Developing Agent-Based Distributed Cooperative Vehicle-Infrastructure Systems in the Connected and Automated Vehicle Environment

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Mechanical Engineering, UC Riverside
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Roadmap of the Dissertation

Intro

Dissertation Basis

Motivation

CAV architecture

Agent-based modeling and simulation

Objectives

Distributed consensus for multi-agent

CVIS with V2V

Consensus control-based CACC

Optimal control-based CACC

CVIS with V2V & I2V

Cooperative eco-driving at signalized intersections

Cooperative merging at highway on-ramps

Dissertation Extension

Conclusions

Publications

Future work
INTRODUCTION AND BACKGROUND
Introduction

105/110 freeway interchange, Los Angeles, CA
Source: Google Map
Introduction

Issues of current transportation systems:

• **Safety** 37,461 people perished in traffic accidents in the U.S. in 2016

• **Mobility** 41 hrs/yr/driver are spent by U.S. drivers in traffic during peak hours in 2017, costing nearly $305 billion in total

• **Environmental sustainability** 11.7 billion gallons of fuel were wasted worldwide due to traffic congestion in 2015
Introduction

Helping solve the issues by **cooperative vehicle-infrastructure systems** with connected and automated vehicles

(source: ETSI)
Research Background

• Generalized connected and automated vehicle (CAV) system
Research Background

- Longitudinal cooperative automation of CAVs using V2X communication

<table>
<thead>
<tr>
<th></th>
<th>Extent of Work using CAVs</th>
<th>Potential Benefit to Transportation Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical Work</td>
<td>Experimental Work</td>
</tr>
<tr>
<td>A. Cooperative adaptive cruise control and platooning</td>
<td>★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>B. Cooperative merging at highway on-ramps</td>
<td>★★★</td>
<td>★</td>
</tr>
<tr>
<td>C. Speed harmonization on highways</td>
<td>★★★</td>
<td>★</td>
</tr>
<tr>
<td>D. Cooperative eco-driving at signalized intersections</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>E. Automated coordination at non-signalized intersections</td>
<td>★★</td>
<td>★</td>
</tr>
</tbody>
</table>

Number of stars denotes the extent of work conducted, and the extent of the benefits to current transportation systems.
DISTRIBUTED CONSENSUS FOR MULTI-AGENT SYSTEMS
Centralized and Distributed Approaches

**Centralized Approaches**
- Assumptions: availability of global team knowledge, centralized planning and coordination, fully connected network
- Practical Issues: limited communication/sensing range, environmental factors

**Distributed Approaches**
- Features: local neighbor-to-neighbor interaction, evolve in a parallel manner
- Strengths: reduced communication/sensing requirement, improved scalability, flexibility, reliability, and robustness
Distributed Consensus for Multi-Agent Systems

Reach global/centralized agreement or consensus by distributed/decentralized cooperation among multiple agents

\[ x_i[k + 1] = \sum_{j=1}^{n} a_{ij}[k] x_j[k], \quad i, j = 1, \ldots, n \]

where \( j \) is the neighbor agent of \( i \)

Schedule the final defense for Ziran

1:00 + 1:00 + 2:00 + 2:00 + 3:00 + 3:00

\[ \frac{6}{6} = 2:00 \]
Distributed Consensus Algorithms for Car Following

Dynamics of a connected vehicle

\[ \begin{align*}
\dot{r}_i(t) &= v_i(t) \\
v_i(t) &= a_i(t)
\end{align*} \]

- **First-order consensus algorithm**

\[ v_i(t) = - \sum_{j=1}^{n-1} a_{ij} k_{ij} \left( r_i(t) - r_j(t) \right), \quad i = 2, \ldots, n, j = i - 1 \]

- **Second-order consensus algorithm**

\[ a_i(t) = - \sum_{j=1}^{n-1} a_{ij} k_{ij} \left[ \left( r_i(t) - r_j(t) \right) + \gamma \left( v_i(t) - v_j(t) \right) \right], \quad i = 2, \ldots, n, j = i - 1 \]

where \( a_{ij} \) is the adjacency matrix of the associated communication graph, \( k_{ij} \) and \( \gamma \) are control gains.
COOPERATIVE ADAPTIVE CRUISE CONTROL
→ MOBILITY BENEFIT
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
Cooperative Adaptive Cruise Control

Distributed consensus-based CACC algorithms for heterogeneous CAVs with predecessor-following

\[
\begin{align*}
\dot{r}_i(t) &= v_i(t) \\
\dot{v}_i(t) &= -a_{ij}k_{ij}[r_i(t) - r_j(t - \tau_{ij}(t))] + l_{if} + l_{jr} + v_j(t - \tau_{ij}(t)) \left( t_{ij}^g + \tau_{ij}(t) \right) b_i \\
&\quad - \gamma a_{ij}k_{ij} \left[ v_i(t) - v_j(t - \tau_{ij}(t)) \right]
\end{align*}
\]

\( i = 2, \ldots, n, j = i - 1 \)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_i(t) )</td>
<td>Longitudinal position of vehicle ( i ) at time ( t )</td>
</tr>
<tr>
<td>( v_i(t) )</td>
<td>Longitudinal speed of vehicle ( i ) at time ( t )</td>
</tr>
<tr>
<td>( \dot{v}_i(t) )</td>
<td>Longitudinal acceleration of vehicle ( i ) at time ( t )</td>
</tr>
<tr>
<td>( a_{ij} )</td>
<td>((i, j))th entry of the adjacency matrix</td>
</tr>
<tr>
<td>( \tau_{ij}(t) )</td>
<td>Communication delay at time ( t )</td>
</tr>
<tr>
<td>( t_{ij}^g )</td>
<td>Inter-vehicle time gap</td>
</tr>
<tr>
<td>( l_{if} )</td>
<td>Length between GPS antenna to front bumper</td>
</tr>
<tr>
<td>( l_{jr} )</td>
<td>Length between GPS antenna to rear bumper</td>
</tr>
<tr>
<td>( b_i )</td>
<td>Braking factor of vehicle ( i )</td>
</tr>
<tr>
<td>( \gamma, k_{ij} )</td>
<td>Tuning parameter</td>
</tr>
</tbody>
</table>

Cooperative Adaptive Cruise Control

\[
\begin{aligned}
\dot{r}_i(t) &= v_i(t) \\
\dot{v}_i(t) &= -a_{ij}k_{ij} \left( r_i(t) - r_j(t - \tau_{ij}(t)) + l_{if} + l_{jr} + v_j(t - \tau_{ij}(t)) \left( t^g_{ij} + \tau_{ij}(t) \right) b_i \right) \\
&\quad - \gamma a_{ij}k_{ij} \left[ v_i(t) - v_j(t - \tau_{ij}(t)) \right]
\end{aligned}
\]

velocity consensus

position consensus

\[ i = 2, \ldots, n, j = i - 1 \]

Predecessor following topology

Direction

GPS Antenna

\[ r_i(t) \]

\[ r_j(t) \]
Cooperative Adaptive Cruise Control

- **Scenario 1: Normal platoon formation**
Cooperative Adaptive Cruise Control

- **Scenario 2: Platoon restoration from disturbances**
  - A step change is applied to the velocity of the leading vehicle
  - All following vehicles are capable to take immediate responses
Cooperative Adaptive Cruise Control

- Merging protocol
Cooperative Adaptive Cruise Control

- Scenario 3: Merging and splitting maneuvers
Cooperative Adaptive Cruise Control

• **Feedforward control: Lookup table for control gain**

Initial states \((\Delta r_{ij}(t_0), v_i(t_0), v_j(t_0 - \tau_{ij}(t_0)))\) varies every time the algorithm is switched on by vehicles

Initial states of vehicles highly affect the convergence of the consensus algorithm

Build up a lookup table to find the optimal value of control gains with respect to different initial conditions
Cooperative Adaptive Cruise Control

Safety Constraint (1\textsuperscript{st} priority)
Evaluated by headway overshoot

\[ r_j \left( t - \tau_{ij}(t) \right) - r_i(t) > l_j, t \in [t_0, t_{consensus}] \]

Efficiency Constraint (2\textsuperscript{nd} priority)
Evaluated by convergence time

\[
\begin{align*}
|r_j \left( t_{consensus} - \tau_{ij}(t_{consensus}) \right) - r_i(t_{consensus})| & \leq \eta_r \cdot \left[ l_j + v_i(t_{consensus}) \cdot \left( t_{ij}^g(t_{consensus}) + \tau_{ij}(t_{consensus}) \right) \right] \\
|v_j \left( t_{consensus} - \tau_{ij}(t_{consensus}) \right) - v_i(t_{consensus})| & \leq \eta_v \cdot \left( t_{consensus} - \tau_{ij}(t_{consensus}) \right)
\end{align*}
\]

\[ |a_i(t_{consensus})| \leq \delta_a \]

\[ |jerk_i(t_{consensus})| \leq \delta_jerk \]

Comfort Constraint (3\textsuperscript{rd} priority)
Evaluated by maximum acceleration/deceleration and maximum jerk

\[
\Omega_i = \omega_1 \cdot \max_{t \in [t_0, t_{consensus}]} (|a_i^{\max}(t)|, |a_i^{\min}(t)|) + \omega_2 \cdot \max_{t \in [t_0, t_{consensus}]} (|jerk_i^{\max}(t)|, |jerk_i^{\min}(t)|), t \in [t_0, t_{consensus}]
\]
TABLE I. Settings of Simulation Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta r_{ij}(t_0)$ (m)</th>
<th>$v_i(t_0)$ (m/s)</th>
<th>$v_j\left(t_0 - \tau_{ij}(t_0)\right)$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>50</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>20</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>-30</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>-80</td>
<td>4</td>
<td>21</td>
</tr>
</tbody>
</table>

TABLE II. SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Convergence time (s)</th>
<th>Maximum jerk (m/s³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Wang</td>
<td>35.9</td>
<td>35.0</td>
</tr>
<tr>
<td>van Arem</td>
<td>29.3</td>
<td>32.1</td>
</tr>
<tr>
<td>Proposed</td>
<td>24.9</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Scenario 1

Scenario 2

Scenario 3

Scenario 4
COOPERATIVE ECO-DRIVING AT SIGNALIZED INTERSECTIONS → ENVIRONMENTAL SUSTAINABILITY BENEFIT
Eco-Approach and Departure

- Utilizes traffic signal phase and timing (SPaT) data to provide driver recommendations that encourage “green” approaches to signalized intersections.
Cooperative Eco-Driving

- Taking advantages of both eco-approach and departure, as well as CACC
Cooperative Eco-Driving

- **System Architecture**

  - Higher Level
  - Cooperative Eco-Driving System
  - State Machines
  - Longitudinal Control Models
  - Role Transition
  - Scenario Transition
  - Eco-Approach and Departure Algorithm
  - CACC Algorithm

- Lower Level
Cooperative Eco-Driving

- Two vehicle types:
  Conventional vehicle and CED vehicles
- Two vehicle roles:
  Leader and follower
- Four longitudinal controllers:
  Human driver model, EAD model, IDM model, and distributed consensus model

Cooperative Eco-Driving

• Role and control models of CED vehicles
Cooperative Eco-Driving

- How cooperative eco-driving system works?

1. Calculate cruising, earliest and latest time-to-arrival value

\[ t_c = \frac{d_1}{v_1} \]

\[ t_e = \frac{d_1 - v_1 \cdot \frac{\pi}{2\alpha}}{v_{lim}} + \frac{\pi}{2\alpha}, \alpha = \min \left\{ \frac{2 \cdot a_{max}}{v_{lim} - v_1}, \sqrt{\frac{2 \cdot jerk_{max}}{v_{lim} - v_1}} \right\} \]

\[ t_l = \frac{d_1 - v_1 \cdot \frac{\pi}{2\beta}}{v_{coast}} + \frac{\pi}{2\beta}, \beta = \min \left\{ \frac{2 \cdot a_{max}}{v_1 - v_{coast}}, \sqrt{\frac{2 \cdot jerk_{max}}{v_1 - v_{coast}}} \right\} \]

2. Run the scenario transition state machine to decide the scenario

3. Assign the time-to-arrival value \( t_{arr} \) to one of \( t_c, t_e, t_l \) based on the selected scenario

4. Propose EAD algorithm for the CED leader with respect to different scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_1 )</td>
<td>current distance to the intersection</td>
</tr>
<tr>
<td>( v_1 )</td>
<td>current speed of vehicle</td>
</tr>
<tr>
<td>( a_{max} )</td>
<td>maximum changing rate of speed</td>
</tr>
<tr>
<td>( jerk_{max} )</td>
<td>maximum changing rate of acceleration or deceleration</td>
</tr>
<tr>
<td>( v_{lim} )</td>
<td>the speed limit of the current roadway</td>
</tr>
<tr>
<td>( v_{coast} )</td>
<td>coasting speed</td>
</tr>
</tbody>
</table>
Cooperative Eco-Driving

• EAD scenarios

Scenario of vehicles:
• Vehicle 1 – Cruise
• Vehicle 2 – Accelerate
• Vehicle 3 – Stop
• Vehicle 4 – Decelerate
Cooperative Eco-Driving

- Algorithms for eco-approach and eco-departure, different scenarios

\[
\begin{align*}
\text{Approach} & : \quad a_{\text{ref}} = v_{d1} \cdot j_1 \cdot \sin(j_1 t), t \in \left[0, \frac{\pi}{2j_1}\right) \\
& \quad a_{\text{ref}} = v_{d1} \cdot j_1 \cdot \sin\left[k_1 \cdot \left(t + \frac{\pi}{k_1} - t_1\right)\right], t \in \left[\frac{\pi}{2j_1}, \frac{\pi}{2j_1} + \frac{\pi}{2k_1}\right)
\end{align*}
\]

\[
\begin{align*}
\text{Departure} & : \quad a_{\text{ref}} = v_{d2} \cdot j_2 \cdot \sin\left[k_2 \cdot \left(t + \frac{\pi}{k_2} - t_{\text{depart}}\right)\right], t \in \left[t_{\text{depart}}, t_{\text{depart}} + \frac{\pi}{2k_2}\right) \\
& \quad a_{\text{ref}} = v_{d2} \cdot j_2 \cdot \sin\left[j_2 \cdot \left(t - t_{\text{depart}} - \frac{\pi}{2j_2} - \frac{\pi}{2k_2}\right)\right], t \in \left[t_{\text{depart}} + \frac{\pi}{2k_2}, t_{\text{depart}} + \frac{\pi}{2j_2} + \frac{\pi}{2k_2}\right)
\end{align*}
\]

1. **Accelerate or decelerate scenario**

\[
v_h = \frac{d_1}{t_{\text{arr}}}, \quad v_{d1} = v_h - v_1, \quad v_{d2} = v_h - v_{\text{tar}}, \quad \text{and} \quad t_{\text{depart}} = \frac{d_2}{v_h}
\]

Maximize \( k_i \) subject to

\[
\begin{align*}
|k_i \cdot v_{di}| & \leq a_{\text{max}} \\
|k_i^2 \cdot v_{di}| & \leq \text{jerk}_{\text{max}}, \quad j_i = \frac{v_h}{d_i} \\
k_i & \geq \left(\frac{\pi}{2} - 1\right) \cdot \frac{v_h}{d_i}
\end{align*}
\]

2. **Stop scenario**

\[
v_h = \frac{v_1}{2}, \quad k_i = j_i = \frac{v_h}{d_i} \cdot \pi, \quad \text{and} \quad t_{\text{depart}} = t_{\text{next s}}
\]
Cooperative Eco-Driving

- Microscopic traffic simulation in pure CAV environment
Cooperative Eco-Driving

Microscopic traffic simulation study is conducted based on the University Avenue corridor in Riverside, CA, with realistic traffic data provided by City of Riverside.
Cooperative Eco-Driving

- Microscopic traffic simulation in mixed traffic environment
Cooperative Eco-Driving

- Microscopic traffic simulation running in PTV VISSIM (3D mode)
## Cooperative Eco-Driving

- **Simulation results**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Vehicle Composition</th>
<th>Energy</th>
<th>NO(_X)</th>
<th>HC</th>
<th>CO</th>
<th>CO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>0% CED &amp; 100% Conventional</td>
<td>3924.2 kJ/km</td>
<td>0.051 g/km</td>
<td>0.015 g/km</td>
<td>1.394 g/km</td>
<td>284.9 g/km</td>
</tr>
<tr>
<td>(2)</td>
<td>0% CED &amp; 100% EAD-Only</td>
<td>3737.5 kJ/km</td>
<td>0.044 g/km</td>
<td>0.013 g/km</td>
<td>1.254 g/km</td>
<td>271.3 g/km</td>
</tr>
<tr>
<td>Reductions ratio with respect to</td>
<td></td>
<td>Sce.(1)</td>
<td>Sce.(2)</td>
<td>Sce.(1)</td>
<td>Sce.(2)</td>
<td>Sce.(1)</td>
</tr>
<tr>
<td>(3)</td>
<td>10% CED &amp; 90% Conventional</td>
<td>-0.3%</td>
<td>-5.4%</td>
<td>7.3%</td>
<td>0.0%</td>
<td>7.8%</td>
</tr>
<tr>
<td>(4)</td>
<td>20% CED &amp; 80% Conventional</td>
<td>-3.1%</td>
<td>-8.2%</td>
<td>14.6%</td>
<td>7.9%</td>
<td>15.4%</td>
</tr>
<tr>
<td>(5)</td>
<td>30% CED &amp; 70% Conventional</td>
<td>-4.0%</td>
<td>-9.2%</td>
<td>20.7%</td>
<td>14.5%</td>
<td>21.8%</td>
</tr>
<tr>
<td>(6)</td>
<td>40% CED &amp; 60% Conventional</td>
<td>-12.0%</td>
<td>-17.6%</td>
<td>25.6%</td>
<td>19.7%</td>
<td>26.2%</td>
</tr>
<tr>
<td>(7)</td>
<td>50% CED &amp; 50% Conventional</td>
<td>-6.5%</td>
<td>-11.8%</td>
<td>33.3%</td>
<td>28.1%</td>
<td>34.4%</td>
</tr>
<tr>
<td>(8)</td>
<td>60% CED &amp; 40% Conventional</td>
<td>-3.1%</td>
<td>-8.2%</td>
<td>37.9%</td>
<td>33.0%</td>
<td>39.6%</td>
</tr>
<tr>
<td>(9)</td>
<td>70% CED &amp; 30% Conventional</td>
<td>-0.9%</td>
<td>-5.9%</td>
<td>42.5%</td>
<td>38.0%</td>
<td>44.3%</td>
</tr>
<tr>
<td>(10)</td>
<td>80% CED &amp; 20% Conventional</td>
<td>3.9%</td>
<td>-0.9%</td>
<td>46.9%</td>
<td>42.8%</td>
<td>49.2%</td>
</tr>
<tr>
<td>(11)</td>
<td>90% CED &amp; 10% Conventional</td>
<td>6.5%</td>
<td>1.8%</td>
<td>49.9%</td>
<td>46.0%</td>
<td>51.0%</td>
</tr>
<tr>
<td>(12)</td>
<td>100% CED</td>
<td>7.1%</td>
<td>2.5%</td>
<td>54.6%</td>
<td>51.1%</td>
<td>56.7%</td>
</tr>
</tbody>
</table>
COOPERATIVE MERGING AT HIGHWAY ON-RAMPS → SAFETY BENEFIT
Cooperative Merging at Highway On-Ramps

- **Drawbacks of traditional on-ramp merging systems**
  - Obstructed vision of drivers
  - Late merging decision
  - Extreme speed changes

(source: Google Map)
Cooperative Merging at Highway On-Ramps

- **Cooperative merging at highway on-ramps**
  - Take advantage of V2V and I2V communication
  - Adopt “ghost vehicle” concept
  - Complete longitudinal formation before merging

Cooperative Merging at Highway On-Ramps

• **System Architecture**

- Vehicle Sequencing Protocol
  - Max reachable speed
  - Estimated arrival time
  - Vehicle sequence identification

- Vehicle Longitudinal Control

- Distributed consensus algorithm
Cooperative Merging at Highway On-Ramps

• System Workflow
Cooperative Merging at Highway On-Ramps

- Simulation in game engine Unity

Video captured during simulation

Key steps during the simulation
Cooperative Merging at Highway On-Ramps

- Compare with human-in-the-loop simulation
- 4 different drivers contribute 20 simulation runs on the driving simulator
Cooperative Merging at Highway On-Ramps

- **Savings in terms of travel time, energy consumption, and pollutant emissions**
- **Calculated for all 7 vehicles in the network**

<table>
<thead>
<tr>
<th></th>
<th>Travel time (s)</th>
<th>Energy (KJ)</th>
<th>HC (g)</th>
<th>CO (g)</th>
<th>CO$_2$ (g)</th>
<th>NOx (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperative merging</td>
<td>218.14</td>
<td>9154.0</td>
<td>0.0094</td>
<td>1.1737</td>
<td>651.29</td>
<td>0.0440</td>
</tr>
<tr>
<td>Human-in-the-loop</td>
<td>233.58</td>
<td>9930.6</td>
<td>0.0200</td>
<td>2.8192</td>
<td>706.54</td>
<td>0.0759</td>
</tr>
<tr>
<td>Reduction percentage</td>
<td>6.6%</td>
<td>7.8%</td>
<td>53.0%</td>
<td>58.4%</td>
<td>7.8%</td>
<td>42.0%</td>
</tr>
</tbody>
</table>
Cooperative Merging at Highway On-Ramps

• Conducting field implementation using real vehicles
CONCLUSIONS AND FUTURE WORK
Main Contributions of the Dissertation

• Developed a high-level **architecture** for agent-based distributed cooperative vehicle-infrastructure systems (CVIS)

• Proposed cooperative automation **applications** in the CAV environment under V2V and/or I2V communication, with each of them bringing one or more benefits to the transportation system

• Developed motion control **algorithms** to realize the desired movements of CAVs in the proposed CAV applications, where algorithms were analyzed qualitatively and quantitatively by various simulation approaches
Future Work Based on the Dissertation

• **Build a more reliable architecture for CVIS**
  • Conduct fault detection/isolation regarding communication impairments or cyberattacks
  • Temporarily/smoothly switch to degraded modes of control, depending less on communication
  • Maintain string stability under special occasions

• **Identify and close the gap between research and implementation**
  • Theoretical research results need to be tested under various realistic conditions to identify this gap
  • Could be both labor-intensive and time-consuming

• **Develop more ready-to-market CVIS with mixed traffic environment**
  • CVIS that work for a pure CAV environment do not necessarily work for a mixed traffic environment, given the uncertainties introduced by other vehicle types in the environment
  • Future development of CVIS may take advantages of advanced sensing & communication technology
Publications Related to the Dissertation


Publications Related to the Dissertation


[14] “A Survey on Cooperative Longitudinal Motion Control of Multiple Connected Automated Vehicles,” IEEE Intelligent Transportation Systems Magazine, under review


Publications Related to the Dissertation

- **Published**: 4 journal articles, 9 conference proceedings (11/13 as the first author)
- **Under review**: 2 journal articles, 2 conference proceedings, 4 U.S. patents
- **Reviewed** more than 50 journal articles and conference proceedings as a reviewer
- Thanks for the hard work from all the co-authors:

UC Riverside

UC Berkeley  Tsinghua University  Toyota Motor North America  Volvo Group North America
Acknowledgement

- Thanks for the support from all members of TSR at CE-CERT

Thank you all! QUESTIONS?