COOPERATIVE APPLICATIONS ON A MANAGED LANE

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INTRODUCTION

• Research Team
  • Federal Highway Administration (FHWA)
  • Leidos, Inc.
  • University of Cincinnati
  • California PATH

• Operations Team
  • Virginia Department of Transportation (VDOT)
  • Transurban

• Lead Investigators
  • Jiaqi Ma, Ed Leslie, Steve Shladover, Zhitong Huang, Robert Ferlis
OUTLINE

• Introduction & Objectives
• Concept of Operations
• Simulation Analysis
• Field Experiment
• Conclusions and Next Steps
OBJECTIVES

Use emerging automation technologies to:

- Reduce recurring congestion on urban freeways
- Improve reliability, reduce travel times, and improve safety
- Reduce fuel consumption and emissions
- Maintain and increase car-sharing options
APPLICATIONS

• Advisory and longitudinal control:
  • Speed Harmonization
  • Platooning
  • Cooperative merging

• Significant US DOT research investments
• Collaboration with automotive OEM’s and states
CAV MANAGED LANE

DSRC (e.g., RSUs)

Detectors (ITS)

TMC

VAD

CAV

V2I

V2V

CAV Managed Lane

General Purpose Lane

Direction

250 m

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STAKEHOLDERS

• Roadway owners and operators, technology providers, vehicle owners

• All stakeholders must have incentives to participate and clear expectations

• Use of roadways must be limited to vehicles that improve utilization

• Need agreement or “compact” with users to set expectations, encourage investments, and measure performance
CONFIGURATION

• Isolation of traffic flow and restriction of access through physical barriers and is favorable to improve CV/CAV traffic stream.

• Managed lanes are operationally primed with vehicle eligibility restrictions and communications infrastructure.

• Managed lanes are technologically and organizationally primed to support CAV operation:
  - toll systems and subsystems
  - systems engineering processes
  - back office and Traffic Management Center (TMC)
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Typical Managed Lane Design/ Configuration Attributes</th>
<th>Overall Favorability for CAV Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Access</td>
<td>Barrier Separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOV Lane (no tolling)</td>
<td>Typically concurrent flow; Less likely to have direct access ramps;</td>
<td>Likely to have continuous access with no physical barrier separation</td>
</tr>
<tr>
<td>HOT Lane</td>
<td>Likely to have direct access ramps; limited entry and exit points</td>
<td>Likely to have physical barrier separation (pylons or concrete barrier)</td>
</tr>
<tr>
<td>Truck and Bus Lane</td>
<td>Different access characteristics exist</td>
<td>Likely to have physical barrier separation</td>
</tr>
<tr>
<td>Express Lane/ Express Toll Lane</td>
<td>Likely to have direct access ramps or weaving lanes</td>
<td>Likely to have physical barrier separation (pylons or concrete barrier in some deployments)</td>
</tr>
<tr>
<td>Dynamic Shoulder Use</td>
<td>No direct access ramps</td>
<td>Typically no physical barrier separation</td>
</tr>
</tbody>
</table>

Note: CAV = connected and automated vehicle. HOT = high-occupancy toll. HOV = high-occupancy vehicle.

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A POSSIBLE SCENARIO

• **Existing** HOV/HOT lane in a congested (peak period, at least) urban corridor

• Very simple topology, with long distances, controllable entry points, and limited (maybe no) exits until the end

• Limit use to vehicles equipped for:
  • Platooning and speed harmonization
  • High occupancy tolls (HOT)
  • Registered car pools
  • HOT users with DSRC and/or transponders
  • Other vehicles with CACC and speed harmonization capabilities
  • Limit carpool/SU based on random selections, tightening over time, to encourage CACC conversion?
A SINGLE-LANE MANAGED FACILITY DEDICATED EXCLUSIVELY TO CV/CAV OPERATION

• **Facility features**
  - Urban corridor with peak period congestion.
  - HOT lanes with dedicated entry and exit points and physical barrier separation.
  - Existing intelligent transportation system (ITS) infrastructure: traffic detectors installed before and after each merging point.
  - TMC data center and server for traffic monitoring and management.

• **Technological features**
  - DSRC-based communication systems (e.g., RSUs) installed at least every 250 meters along the freeway for continuous two-way V2I communication.
  - Automated ramp vehicle control with or without closed-loop ramp metering.
  - Real-time data communicated via DSRC—along with traditional data from traffic detectors installed upstream and downstream each merging area.
  - Central server located at the TMC and upgraded to accommodate new CAV technologies, including processing CAV data and running new CAV algorithms for the bundled application.
A SINGLE-LANE MANAGED FACILITY DEDICATED EXCLUSIVELY TO CV/CAV OPERATION

• **Operational features**
  • All vehicles that use the ramp and facility (**HOVs as well as travelers willing to pay**) would be:
    • Registered
    • DSRC-equipped
  • Eligibility rules are only for peak periods.
  • Speed limits are higher for the managed lane than the general purpose lanes to further improve throughputs.
    • (In some cases, higher speed limit does not increase throughput – it declines when get higher because of the need for longer following distances speeds.)

• **Operational Policies to Encourage Market Penetration of CAV**
  • *Incentives and toll discount:* Incentivizing CAV vehicles through toll concessions or rebates during specific time-periods
  • *Adjust existing occupancy policies to accommodate additional CAV traffic:*
    • Raise HOV 2+ restriction to HOV 3+ during peak periods alongside toll concessions for CAVs
    • Critical at managed lanes where HOV demand is already high and the addition of CAV traffic is likely to cause additional demand.
**HOW TO ORGANIZE A CACC PLATOON**

If D < threshold

\[ a_{sv} = k_2(d - t_{hw}v_{sv} - L) + k_3(v_l - v_{sv}) \]

If time gap > 2 s

\[ a_{sv} = k_1(v_f - v_{sv}) \]

Else

\[ v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \]

\[ a_{sv}(t) = \left( v_{sv}(t) - v_{sv}(t - \Delta t) \right) / \Delta t \]

\[ e_k(t) = d(t - \Delta t) - t_1 v_{sv}(t - \Delta t) - L \]

\[ \dot{e}_k(t) = v_l(t - \Delta t) - v_{sv}(t - \Delta t) - t_1 a_{sv}(t - \Delta t) \]

\[ d_{REQ} = -0.165 + 0.685 \cdot d_l + 0.080 \cdot \zeta - 0.00889 \cdot (v_{sv} - v_l) \]

\[ \zeta = \begin{cases} 
1 & v_l > 0 \\
0 & \text{otherwise} 
\end{cases} \]

Liu et al. (2017)
CACC PLATOON

CACC Platoon, maximum size = 10

Inter platoon gap

Intra platoon gap

Hysteresis

1.5 s < gap < 2 s

0.6 ~ 1.1 s
COOPERATIVE MERGE

Scanning gap

Release onramp vehicle

Virtual Platoon

Keep gap

VL
COOPERATIVE MERGE (CONT’D)

Onramp vehicle merging

Keep gap

Merging

Gap regulation

Direction

Keep gap

Direction

Direction

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(a) Benchmark without trajectory smoothing.

(b) CAV-based trajectory smoothing.
simulation

COOPERATIVE APPLICATIONS ON A MANAGED LANE
SIMULATION OVERVIEW

• Simulation on two networks
  • Synthetic merging segment (similar to the field experiment site)
  • On-going: Calibrated I-66 simulation network with hypothetical managed lanes

• Questions
  • Capacity enhancement under different MP
  • Operational insights
SIMULATION

6-Vehicle CACC String

Lead Vehicle in CACC String (CAV or VAD)

1.5 second Inter-platoon gap to facilitate merge

~0.6 second Intra-platoon

1.5 second Inter-platoon gap to facilitate merge

Merging Vehicle

Identified Gap
FLOW-DENSITY DIAGRAMS
PIPELINE CAPACITY CHANGES UNDER DIFFERENT MARKET PENETRATION

Max = 3604 vplph
# SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>MP</th>
<th>ML Vol. (v/l/h)</th>
<th>Merge Vol. (v/l/h)</th>
<th>Throughput (Coop / Non-coop) (v/l/h)</th>
<th>Avg. Delay (Coop / Non-coop) (v/l/h)</th>
<th>Pipeline Capacity (v/l/h)</th>
<th>Increase of Throughput</th>
<th>Reduction of Average Delay</th>
<th>Reduction From Pipeline Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>2800</td>
<td>389</td>
<td>3184</td>
<td>32.01</td>
<td>3288</td>
<td>11.72%</td>
<td>80.46%</td>
<td>-3.16%</td>
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<td>2850</td>
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<tr>
<td>70%</td>
<td>2700</td>
<td>240</td>
<td>2924</td>
<td>44.74</td>
<td>3192</td>
<td>16.12%</td>
<td>60.01%</td>
<td>-8.40%</td>
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<td></td>
<td></td>
<td>2518</td>
<td>111.87</td>
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<td></td>
<td>-21.11%</td>
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<tr>
<td>30%</td>
<td>2050</td>
<td>475</td>
<td>2405</td>
<td>33.36</td>
<td>2412</td>
<td>1.73%</td>
<td>63.89%</td>
<td>-0.29%</td>
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<td>2364</td>
<td>92.40</td>
<td></td>
<td></td>
<td></td>
<td>-1.99%</td>
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<tr>
<td>0%</td>
<td>1970</td>
<td>382</td>
<td>N/A</td>
<td>N/A</td>
<td>2316</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
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<td></td>
<td></td>
<td>2073</td>
<td>132.23</td>
<td></td>
<td></td>
<td></td>
<td>-10.49%</td>
</tr>
</tbody>
</table>
Field experiment

COOPERATIVE APPLICATIONS ON A MANAGED LANE
STAKEHOLDERS

• Testing was made possible by a Memorandum of Understanding (MOU) between FHWA, Virginia DOT, and Transurban
  • FHWA: research sponsor
  • VDOT: roadway owner
  • Transurban: roadway operator

• Close coordination between the three stakeholders, and Virginia State Police, was essential to success
CARMA FLEET

• Level 1 Automation
• 5.9 GHz DSRC
• Cellular/LTE
• Precision GPS
• Data Collection and Processing
• Radar
CONTROL SYSTEM

- Low-level interface implemented on real-time platform
- Control algorithms built on CARMA with ROS

**GNSS**: Global Navigation Satellite System  
**BSM**: Basic Safety Message  
**CAN**: Controller Area Network
INTEGRATED HIGHWAY PRIORITY PROTOTYPE

• Control software development and integration into new CARMA Platform
  ✓ Integrates multiple freeway algorithms
  ✓ Will use algorithms designed under a separate task
  ✓ Basic simulation before deploying to vehicles

• Validation testing support at Aberdeen Test Center

• Support the public road test
TEST ROUTES

NO TRAFFIC

LIGHT TRAFFIC

SOUTHBOUND

NORTHBOUND
MOBILE DSRC ROADSIDE UNIT

• Provides infrastructure component of cooperative merge
• Cellular connection for remote administration
SOUTHBOUND MERGE

4 Vehicle Platoon

Police Escort

Merge Vehicle
NORTHBOUND MERGE

Merge Vehicle

4 Vehicle Platoon

Police Escort

NC

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TEST CASES

• Manual Case: As the last vehicle of the platoon passes 300 meters ahead of the merge area, release merging vehicle from waiting area.

• Automated Case: As platoon approaches merge point
  • RSU detects platoon
  • Calculates a merge point
  • transmits information to the waiting merging vehicle.
  • The merging vehicle follows trajectory (speed) from RSU to meet the requirements
PRELIMINARY RESULTS

4 VEHICLES LEAVE STAGING AREA

4 VEHICLES FORM PLATOON

MERGE VEHICLE IN POSITION

SPEED HARM ZONE BEGINS

MERGE VEHICLE RELEASED

PLATOON DISSOLVES

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PRELIMINARY RESULTS

I-95 testing - (20180625-104407)

- 4 vehicles leave staging area
- 4 vehicles form platoon
- Merge vehicle in position
- Speed harm zone begins
- Merge vehicle released
- Platoon dissolved
- Speed harm zone begins
- Merge vehicle in position
- Platoon formation

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LESSONS LEARNED

• Operations and Research are different mindsets
  • Research team needs to plan more than usual
  • Operations team needs to be more flexible than usual

• Cellular connection is not guaranteed

• Virginia State Police can provide a wealth of practical knowledge

• Communication is key before, during, and after
FOR MORE INFORMATION...

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