Breakout Session # 23: CAV Early Deployment Alternatives

Summary of Key Findings and Lessons Learned

FHWA CAV Research Results and Next Steps to Deployment

• Cooperative Adaptive Cruise Control – Light Vehicle Platooning (longitudinal control)
  • Proven concept feasibility
  • Single OEM platform
  • Next steps: platoon stability, performance character, light/heavy vehicle stream, infrastructure

• Signalized Intersection Approach and Departure - GlidePath
  • Single vehicle, single intersection
  • 7% fuel improvement manually, 22% fuel savings
  • Next steps: two vehicles, two intersections

• Speed Harmonization
  • Modeling streams of vehicles receiving speed control recommendations from TMC
  • Reduce congestion and potential to double vehicle capacity
  • Next steps: system-wide benefits from CAV at various deployment scales
**Breakout Session # 23: CAV Early Deployment Alternatives**

**Recommended Action Items**

- Begin to address real-world deployment issues
- CACC – Light Vehicle Platooning (longitudinal control)
  - Ingress/Egress merging; infrastructure impact/premature damage
  - Optimum size of platoon; gap/headways; optimum vehicle performance criteria to engage; handshake
  - Early transition using managed lanes; Dedicated lane? Left side? Right Side?
  - Lane change issues: visibility limitations of lead vehicle
- Signalized Intersection Approach and Departure - GlidePath
  - Mixed Traffic impacts
  - Connected and non-connected vehicles in stream
  - Vehicle performance characteristics in algorithm for each vehicle
- Speed Harmonization
  - Operating agency engagement early in field testing
  - Benefits that justify investment
- Cybersecurity
  - Infrastructure vulnerability; vulnerable vectors into vehicle as messages/requests go to vehicle
  - Federal DOT Role unclear
Performance Analysis of CACC Impact on Freeway Traffic through Simulation

Xiao-Yun Lu (Ph.D.), Steven E. Shladover (Sc.D.), Hao Liu (Ph.D.), Hani Ramezani (Ph.D.), Dali Wei (Ph.D.), David Kan, Fang-Chieh Chou

PATH, U. C. Berkeley

7/11/2017
Outlines

- Traffic Modeling in Simulation
- Managed Lane Impact for CACC Operation
- CACC Operation Performance
- Conclusion
Traffic Modeling in Simulation - Baseline

- Simulation platform: Aimsun
- Freeway corridor SR 99 NB modeling with field data
  - Elk Grove ➔ Intersection with SR50
  - 16 onramps
  - 11 off-ramps
  - with metering
- 5 minute onramp and most upstream mainline flow data of PeMS with some clean-ups and modifications used for demand
Traffic Modeling in Simulation - Parameter Selection

- **Model parameters determination:**
  - Reaction time: 0.8s
  - Max acceleration/deceleration: $2 \text{m/s}^2 / -4 \text{m/s}^2$
  - Mean desired headway: 1.4s
  - Lane changing anticipatory distance: 1.5km

- **Special treatments:**
  - Most upstream bottleneck: reaction time 1.0s
  - Most downstream bottleneck: reaction time 0.4s
  - Lane changing anticipatory distance 0.6km

- **CACC Driver Behavior Modeling**
  - Passenger car: based on 4 CACC car test data
  - Driving mode: CC, ACC, and CACC
Traffic Modeling in Simulation – Baseline Calibration

- Flow comparison with field data:
  - GEH < 5 for > 85% of time
  - *It is satisfied at more than 95% of time*

- Speed comparison with field data (contour plot):

![Field Data](image1)

![Simulation Data](image2)
Managed Lane Impact for CACC Operation - DLC

- Discretionary Lane Change (DLC) Restriction for CACC veh: can increase the capacity at higher CACC%, but has little effect on merging (encouraging platoon keeping)

- Little impact on the capacity at merge since it cannot reduce the disturbances by the ramp mandatory LC
Managed Lane Impact for CACC Operation

- Managed Lane (ML) for CACC Veh: Changing access strategy \(\Rightarrow\) reduce the number of mode switch \(\Rightarrow\) can increase the capacity at lower CACC%  
  - Pros: Uninterrupted CACC string operation in the managed lane  
  - Cons: Possible congestion at ingress/egress; Drivers may miss the entrance/exit
Managed Lane Impact for CACC – Onramp Demand Increase

- Mainline traffic input: same as the capacity without ML
- On-ramp traffic input: 300, 600, 900, 1200, and 1500 veh/h
- CACC%: 40%, 60% and 80%
- Number of MLs: 1 ML for 40% CACC case; 1 and 2 MLs for 60% CACC case; and 1, 2, and 3 MLs for 80% CACC case

- ML increases the capacity at 40% and 60% CACC cases, especially when the ramp input is larger than 600 veh/hr
- It has little effect at 80% CACC case
CACC Operation Performance with ML, DLC & VAD

- VAD (Vehicle Awareness device; assumed 20% of manually driven vehicle) – has some positive impact
- Performance compared to 0% CACC:
  - VTT: total Vehicle Time Travelled
  - Distance mean speed

<table>
<thead>
<tr>
<th>CACC%</th>
<th>VTT Reduction</th>
<th>Speed Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>-0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>40%</td>
<td>-14.8%</td>
<td>14.1%</td>
</tr>
<tr>
<td>60%</td>
<td>-20.3%</td>
<td>21.3%</td>
</tr>
<tr>
<td>80%</td>
<td>-23.1%</td>
<td>25.8%</td>
</tr>
<tr>
<td>100%</td>
<td>-23.8%</td>
<td>27.9%</td>
</tr>
</tbody>
</table>
CACC Operation Performance with ML, DLC & VAD

- Speed contour plots: improvement pattern vs. CACC market penetration
- At 40% CACC, the most severe bottleneck near post-mile 292 is completely removed
- CACC also improves the corridor traffic
Conclusion

- CACC string operation with public traffic on freeway could significantly improve overall traffic performance by increasing mainline capacity if we adopt:
  - Managed Lanes: aggregating CACC vehicles in certain lanes such as HOV Lane(s)
  - Restricting Discretionary Lane Changes: keeping CACC strings
  - with VAD deployment: act as leader vehicle of a CACC string
- It has some but not significant improvement in merging area – needs more research
Cooperative Automation – Improving System Performance

Welcome to session 23
AV Early Deployment Alternatives

Dale Thompson
Lead Research Engineer
FHWA Office of Operations Research & Development
Presentation Overview

Who we are
  • Saxton Transportation Operations Laboratory (STOL)

Our Focus
  • Cooperative Automation Research
  • Infrastructure Leadership

Partnership Opportunities
  • Collaboration

Q&A
Saxton Transportation Operations Laboratory
Tuner-Fairbank Highway Research Center

- Nation’s premier surface transportation research facility
- Home to eminent transportation scholars & state of the art research vehicle fleet
Saxton Transportation Operations Laboratory
Innovation Drive - Urban Testing Environment
Cooperative Automation Research Focus

**ROAD/VEHICLE AUTOMATION**
- Connected/Automated Light Vehicle and Truck Platooning
- Signalized Intersection Approach and Departure
- Automated Traffic Flow Optimization
- Proof-of Concepts
  - Lane Change, Merging & Weaving Operations

**CONNECTED VEHICLES**
- V2I Communications
- V2V Communications
- Hardware Interoperability Testing
- Software Applications
Automated Vehicles...on a road near you?

Momentum towards full automation

But without cooperative communications, we can’t unlock system-level benefits.
Most major manufacturers currently offer Level 1 systems (e.g., lane keep assist, adaptive cruise control);

some offer Level 2 systems (e.g., Tesla Autopilot, Audi Traffic Jam Assist).
Connectivity - Adding the binding tissue
And it has to work everywhere...all the time!
Anywhere, everywhere...all the time!
Remember the Ultimate Goal

• End game is not just about creating the perfect vehicle
• Vehicles have to work effectively within the transportation system and cater to all users & every scenario possible
What are we doing to achieve this...

• We are investing heavily in cooperative technology development
  – FHWA Cooperative Automation Research => Communication + Automation
• We are working on algorithms & test plans
• Help us build a robust connected infrastructure
FHWA Cooperative Automation Research

FHWA has been funding research into Level 1 applications

- **Connected/Automated Light Vehicle and Truck Platooning**
  Cooperative Adaptive Cruise Control (CACC) via Vehicle-to-Vehicle (V2V)

- **Signalized Intersection Approach and Departure GlidePath** via Vehicle-to-Infrastructure (V2I)

- **Automated Traffic Flow Optimization**
  Speed Harmonization via Vehicle-to-Infrastructure (V2I)

- **Proof-of Concepts**
  Lane Change, Merging and Weaving Operations
How Connectivity Helps – Connected/Automated Signalized Approach & Departure

- Test examines the environmental and fuel economy benefits of partial-automation
- Result: **22% fuel economy improvement** with partial automation versus 7% with manual driving
- Time saved from reducing start-up loss
- Imagine how much time & fuel can be saved across 300,000 signalized intersections nationwide
- We are doing more to bring technology like this to our roads

Credit: USDOT
How Connectivity Helps – Connected/Automated Light Vehicle

- Almost doubles the lane capacity
  - Reduced headways (0.6 seconds)
  - Reduced need for building additional infrastructure across the country
- Remember, new roads cost a lot (~ $2 million/mile)

Credit: USDOT/USArmy
How Connectivity Helps – Connected/Automated Truck Platooning

• Reduced drag improves fuel efficiency
• Faster responses to hard braking by preceding/lead vehicle

• Seamless freight transportation powers the economic engine
• Goods worth more than $49 billion each day moves everyday on our network
• Growing demand - 17 Billion tons (2012) to 25.3 Billion tons (2045)
All this leads to a lot of data...

As part of our research, we collect, analyze and share our data
  – Our intent is to share data

Comprehensive Test Plans

Somethings that work well and some don’t

Typical track day:
  • ~60GB data
  • ~100GB video
We do a LOT of testing...with our partners

- Wire Mounted Traffic Signals
- Closed-Loop Test Track
- Ramps
- Pole-Mounted Traffic Signal
- Flat Space Open Testing
- Skid Pad
- DSRC / Wi-Fi
- V2I Communications

- 4.5 mile long
- 207-foot wide tri-oval track with wide safety runoff areas
- Traffic Signals
- DSRC / Wi-Fi
- V2I Communications
Testing and Evaluation of Platooning Concepts to Identify Benefits for Mobility

- Understand the stability of platooning and interaction at highway interchanges involving merging, diverging and lane change to address bottlenecks

- Investigate the interaction between Light and Heavy vehicle platoons as truck platooning becomes more common on major corridors

- Develop performance characteristics for platooning with different vehicles types (i.e. Car, Truck, SUV, etc.) to support modeling and simulation

- Effects of platooning in traffic and role of infrastructure to reduce travel time and increase throughput
### Connected Automation Roadmap

#### Stakeholder Engagement
- **2016**: CACC / CAMP
  - Deployment Readiness
  - Field Operational Tests
- **2017**: EAD / CAMP
  - Proof-of-Concept
  - Demonstration
  - Benefits
- **2018**: Applied Research
  - Development
  - Testing
- **2019**
- **2020**
- **2021**
- **2022**
- **2023**
- **2024**
- **2025**

#### Proof-of-Concept, Demonstration, and Benefits
- **2017**: CACC Small Scale Test Phase 1 (CAMP)
- **2018**: CACC Small Scale Test Phase 2 (CAMP)
- **2019**: CACC High Performing Vehicle Streams (PATH)
- **2020**: CAV Level 2 – Merging, Lane Balancing Concepts
- **2021**: CAV Level 2 – Policy strategies and revised ConOps
- **2022**: CAV Level HAV – Policy strategies and revised ConOps
- **2023**: EAD (STOL & CAMP)
- **2024**: EAD (STOL & CAMP)
- **2025**: EAD (STOL & CAMP)

#### Applied Research, Development, and Testing
- **2016**: EAD / CACC FO T, CAV (ATCMTD)
- **2017**: NIDTLR Robotics
- **2018**: NIDTLR Robotics
- **2019**: NIDTLR Robotics
- **2020**: NIDTLR Robotics
- **2021**: NIDTLR Robotics
- **2022**: NIDTLR Robotics
- **2023**: NIDTLR Robotics
- **2024**: NIDTLR Robotics
- **2025**: NIDTLR Robotics

#### Deployment Readiness, Field Operational Tests, Early Deployments
- **2016**: CAV AMS Test (STOL)
  - Eco Approach Departure (EAD)
  - Phase 1 (CAMP)
- **2017**: EAD (STOL & CAMP)
- **2018**: EAD (STOL & CAMP)
- **2019**: EAD Phase 2 (CAMP)
- **2020**: EAD Phase 2 (CAMP)
- **2021**: EAD Phase 2 (CAMP)
- **2022**: EAD Phase 2 (CAMP)
- **2023**: EAD Phase 2 (CAMP)
- **2024**: EAD Phase 2 (CAMP)
- **2025**: EAD Phase 2 (CAMP)

#### Policy, Guidance, Support
- **Current**: EAD Phase 2 (CAMP)
  - CAV AMS Tool, Phases 3 & 4
  - CAV Prototype 1 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 2 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 3 – Testing and Evaluation Capability (Level 1)
  - CAV AMS Tool, Phases 3 & 4
  - CAV Prototype 1 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 2 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 3 – Testing and Evaluation Capability (Level 1)

- **Planned**: EAD Phase 2 (CAMP)
  - CAV AMS Tool, Phases 3 & 4
  - CAV Prototype 1 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 2 – Testing and Evaluation Capability (Level 1)
  - CAV Prototype 3 – Testing and Evaluation Capability (Level 1)

---

**Current: **

**Planned:**
# Research Collaboration

The diagram illustrates the collaboration between ATC (Aberdeen Test Center), STOL (SAXTON Laboratory), and Volpe.

## ATC
- Testing
- Evaluation
- Data Acquisition

## STOL
- System development
- System integration

## Volpe
- Test Plan development
- Testing Oversight
- Data Analysis
Project Breakdown

• CARMA Platform Development
• Algorithm Re-hosting & Refinement
  – Platooning
  – Intersection approach and departure
  – Lane change & merge
  – Speed harmonization
• GlidePath Enhancement
• Integrated Highway Priority Prototype
• Connected Truck Prototype
CARMA Platform

Vehicle reusable/portable Control System Structure

Transportation Strategies

Environment Manager

Vehicle Interface Layer

Device Driver Layer

DSRC OBU
Positioning System
ADMAS

Android Device

Driver UI
Observer UI

Vehicle-specific

Host Vehicle

Controllers
DSRC antenna
GPS antenna
Sensors (e.g., Radar, Camera)

OEM (Original Equipment Manufacturer) Hardware (e.g., CAN)

Stop Data
EcoDrive Off
GO

Distance to Stop Bar
Start
Stop Bar
End

Selected Speed
Current Speed

Speeding Up

DSRC antenna
GPS antenna

ADMAS

Host Vehicle

CARMA Platform

Original Equipment Manufacturer Hardware

TSLP
GM
Ford

Toyota
Lexus
Honda
Acura

Nissan
Infiniti
Hyundai
KIA
VW
Audi
BMW
System Testing Convention

- **Verification test**
  - Planned & executed by **STOL**
  - Typically executed at TFHRC or FLETC
  - Informally verifies that functionality meets stated requirements
- **Comprehensive (Validation) test**
  - Planned & managed by **VOLPE**
  - Typically executed by **ATC**
  - Validates that the system meets customer needs
- **Exception:** GlidePath comprehensive tests will be performed by **STOL** at TFHRC
- **All test phases will involve defect fix & retest as needed**
Algorithm Evolutions

- Eco-approach and departure (GlidePath)
  ✓ Port of advanced algorithm to be developed under this project to the new architecture

- Platooning
  ✓ Update the CACC algorithm proven under earlier task order

- Lane change & merge
  ✓ Port the application to the new architecture

- Speed harmonization
  ✓ Second generation capability developed under an earlier task, but not yet fully tested
• Modify Ford Escape - add forward radar
• Update guidance algorithm
  ✓ Single vehicle traversing multiple intersections
  ✓ Accommodate a NCV in the intersection queue
  ✓ Integrate infrastructure sensing of queue discharge
• Validation testing at TFHRC
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 ATC

• Support the STOL 1 - Task Order 26
Connected Truck Prototype

- Mixed platoon – heavy truck with passenger cars
- Control software enhancement and integration
  - Implement CARMA platform hardware (PC, CAN interface, data acquisition, light bar, etc.)
  - Develop basic longitudinal control for heavy truck
  - Adapt the platooning algorithm to truck complexities
  - Preliminary functional testing at VTTI test track
- Validation testing support at ATC