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

- **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)

(source: connectedvehicle.org)

(source: USDOT)
Merging of Connectivity and Automation

- **Autonomous Vehicle**: Operates in isolation from other vehicles using internal sensors.
- **Connected Vehicle**: Communicates with nearby vehicles and infrastructure.
- **Connected Automated Vehicle**: Leverages autonomous and connected vehicle capabilities.
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

$s_h$

$\nu_{hs,avg}, \nu_{hs,i}$

$\nu_{rs,avg}, \nu_{rs,j}$

Merging Point

V2I Communication Starting Point

RSU-Equipped Infrastructure
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)
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 $v_m = v_{rm-max}$

$$
\begin{align*}
    t_{h_i} &= \frac{2a_{max}(s_h-s_r)-(v_{hs_i}^2+v_{rs_{avg}}^2)+2v_{hs_i}\sqrt{v_{rs_{avg}}^2+2a_{max}s_r}}{2a_{max}\sqrt{v_{rs_{avg}}^2+2a_{max}s_r}} \\
    t_{r_j} &= \frac{-v_{rs_j} + \sqrt{v_{rs_j}^2 + 2a_{max}s_r}}{a_{max}}
\end{align*}
$$
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
Algorithm 1. Distributed consensus algorithm for physical predecessor-follower.

\[ a_k = -\delta \left[ (s_k - s_p + s_{head}) + \gamma (v_k - v_p) \right] \]
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
Algorithm 2. Distributed consensus algorithm for “ghost” predecessor-follower.

\[ a_k = -\alpha \delta \left[ (s_k - s_p + v_m t_{\text{head safe}}) + \gamma (v_k - v_p) \right] - \beta (v_k - v_m) \]
Distributed Consensus-Based Cooperative Merging Protocol
Distributed Consensus-Based Cooperative Merging Protocol

Algorithm 2. Distributed consensus algorithm for “ghost” predecessor-follower.

\[ a_k = -\alpha \delta [(s_k - s_p + v_m t_{\text{head safe}}) + \gamma (v_k - v_p)] - \beta (v_k - v_m) \]
Distributed Consensus-Based Cooperative Merging Protocol
Simulation Study
Simulation Network
Simulation Results

Lower Traffic Flow

Baseline

Proposed Protocol

[Graphs showing speed versus time for baseline and proposed protocol]
Simulation Results

Higher Traffic Flow

Baseline

Proposed Protocol
## Simulation Results

<table>
<thead>
<tr>
<th></th>
<th>Travel Time (s)</th>
<th>Speed (m/s)</th>
<th>CO (g)</th>
<th>NOx (g)</th>
<th>CO₂ (g)</th>
<th>Energy (KJ)</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>42.77</td>
<td>29.02</td>
<td>1.37</td>
<td>0.32</td>
<td>270.36</td>
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<td>Proposed Protocol</td>
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<td>5.33%</td>
<td>3.44%</td>
<td>0.73%</td>
<td>3.13%</td>
<td>0.51%</td>
<td>0.36%</td>
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### Lower Traffic Flow

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<tr>
<th></th>
<th>Travel Time (s)</th>
<th>Speed (m/s)</th>
<th>CO (g)</th>
<th>NOx (g)</th>
<th>CO₂ (g)</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>43.50</td>
<td>27.86</td>
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<tr>
<td>Proposed Protocol</td>
<td>38.92</td>
<td>29.95</td>
<td>1.30</td>
<td>0.29</td>
<td>258.91</td>
<td>3600.31</td>
</tr>
<tr>
<td>Improved</td>
<td>10.50%</td>
<td>7.50%</td>
<td>2.99%</td>
<td>6.46%</td>
<td>0.67%</td>
<td>0.67%</td>
</tr>
</tbody>
</table>

### Higher Traffic Flow
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 be 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
Contributors of the Study

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Thank you

Ziran Wang