol



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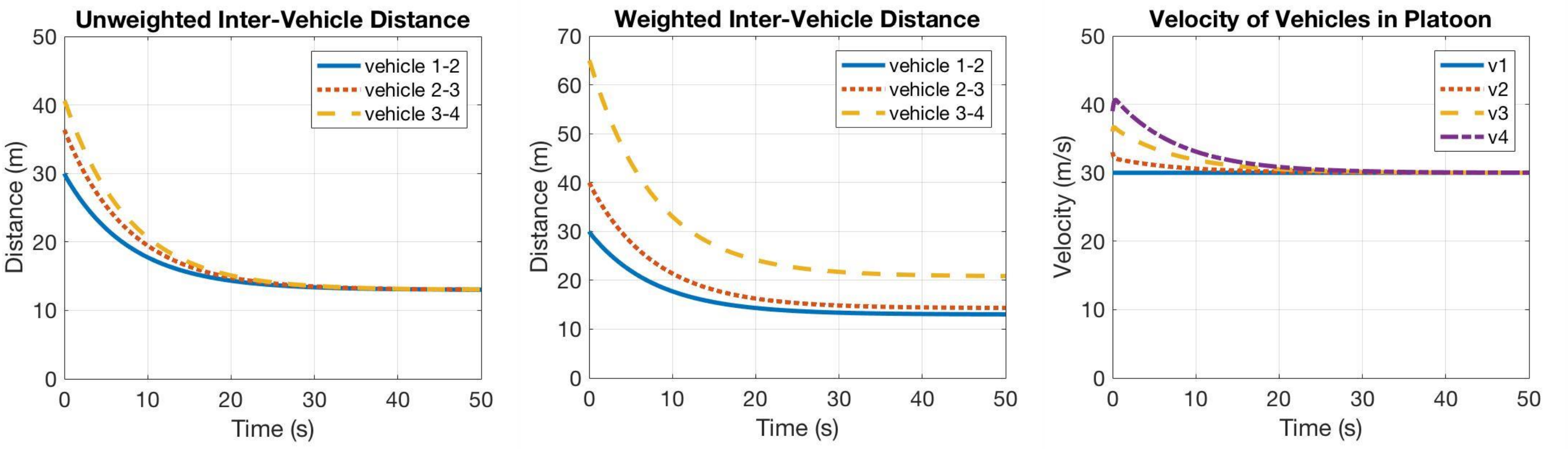
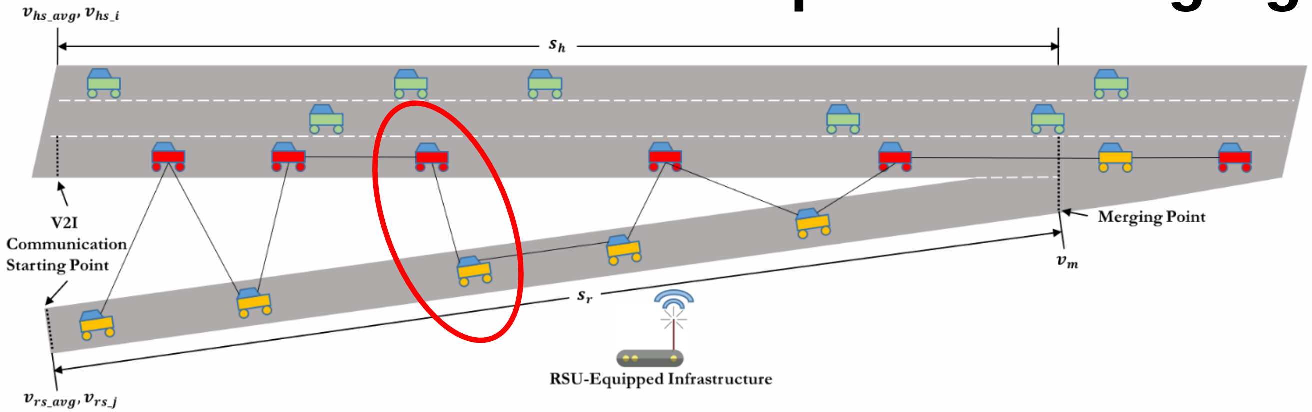


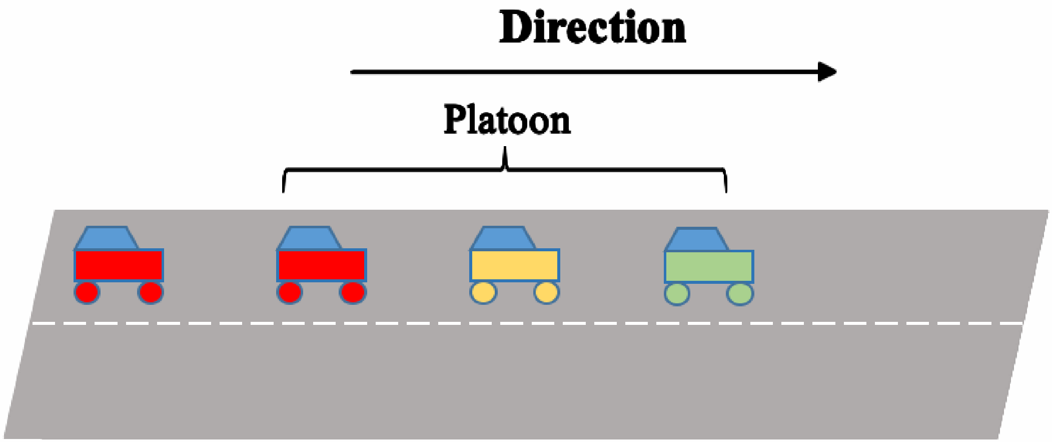
Distributed Consensus-Based Cooperative Merging Protocol



Algorithm 2. Distributed consensus algorithm for **"ghost"** predecessor-follower.

$$a_k = -\alpha\delta\left[\left(s_k - s_p + v_m t_{head\_safe}\right) + \gamma\left(v_k - v_p\right)\right] - \beta\left(v_k - v_m\right)$$

Distributed Consensus-Based Cooperative Merging Protocol



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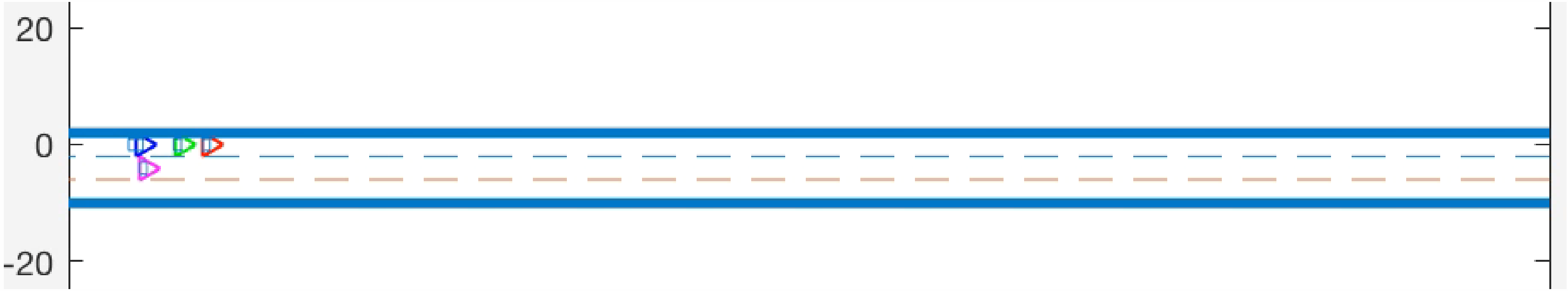

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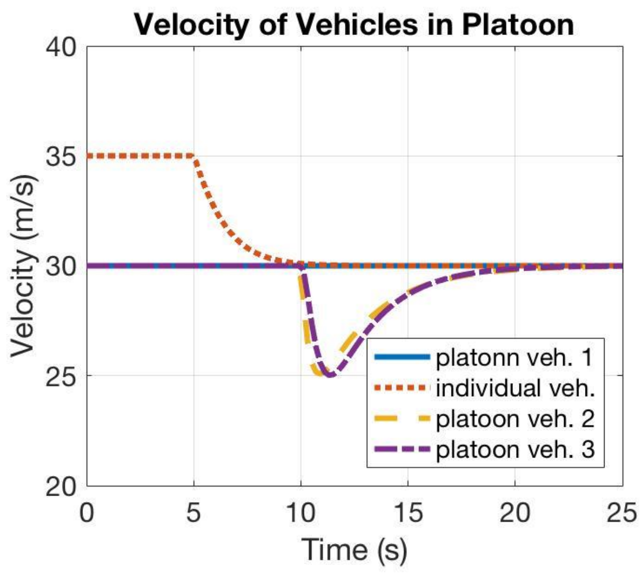
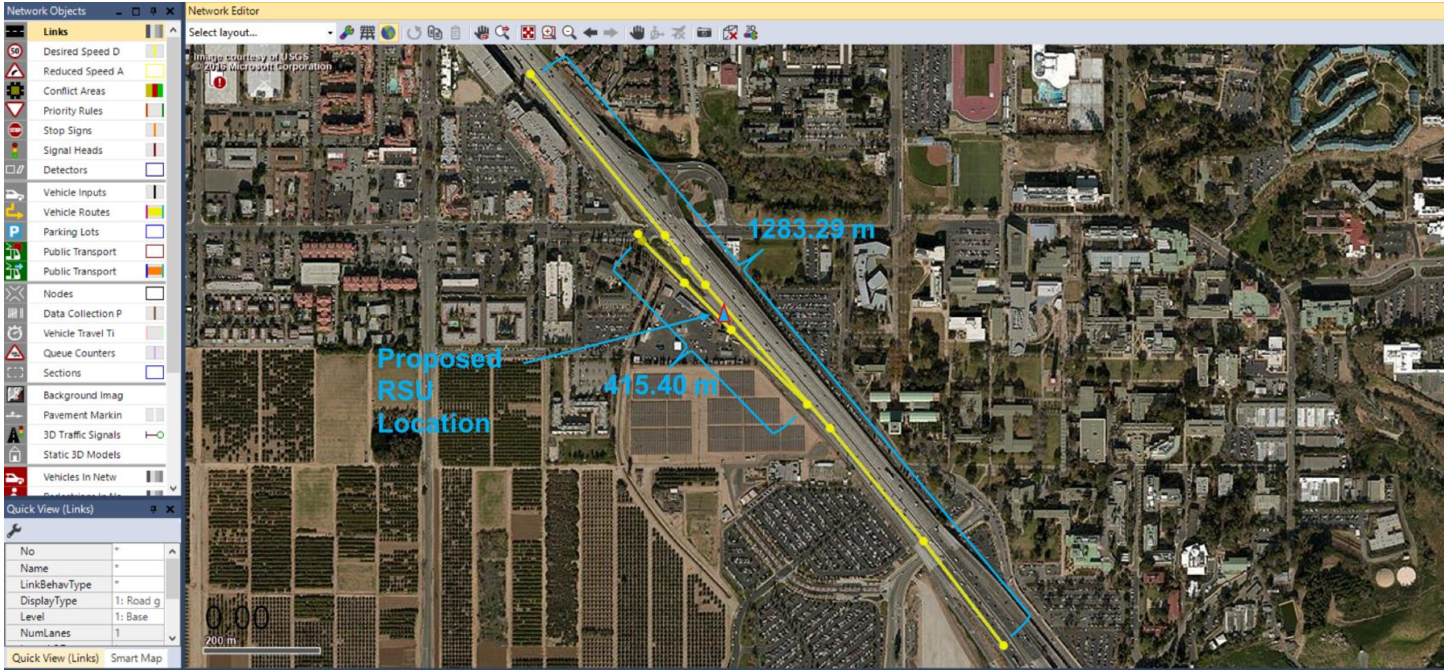
Distributed Consensus-Based Cooperative Merging Protocol



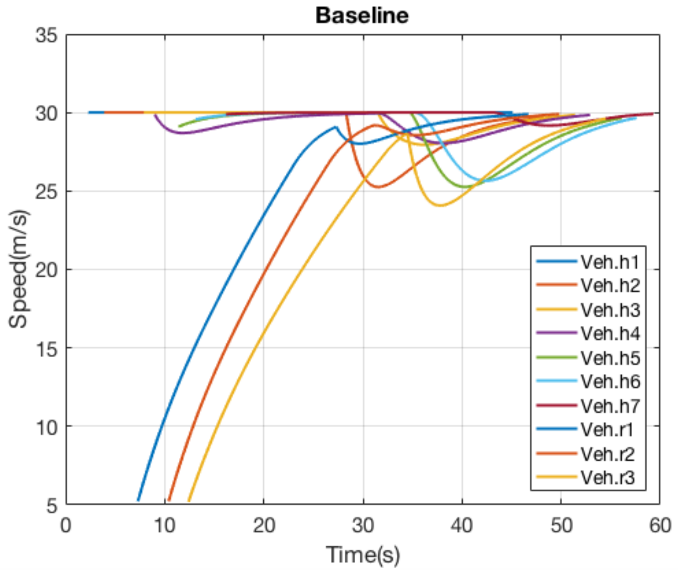
Simulation Study

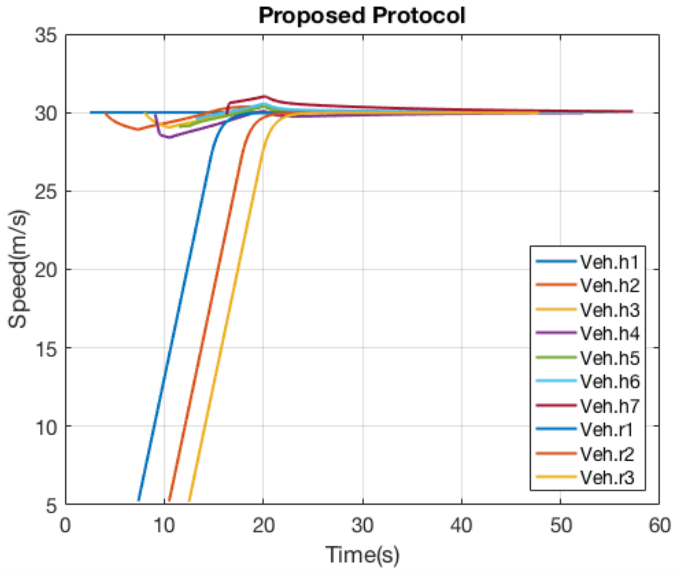
Simulation Network



Simulation Results

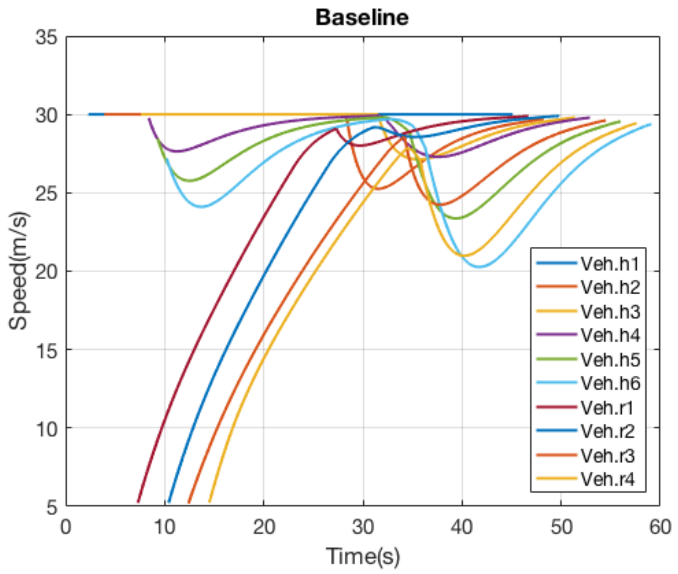
Lower Traffic Flow

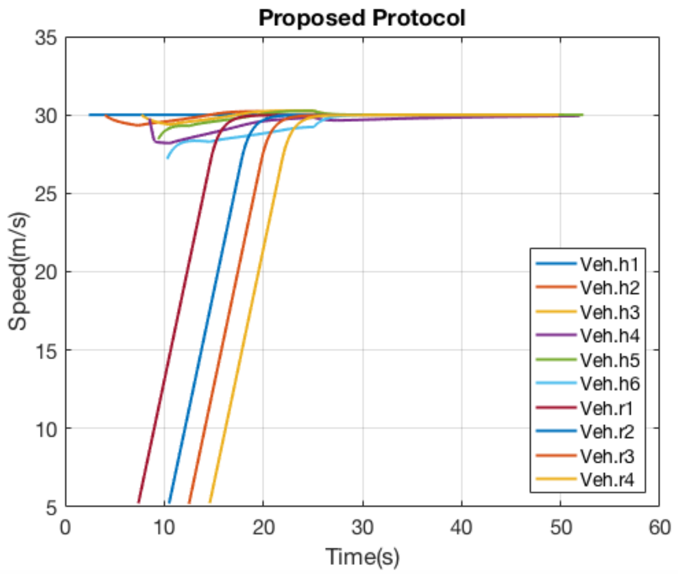




Simulation Results

Higher Traffic Flow





Simulation Results

Lower Traffic Flow

	Travel Time (s)	Speed (m/s)	CO (g)	NOx (g)	CO_2 (g)	Energy (KJ)
Baseline	42.77	29.02	1.37	0.32	270.36	3759.39
Proposed Protocol	40.49	30.02	1.36	0.31	269.99	3746.20
Improved	5.33%	3.44%	0.73%	3.13%	0.51%	0.36%

Higher Traffic Flow

	Travel Time (s)	Speed (m/s)	CO (g)	NOx (g)	CO_2 (g)	Energy (KJ)
Baseline	43.50	27.86	1.34	0.31	260.67	3624.72
Proposed Protocol	38.92	29.95	1.30	0.29	258.91	3600.31
Improved	10.50%	7.50%	2.99%	6.46%	0.67%	0.67%

Conclusions and Future Work

Conclusions

- **A distributed consensus-based cooperative methodology for highway on-ramp merging has been proposed**
- **The vehicle sequencing protocol has been developed to assign SIDs to different vehicles based on their estimated arrival time**
- **A comprehensive simulation study has been conducted based on the traffic network near UCR campus area**

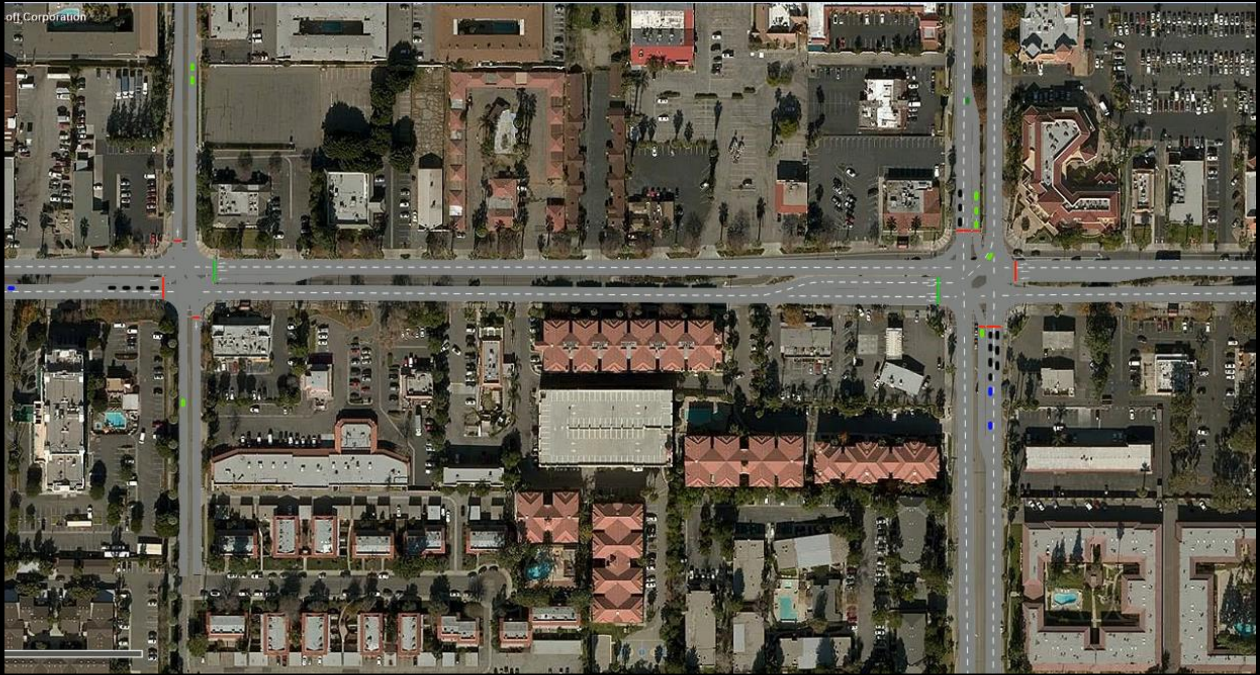
Future Work

- The study of the effect on the entire highway corridor by applying the proposed protocol
- More realistic factors of the traffic simulation network can considered, e.g., road grade, communication delay
- No existing transportation system can guarantee all vehicles are connected and automated, i.e., mixed traffic should be studied

City of Riverside Innovation Corridor

- **All traffic signal controllers are being updated to be compatible with SAE connectivity standards**
- **UC Riverside is providing the Dedicated Short Range Communication modems in each traffic signal**

Integrate with Signalized Corridors



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Contributors of the Study

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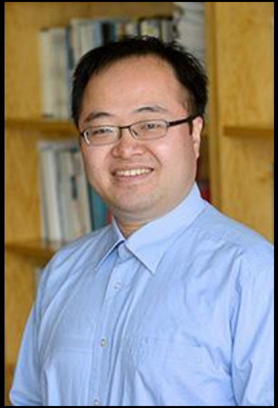

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Thank you

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