Development and Assessment of CACC for Cars and Trucks

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Overview

• Cooperative ACC vs. Platooning
• History of CACC development and evaluation
• Traffic micro-simulation modeling
  – Manual driving behavior models
  – CACC and ACC vehicle following models based on full-scale vehicle test results
  – Simplified network for performance assessment
• CACC performance based on simulation results
• Truck CACC system development and evaluation
  – Experimental results
  – Traffic simulation results
Cooperative ACC vs. Platooning

- Cooperative vehicle following using V2V coordination
- SAE Level 1 automation, but could be extended higher
- V2V providing information beyond sensor line of sight
- Enabling coordination of vehicle actions for safety, smoothness and traffic flow stability

**Tightly-coupled platoon**
- First vehicle (or driver) supervises
- Joining/departing authorized by leader
- Constant clearance-gap separation
- Generally enables shorter gaps

**Cooperative ACC (CACC)**
- Ad-hoc combination of vehicles
- Drivers can join or depart at will
- Constant time-gap separation
Long-Term Significance of CACC Studies

- CACC likely to be first V2V cooperative automation to be deployed (trucks first, then buses and cars)
- Longitudinal control performance the same as higher levels of cooperative automation (good prediction of future automation system performance)
PATH History of Relevant Prior Research

- Development and evaluation of closely-coupled platoon systems from 1988-2003 (cars, trucks, buses)
- Caltrans-sponsored CACC development 2003-06 (2 Nissan FX-45s)
- Field testing of driver acceptance under FHWA EARP sponsorship, with Caltrans cost share 2007-2010
- Second-generation system development, under Nissan sponsorship 2010 – 2012 (4 Infiniti M56s)
- FHWA EARP Project “Using CACC to Form High-Performance Vehicle Streams” 2013-2017 (simulation results to be shown)
- FHWA STOL implementation of CACC on 5 Cadillac SRXs (2015)
- FHWA EARP Project “Partially Automated Truck Platooning”
Using CACC to Form High-Performance Vehicle Streams

- FHWA EARP Project, with Caltrans cost sharing
- U.C. Berkeley and TU Delft collaboration, using models from both
- PATH research team: Dr. Hao Liu, Dr. Xiao-Yun Lu, David Kan, Fang-Chieh Chou, Dr. Dali Wei
- Obtain authoritative predictions of traffic impacts of ACC and CACC at various market penetrations
  - Realistic ACC and CACC car-following models based on experimental data
  - Combining Berkeley and Delft micro-simulation models of traffic behavior
- Define strategies for managing ACC and CACC operations to achieve best traffic impacts
  - Concentrating them in managed lanes on the left
  - Using DSRC (VAD) vehicles as leaders even if not CACC capable themselves
  - Active local coordination as well as ad-hoc clustering
Modeling to Predict CACC Traffic Impacts

- Detailed micro-simulations to represent interactions with manually driven vehicles, including lane changing
- Baseline manual driving models – NGSIM Oversaturated Flow model (Berkeley) and MOTUS (TU Delft)
  - Extensive enhancements to both models to represent detailed vehicle-vehicle interactions accurately
  - NGSIM implementation in Aimsun, with SDK modules added
- ACC and CACC car following models derived from PATH-Nissan experiments on full-scale test vehicles
- Additional higher-level CACC maneuvering models
Manual Driving Model

- At each update interval, the driving mode is determined for each vehicle, and the speed, position and travel lane are updated based on the mode:
  - \textit{CF}: Regular car following mode
  - \textit{LC}: Lane change mode
  - \textit{ACF}: After lane changing car following mode
  - \textit{BCF}: Before lane changing car following mode
  - \textit{RCF}: Receiving car following mode
  - \textit{YCF}: Yielding (cooperative) car following mode
Manual Driving Model

The structure of the manual driving model

Start → Need LC? → No → Need YCF? → No → Need ACF? → Yes → ACF → Yes → YCF → No → BCF → Yes → LC

Need RCF? → Yes → RCF

Accept gap? → Yes → LC → No
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

- Length: 13 miles
- Morning peak: 6-9 AM
- 16 on-ramps
- 11 off-ramps
- Recurrent delay is mainly caused by high on-ramp demand
- On-ramps are metered

The 5-minute interval vehicle count and speed data observed at reliable detectors are used as the benchmark data.

- Detector: not considered in calibration
- Detector: considered in calibration
- Interchange
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

Geometry change: 3 lanes → 4 lanes

Major bottleneck with a busy on-ramp and a weaving area

Weaving bottleneck: more than half vehicles take the interchange to Highway 50, while there is heavy merging traffic from the upstream on-ramp

HOV lane and ramp metering activated during the morning peak

Modeling the complicated network in Aimsun
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

<table>
<thead>
<tr>
<th>Detector Location (post-mile)</th>
<th>Target</th>
<th>Cases</th>
<th>Cases Met</th>
<th>% Met</th>
<th>Target Met?</th>
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<tr>
<td>294.7</td>
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<td>915</td>
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<tr>
<td>295.3</td>
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<td>909</td>
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<td>Overall</td>
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<td>13020</td>
<td>12542</td>
<td>96.3%</td>
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</tr>
</tbody>
</table>

To get good GEH result, we must accurately model:

- Intensity and duration of the traffic congestion
- Congestion due to merging, diverging and weaving traffic
- Peak and non-peak traffic

\[
GEH(k) = \sqrt{\frac{2[M(k) - C(k)]^2}{M(k) + C(k)}}
\]

\(k\): ID of the 5-min time interval
\(M\): simulated flow
\(C\): observed flow
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

The calibrated model can accurately replicate the spatial and temporal characteristics of the traffic along SR99.
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

- Comparison of fundamental diagrams of simulated and field observed flow-density relationships
- Two sample replications at Station 292.8
Animation of Base Case (Manual Driving)

8400 vehicles/hour on mainline approach + 1200 vehicles/hour from onramp

30m

Q 120m

Acceleration lane = 155m
CACC and ACC Car-Following Models

- Data collected using programmed speed change profiles on first car, with three followers tracking it
- Simple models representing car following dynamics derived from test data using Matlab System Identification toolbox
- Model predictions of responses compared with test data to verify accuracy
Adaptive Cruise Control with and without V2V Cooperation (AACC and CACC)

Autonomous (no communication)  
at minimum gap of 1.1 s

Cooperative (V2V communication)  
at minimum gap of 0.6 s
Comparison of Performance

Autonomous (no communication)

Cooperative (V2V communication)
ACC Model

- **Time gap distribution**
  (from field test)
  - 1.1 sec  50%
  - 1.6 sec  20%
  - 2.2 sec  30%

- **Speed regulation**
  \[ a_k = 0.4(v_{k-1} - v_k) \]

- **Gap regulation**
  \[ a_k = 0.23(g_k - t_h v_k) + 0.07(v_{k-1} - v_k) \]
CACC Model Overview

- Desired time gap (DTG, sec)
- Number of vehicles in the preceding string (Np)
- Time gap (TG, sec)
- Desired speed (DSPD)
- Speed (SPD)

Activate CACC system

CACC Follower

True

CACC Leader

False

Is Np < 20? AND Is TG < 2.0?

Was in speed regulation mode?

True

Speed regulation

Track DSPD

False

Gap regulation

Track DTG

Is TG > 1.5 sec?

Is TG > 1.5 sec?

*The speed is always upper bounded by driver desired speed no matter what state vehicle is in.*
CACC Model – Form and Parameter Values

- **Speed regulation**
  \[ a_k = 0.4(v_{k-1} - v_k) \]

- **Gap regulation**
  \[ v_{cmd} = v_t + 0.45e_t + 0.0125\dot{e}_t \]
  \[ e_t = g_t - t_h v_t \]

  - \( g_t \): preceding gap (m)
  - \( t_h \): driver desired time gap (sec)
  - \( v_t \): subject vehicle speed (m/s)
  - \( v_{cmd} \): subject vehicle speed command (m/s^2)

Time gap distribution from field test

- 0.6 sec 50%
- 0.7 sec 25%
- 0.9 sec 10%
- 1.1 sec 15%
AACC Model Predictions and Test Results

Speeds
(Test above, model below)

Accelerations
(Test above, model below)
CACC Model Predictions and Test Results

**Speeds**
(Test above, model below)

**Accelerations**
(Test above, model below)
Additional Collision Avoidance Logic

- **CAMP forward collision warning algorithm**

Compute $d_{REQ}$

$d_{REQ} > 0$?

Yes

No warning, continue CACC mode

No

Assuming the subject vehicle adopts $d_{REQ}$ and the preceding vehicle keeps the current acceleration, compute the minimum clearance-gap required for the subject vehicle to avoid the rear-end collision.

Current gap < minimum gap?

Yes

Trigger alarm, switch to manual driven mode

No

$d_{REQ}$: acceleration required for the subject driver to avoid the rear-end collision
Simple Highway Network Layout for Assessing Key Performance Trends

- Four-lane mainline highway, traffic generated further upstream
- One-lane on-ramp, volume ranging from 300 to 1200 veh/hr
- One-lane off-ramp, volume ranging from 5% to 20% of mainline
- On-ramp and off-ramp are 1.5 km apart
- Simulate far enough upstream and downstream to stabilize results
Aspects of Performance Tested in Simulation

• Maximum downstream throughput achievable under various conditions
• Travel times and delays traversing the test section
• Effects of variations in:
  – ACC, CACC market penetration
  – On-ramp and off-ramp traffic volumes
  – Maximum allowable CACC string length
  – Minimum gap between CACC strings
  – Priority use of left-side managed lane
  – Availability of automated merge/lane change coordination
Simulation Results with CACC Operations

- Freeway capacity increases because of CACC string operation
  - Small probability of forming CACC strings under low CACC market penetration
  - CACC strings are often interrupted by lane change maneuvers in the traffic stream and interactions with heterogeneous traffic
- Traffic management strategies are needed to help create CACC strings and maintain their operation
Simulation Results – Traffic Management

- Traffic management strategies considered:
  - Discretionary lane change (DLC) restriction for CACC vehicles when they are in the CACC string—reducing disturbances from lane changes
  - CACC managed lanes (ML)—reducing interactions of CACC vehicles and manually driven vehicles and increasing concentration of CACC vehicles together
  - Equipping manually driven vehicles with Vehicle Awareness Devices (VAD)—creating more CACC strings under low CACC market penetration
Lane Capacity Increases for Different Strategies

- Quadratic increase of capacity as the CACC market penetration increases
- The ML strategy works best under the following conditions:
  - 40% CACC with 1 ML,
  - 60% CACC with 2 MLs,
  - 80% CACC with 3 MLs
- Different strategies are best under different CACC market penetrations
Throughput Limitations as On-Ramp Volume Grows

- Downstream throughput reduces as on-ramp traffic increases
- It maintains quadratic trend with CACC market penetration

The throughput is measured downstream from the merging area and averaged by lane.

Ramp traffic in veh/hr/lane
Mainline traffic volume equals the base case pipeline capacity shown in the previous slide.
Managed Lane Throughput Advantage

The ML strategy increases the capacity of the merging area
- Without ML, all freeway lanes became congested as the ramp traffic was loaded (capacity reduction)
- With ML, CACC vehicles concentrate in lane 4, leading to an effective use of the lane
- The general-purpose lanes become congested in both cases

Mainline input: 9600 veh/h, on-ramp input: 1500 veh/h
Lane 4 is the managed lane in the ML case
Results for Lane 1 and 2 are similar to those of lane 3
Effects of Management Strategies on Throughput at Merging Section

Throughput of the merging section with 40% CACC

- ML and VAD strategies can increase the throughput of the on-ramp merging area
  - ML redistributes traffic load across lanes—creating more gaps in the general purpose lane
  - VAD increases the queue discharging flow by enabling more CACC usage
- DLC restriction strategy has little effect because it does not change lane change behaviors of the merging traffic

Mainline upstream input: 9600 veh/h
Higher Exiting Traffic Impacts on Throughput

- Increase of capacity when CACC grows from 0% to 20% and off-ramp traffic > 15%
- When off-ramp traffic is more than 20% of mainline volume, traffic management strategy is needed to address the large exiting flow, especially for the 80% and 100% CACC market penetration cases.
Simulation Animations

40% CACC

40% CACC with ML

In both cases: mainline input—9600 veh/h, on-ramp input—1200 veh/h
Primary Findings from CACC Simulations (1/2)

- If CACC string length is not limited, strings grow very long, interfering with lane changing (limit to 10 vehicles)
- Choose inter-string clearance gap to balance between efficient use of space and leaving gaps to permit lane changing (1.5 s looks reasonable)
- Performance is sensitive to assumptions about propensity of drivers to change lanes to go faster (DLC)
- Managed lanes improve traffic conditions only in certain cases (when CACC market penetration and number of managed lanes are well matched)
Primary Findings from CACC Simulations (2/2)

- Throughput improvement is quadratic with CACC market penetration
- With CACC gap preferences from our field test, highway throughput could increase about 50% with 100% CACC
- Additional throughput increases need active merge and lane change coordination
Development and Testing of Truck Cooperative ACC System

- Project sponsored by Federal Highway Administration, Exploratory Advanced Research Program (EARP), with cost sharing from California Department of Transportation (Caltrans)
- Measuring energy saving potential and driver preferences for different gap settings
- Simulating impacts on traffic and energy use in a high-volume freight corridor
- PATH research team: Dr. Xiao-Yun Lu, Dr. Hani Ramezani, Dr. Shiyan Yang, John Spring, David Nelson
Cooperative Adaptive Cruise Control System

- Build on production Volvo ACC system
- Add V2V communication by 5.9 GHz DSRC
  - Vehicle location
  - Speed, acceleration, braking, commands
- Short gap settings enabled:
  - 0.6, 0.9, 1.2, 1.5 s
  - 57, 86, 114, 143 ft @ 65 mph
- Coordinated braking
Testing to Measure Energy Consumption

- International collaboration with Transport Canada and National Research Council of Canada
- Testing in Blainville, Quebec on 4-mile oval track
  - SAE standard test procedure
  - 64-mile continuous drive per run
  - 3 runs repeated and averaged
  - Auxiliary fuel tanks weighed on each run
Testing Procedures
Testing at 0.6 s Time Gap in Blainville
Energy Savings For 3-Truck CACC String Compared to Single Truck with Standard Trailer

Energy Saving with Standard Trailers, 65 mph

Average Savings, Standard and Aerodynamic, compared to Standard

- Trailing
- Middle
- Lead

fuel consumption reduction [%] (ref. to individual vehicle of same config.)

vehicle spacing [m]

time gap Δt [s]
Main Experimental Findings

- With standard trailers, trucks can save 5% energy on average in a three-truck CACC string
- With aerodynamic trailers, these savings grow to 12-14% compared to standard-trailer solo driving
- Drag savings not very sensitive to time gap values from 0.6 s to 1.5 s (57 to 143 ft. at 65 mph)
- Lead truck saves limited energy in this range of gaps.
- Third truck saves the most energy
- Effects of short gaps and aerodynamic trailers reinforce each other
- Further studies are needed for shorter and longer gaps
Simulating Impacts in a Congested Freight Corridor (I-710, LA-Long Beach)

• 16 miles of I-710 NB, coded in Aimsun plus additional features in SDK

• 21 off ramps & 20 on ramps

• Truck vehicle following models derived from truck experiment results
  
  (models will be published later)
Modeling I-710 Corridor in Aimsun

Example of restricted geometric conditions
Modeling I-710 Corridor in Aimsun

Example of a major on-ramp from I-105
Simulation Conditions

- Shortest desired gap for truck CACC: 0.6 sec
- 100% penetration rate for truck CACC, with cars all manual
- No lane change cooperation by trucks in CACC string
- Desired gap for trucks in manual mode: 1.5 sec
- Effects of desired gap & penetration rate, among other factors, will be studied
Simulation Results: Vehicle Speeds (with and without truck CACC)

Average speeds at 13 detector stations

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### Simulation Results: Vehicle Speeds (with and without truck CACC)

**Average speeds at 13 detector stations**

<table>
<thead>
<tr>
<th>Post Mile</th>
<th>Manual trucks &amp; cars</th>
<th>Truck CACC &amp; manual cars</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.45</td>
<td>-0.86</td>
</tr>
<tr>
<td>3</td>
<td>4.72</td>
<td>10.00</td>
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<tr>
<td>6</td>
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<td>0.00</td>
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<tr>
<td>17</td>
<td>-0.86</td>
<td>-0.86</td>
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</tbody>
</table>

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**Avg. Speed Improvement (mph):**

- Manual trucks & cars
- Truck CACC & manual cars
Simulation Results: Total Traffic Volume

Volume per lane (vphpl)
% Improvement

<table>
<thead>
<tr>
<th>Post Mile</th>
<th>Manual trucks &amp; cars</th>
<th>Truck CACC &amp; manual cars</th>
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<tr>
<td>17</td>
<td>3400</td>
<td>3460</td>
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</table>
Simulation Results: Truck Speeds

![Graph showing truck speeds and improvement](image_url)

**Simulation Results: Truck Speeds**

- **Post Mile:** Mileage along the x-axis, ranging from 2 to 17.
- **Speed (mph):** Speed along the y-axis, ranging from 0 to 70 mph.
- **Improvement (mph):** Improvement in speed due to CACC technology.

### Key Observations:
- **Manual trucks & cars:** Consistent with traditional driving conditions.
- **Truck CACC & manual cars:** Demonstrates improved speed and efficiency with the CACC technology.

#### Speeds and Improvements:
- **Post Mile 2:**
  - Manual: 3.76 mph
  - CACC: 10.76 mph (Improvement: 7.00 mph)
- **Post Mile 3:**
  - Manual: 3.52 mph
  - CACC: 10.76 mph (Improvement: 7.24 mph)
- **Post Mile 6:**
  - Manual: 7.15 mph
  - CACC: 7.62 mph (Improvement: 0.47 mph)
- **Post Mile 7:**
  - Manual: 10.76 mph
  - CACC: 7.10 mph (Improvement: 3.66 mph)
- **Post Mile 8:**
  - Manual: 4.38 mph
  - CACC: 7.15 mph (Improvement: 2.77 mph)
- **Post Mile 9.5:**
  - Manual: 12.33 mph
  - CACC: 10.00 mph (Improvement: 2.33 mph)
- **Post Mile 10:**
  - Manual: 11.78 mph
  - CACC: 12.33 mph (Improvement: 0.55 mph)
- **Post Mile 12:**
  - Manual: 26.73 mph
  - CACC: 12.78 mph (Improvement: 13.95 mph)
- **Post Mile 12.2:**
  - Manual: 6.36 mph
  - CACC: 12.78 mph (Improvement: 6.42 mph)
- **Post Mile 12.5:**
  - Manual: 5.28 mph
  - CACC: 12.78 mph (Improvement: 7.50 mph)
- **Post Mile 13:**
  - Manual: 5.28 mph
  - CACC: 1.00 mph (Improvement: -4.28 mph)

### Analysis:
- The CACC technology demonstrates significant improvements in speed and efficiency compared to manual driving conditions, especially in the early stages of the simulation.
- The improvements range from 2.33 mph to 13.95 mph, indicating that CACC can be highly effective in reducing traffic speeds and congestion.

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**Note:** For detailed analysis and further insights, please refer to the full report or presentation. This summary provides key highlights to understand the impact of CACC on truck speeds.
Simulation Results: Truck Traffic Volume
Simulation Results: Network Level Summary

- Average travel speed increased
  - 14.2% for trucks  (From 39.4 mph to 46.0 mph)
  - 5.6%  for cars     (From 44.6 to 47.3 mph)
  - 6.9%  for all     (From 43.8 to 47.1 mph)
Future Truck Simulation Studies

• Study operational effects of:
  — Lower market penetration rates
  — Longer desired gaps between trucks
  — Aggressive lane changers

• Network-wide effects such as
  — Travel time distribution
  — Effects on complete trips
  — Energy savings by trucks and all traffic
Concluding Comments

• Much to learn from full-scale testing of CACC vehicles combined with detailed simulations of traffic impacts
  – Complementary methods for handling different effects
  – Simulation models must be developed and used very carefully to produce realistic results
• Effects are subtle and require careful study
• V2V coordination is key to achieving traffic and energy saving benefits