Project ID: #eems031

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Traffic Micro-Simulation of Energy Impacts of CAV Concepts at Various Market Penetrations

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Lawrence Berkeley National Laboratory

DOE VTO Annual Merit Review
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ENERGY EFFICIENT MOBILITY SYSTEMS PROGRAM INVESTIGATES

MOBILITY ENERGY PRODUCTIVITY

THROUGH FIVE EEMS ACTIVITY AREAS

Advanced R&D Projects

Living Labs

Smart Mobility Lab Consortium

Core Evaluation & Simulation Tools

HPC4Mobility & Big Transportation Data Analytics

OVERVIEW

- **Timeline**
  - **Project start date: Jan 1 2017**
  - **Project end date: Jun 30 2019**
  - **Percent complete: 50%**
- **Budget**
  - **Total project funding $390K**
    - **100% DOE/VTO**
  - **Funding for FY 2017: $140K**
  - **Funding for FY 2018: $250K**
- **Barriers**
  - **To understand fuel saving benefits for traffic in a network with different levels of CACC vehicle market penetrations through simulation;**
- **Partners**
  - **LBNL (project lead)**
  - **UC Berkeley**
  - **ANL**

RELEVANCE AND OBJECTIVES

- **Relevance**
  - **Vehicle energy savings in real world traffic mainly affected by factors at three levels: (a) meso/macroscopic traffic patterns; (b) local vehicle following behavior; and (c) vehicle level: control & powertrain/drivetrain characteristics**
  - **Progressive market penetration of CAVs and Active Traffic Management (ATM) changes the traffic pattern significantly**
  - **Field test of CACC (Cooperative Adaptive Cruise Control) impact on energy savings is cost prohibitive**
- **Objectives**
  - **FY 17**
    - **Simulating energy saving benefit for CACC operation on a freeway pipeline section with simple lane management only**
    - **Simulating energy saving benefit for Truck CACC operation on urban freeway corridors**

CHALLENGES AND OBJECTIVES

- FY 18
  - To simulate energy saving benefit for Truck CACC Operation on a rural freeway corridor
  - To Simulate energy saving benefit for Truck CACC Operation on urban freeway corridors with Coordinated Ramp Metering (CRM), Variable Speed Limit/Advisory (VSL/VSA), and Coordinated Onramp Merging
  - To simulate energy saving benefit for CACC operation along an arterial corridor with multiple signalized intersections with coordinated traffic signal controls
- FY 19 (go/no-go)
  - To simulate energy saving benefit for CACC (both passenger cars and trucks) in a traffic network including both freeway corridor and arterial corridor(s) with (a) ATM on freeway; (b) coordinated signal control on arterial(s); and (c) coordination of the two subsystems

APPROACH – FY17

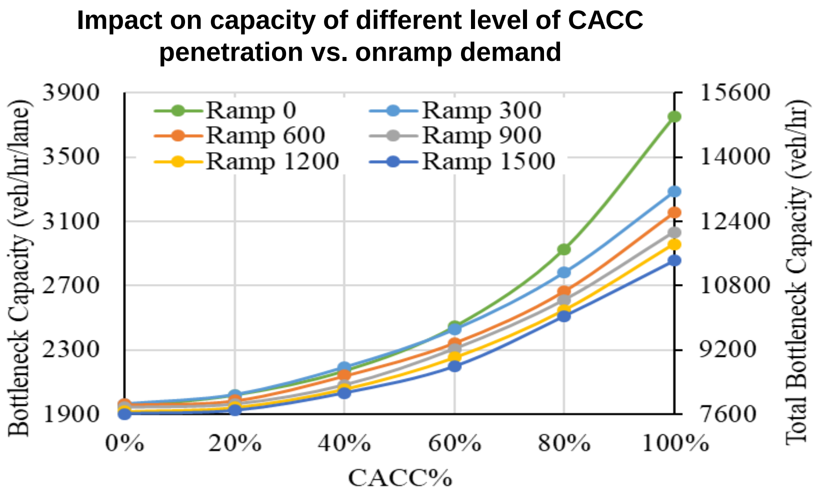
1. **Modeling and calibrating freeway corridor traffic for status quo using NGSIM data and newly collected PeMS data**
2. **Modeling passenger vehicle CACC string maneuvers: following other vehicles (with or without V2V comm.), dynamic interaction between strings, lane changing, merging from onramp, exiting from off-ramp**
3. **Adopting ATM strategies: simple Lane Management**
4. **Modeling truck CC/ACC/CACC: vehicle following behavior based on full-scale vehicle test data on freeway and test track**
5. **Calibrating/revising MOVES for truck fuel consumption analysis based CAN-Bus fuel rate data from field (freeway and test-track) tests**
6. **Modeling CACC operation at a simple signalized intersection**
7. **Evaluating fuel saving impact at a variety of market penetration levels for simple freeway pipeline section and a simple intersection**

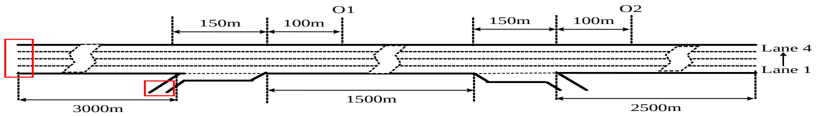
SCHEDULES – FY17

Evaluation of Energy Impacts of CAVs through Traffic Microsimulation - Schedule																
SAMRT Mobility CAVs Pillar FY 17																
Subtasks / Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Modeling and calibrating freeway corridor traffic for status quo using NGSIM data and newly collected PeMS data	■	■	■													
2: Modeling passenger vehicle CACC string maneuvers		■	■	■	■	■										
3. Adopting ATM strategies: simple Lane Management							■	■								
4. Modeling truck CC/ACC/CACC with field test data									■	■	■	■				
5. Calibrating/revising MOVES for truck fuel consumption analysis									■	■	■	■	■	■		
6. Modeling CACC operation at a simple signalized intersection															■	■
7. Evaluating fuel saving impact at a variety of market penetration levels for simple freeway pipeline section and a simple intersection													■	■	■	■

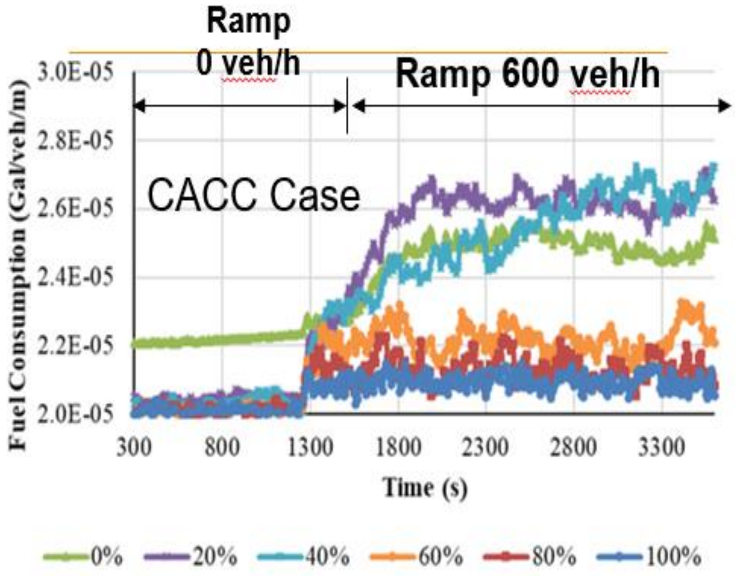
ACCOMPLISHMENTS: Freeway Pipeline Section – FY17

- **Impact on Capacity**



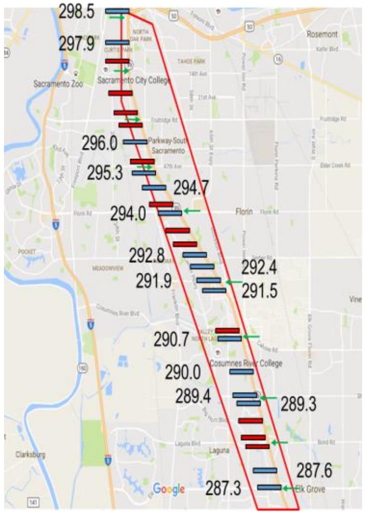


- **Impact on Energy Saving**
  - **MOVES model for estimating the fuel saving**
  - **Plot shows the normalized fuel rate in gallon per vehicle per meter**
  - **Energy consumption drops with CACC% increases**
  - **Connectivity and coordination are important**

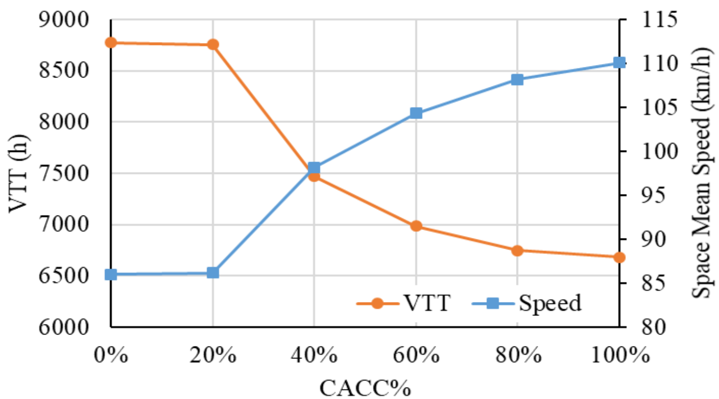


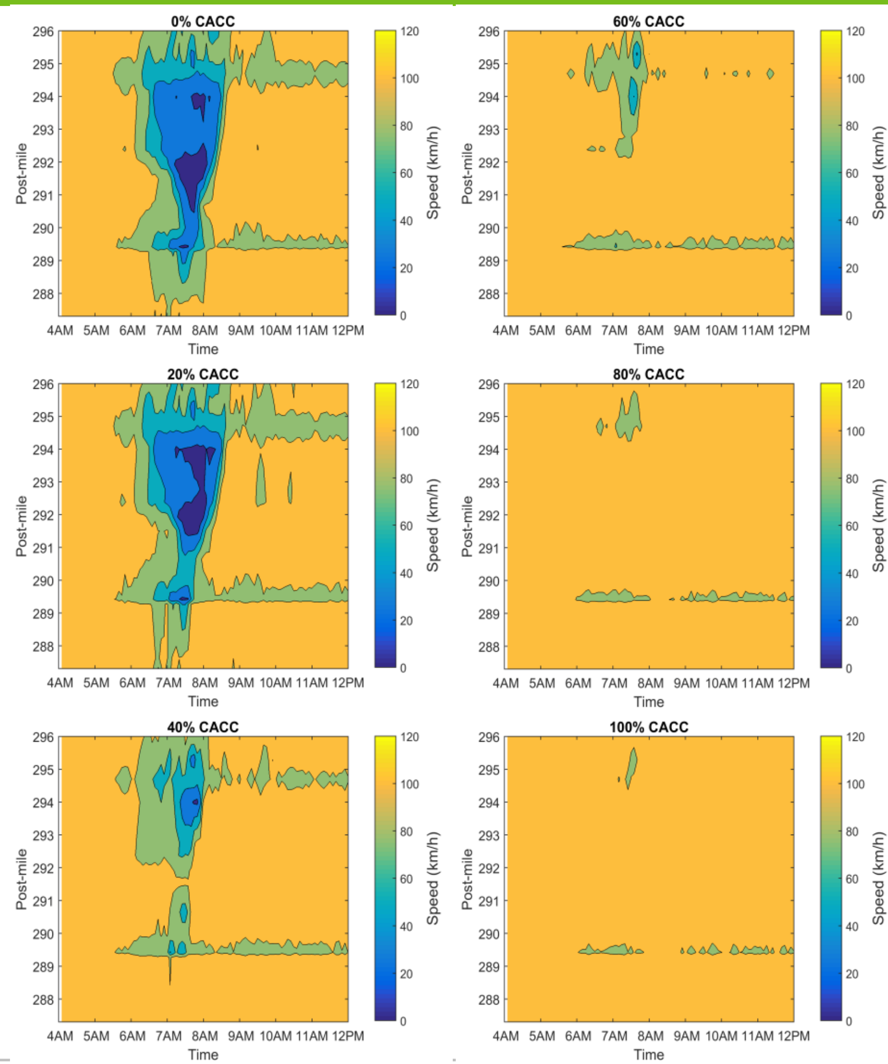
ACCOMPLISHMENTS: Freeway Corridor SR-99 NB – FY17

- VTT decreases and speed increases with the CACC market penetration.
- No significant change between 0% and 20% CACC case



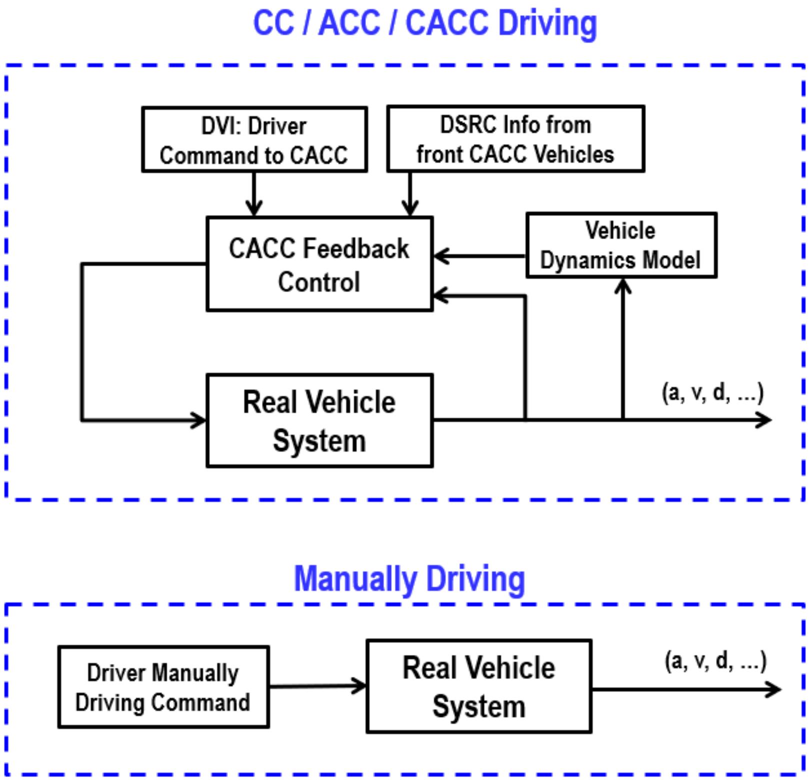
CACC penetration impact on Space Mean Speed





ACCOMPLISHMENTS: Truck CACC Modeling – FY17

- **Modeling dynamic interactions with other vehicle for microscopic traffic simulation: to build simple vehicle following model to replace complicated feedback control system based on test data**



ACCOMPLISHMENTS: Truck CACC Modeling – FY17

- To determine acceleration of the subject vehicle:

For Cruise Control (CC) mode:

$$a_m(t+1) = 0.3907\left(v_{ref}(t) - v(t)\right)$$

$v_{ref}(t)$: Reference speed

$v(t)$: Speed of the subject vehicle

For Adaptive CC (ACC) mode:

$$a_m(t+1) = 0.0561\left[d(t) - t_{des}^{ACC}v(t)\right] + 0.3393\left[v_{prec}(t) - v(t)\right]$$

$d(t)$: Distance gap

t_{des}^{ACC}: Desired time gap, selected to be 2.2 sec

$v_{prec}(t)$: Speed of the preceding vehicle

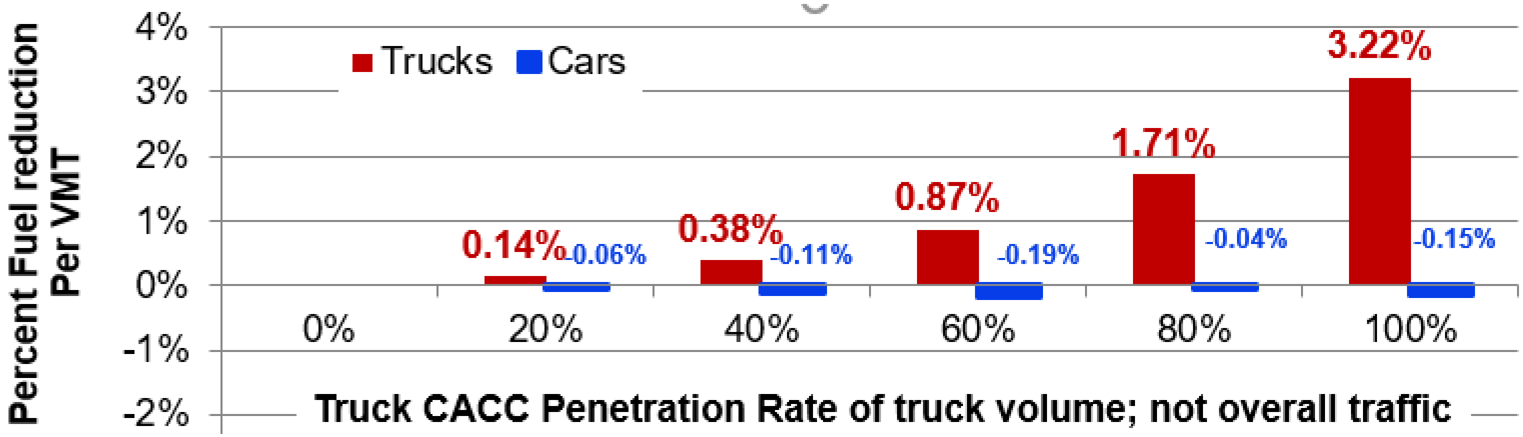
For Cooperative ACC (CACC) mode:

$$a_m(t+1) = 0.0074\left[d(t) - t_{des}^{CACC}v(t)\right] + 0.0805\left[v_{prec}(t) - v(t) - t_{des}^{CACC}a(t)\right]$$

t_{des}^{CACC}: Desired time gap, evenly distributed between 1.2 sec and 1.5 sec

ACCOMPLISHMENTS: Urban Freight Corridor I-710 – FY17

- **I-710 Configuration**
  - **Mostly 3 lanes; some section has 4~6 lanes**
  - **No HOV lane and no metering**
  - **20 on-ramps and 21 off-ramps**
- **Truck percentages between 15% ~ 19% of all traffic**
- **CACC Truck desired T-Gap: 1.2 sec (50%) and 1.5 sec (50%)**
- **Majority of the fuel savings comes from:**
  - **Mobility improvement & Aerodynamic drag reduction**



ACCOMPLISHMENTS: Revising/Refining MOVES – FY17

- **Calibrated for different weights: *13.5, 29.5, 50.6* tons**
- **Calibrated aerodynamic drag coefficient for truck at different positions**
- **Original MOVES model: Scaled Tractive Power (STP)**

$$STP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + (Mv_t a_t + g\, sin\theta)}{f_{scale} = 17.1}$$

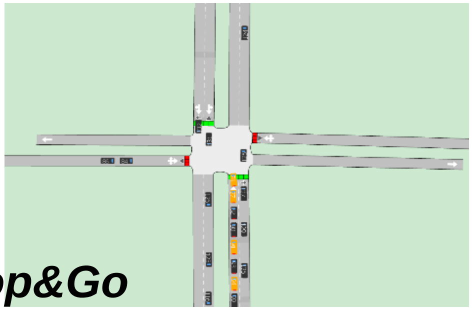
Model 1 (isolated truck): with weights M , and a given speed class; based on CAN Bus fuel rate data:

$$R(fuel\ rate) = a_0 + a_1 \cdot M + a_2 \cdot STP + a_3 \cdot STP^2$$

Model 2 (followers): for a given position and speed bin, fuel reduction is function of position and gap d in CACC string

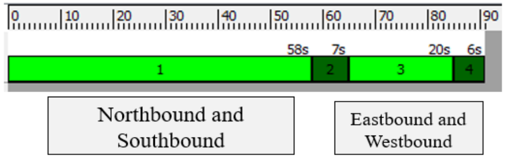
$$fuel\ reduction = f_0(d) + f_1(d) \cdot \log(STP_0 + 2.0)$$

ACCOMPLISHMENTS: Simple Signalized Intersection – FY17

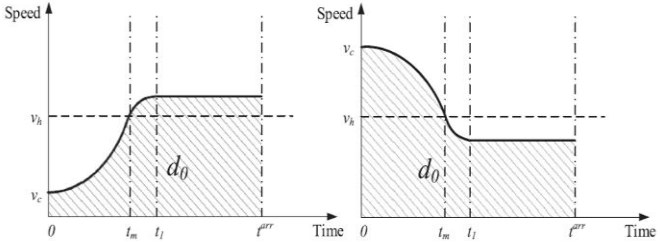


- **Intersection configuration:**
  - **2-lane major road and 1-lane minor road**
  - **No turning movement considered**
- **CACC string driving with longitudinal control including *Stop&Go***
- **CACC: 0%; 100%; 100% CACC with speed advisory**
- **Traffic hourly demand: 1500 major & 300 minor; and 3000 major & 600 minor**
- **Traffic control: Fixed traffic signal phase and timing**
- **Trigonometric speed profile; shape parameter is the decision variable; objective function is to minimize total tractive power (for energy saving)**

Traffic control strategy

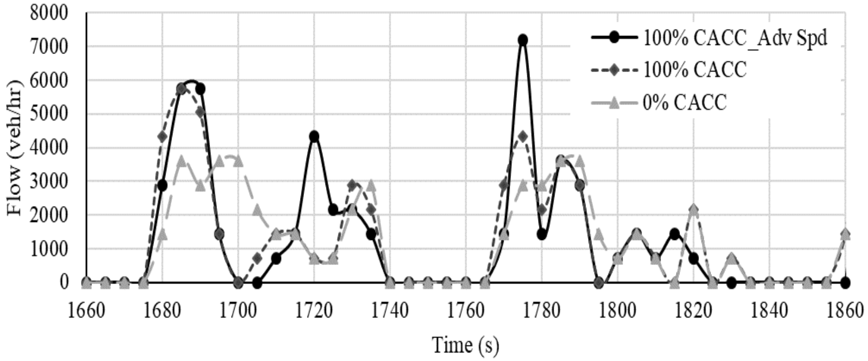


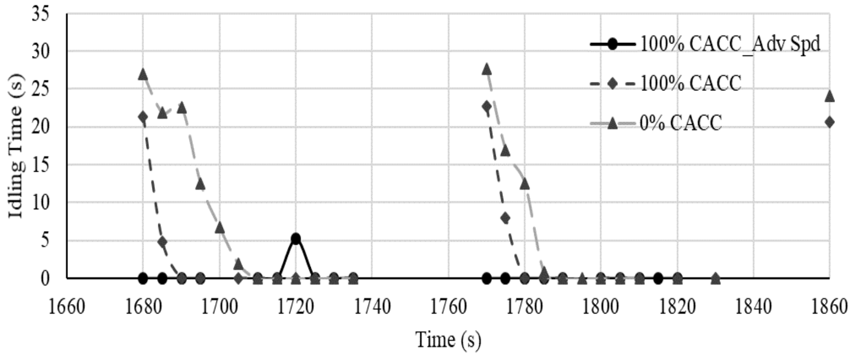
Speed shape profiles



ACCOMPLISHMENTS: Simple Intersection – FY17

- **Simulation Results:**
  - **The CACC operation can significantly increase mobility performance**
  - **With the optimal speed advisory, the idling time is greatly reduced while the mean speed and flow remain the same**
  - **Observation of flow increase and idling time reduction for major road with 1500 [veh/hr] due to behavior changes in both arrival and departure**
  - **Over 40% energy saving has been observed; but this would be degraded for complicated intersection and an arterial corridor;**





COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS – FY17

- Provided systematic simulation data in required format (SR99 NB and I-710) to ANL (Aymeric Rousseau) for national level energy saving studies (CAVs Task 7A.2.1)
- Used ANL (Aymeric Rousseau) provided Matlab code of Autonomie for off-line estimation of fuel consumption:
  - Saving simulation data for each scenario
  - Running Autonomie Matlab code for fuel consumption analysis

REMAINING CHALLENGES AND BARRIERS

- **To simulate fuel saving benefit for CACC vehicle operation along a freeway corridor with ATM including CRM, VSL/VSA, and Coordinated Merge**
- **To build a more accurate fuel consumption estimation model**
- **To simulate fuel saving benefit for CACC vehicle operation along an arterial corridor with Coordinated Traffic Signal Control (CTSC)**
- **To simulate fuel saving benefit for CACC vehicle operation in a traffic network with freeway corridor with ATM and arterial corridors with CTSC; and coordination of the two traffic control systems**

APPROACH - FY18

- **Fuel saving modeling: refine MOVES for more accurate fuel consumption for trucks and passenger cars and looking into Autonomie as well**
- **Freeway corridor traffic with CACC –SR99 NB**
  - **Adopt more ATM strategies we have field-tested including**
    - **CRM and VSL/VSA**
    - **Combined with better Lane Management strategy**
- **CACC truck simulation for rural freeway corridors**
- **Arterial Corridors with CACC**
  - **Developing simulation model for a typical arterial corridor**
  - **Developing Optimal Traffic Signal Control strategy for Coordinated CACC string and traffic signal control along an arterial:**
    - **To minimize fuel consumption**
    - **To maximize throughput**
- **Analyzing fuel saving impact with variety of CACC penetration levels for both freeway and arterial corridors**

N.B. Any proposed future work is subject to change based on funding levels

MILESTONES – FY18

Evaluation of Energy Impacts of CAVs through Traffic Microsimulation - Schedule																
SAMRT Mobility CAVs Pillar																
Subtasks / Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. truck energy consumption model improvement & calibration using field test data	■	■	■	■												
2: modeling truck CACC operation on rural freeway for fuel consumption evcaluation	■	■	■	■	■	■										
3. modeling baseline traffic at arterial corridor intersections with field data	■	■	■	■												
4. Creative development of Active Traffic Management strategies for freeway	■	■	■	■	■	■	■	■	■	■	■	■				
5. Creative development of Active Traffic Management strategies for arterial	■	■	■	■	■	■	■	■	■	■	■	■				
6. Fuel consumption evaluation of CACC impact on freeway corridor traffic													■	■	■	■
7. Fuel consumption evaluation of CACC impact on arterial corridor traffic													■	■	■	■

APPROACH – FY 19

- Select a typical freeway network with:
  - A freeway corridor
  - One or more arterial corridors
  - High traffic demand with certain levels of trucks volume
- Model traffic network in Aimsun and implement CC/ACC/CACC modeling in MicroSDK
- Refine and implement coordination and control strategy
  - ATM for freeway
  - Coordinated traffic signals for arterial corridor
  - Coordination between the two subsystems for energy savings
- Simulate fuel consumption for a variety levels of market penetrations of CACC passenger cars and heavy-duty trucks

N.B. Any proposed future work is subject to change based on funding levels

SUMMARY

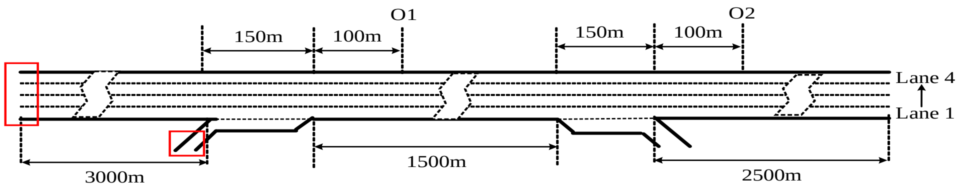
- Refined urban freeway corridor micro-simulation for SR99
- Developed truck CC/ACC/CACC vehicle following models
- Analyzed fuel saving benefits for simple freeway pipeline section
- Adopted simple ATM strategies (lane management) for traffic improvement
- Developed a simple intersection mode with speed advisory for CACC vehicles
- Revised MOVES model for truck CACC fuel saving analysis with test data
- Conducted energy saving analysis for truck CACC on freight corridor
- Results applicable to alternative powertrain vehicles
- To analyze fuel savings impact in FY-18 with simulation for:
  - CACC operation in traffic on rural freeway & arterial corridors
  - Incorporating more creative ATM strategies for better energy savings
- FY 19 (go/no-go)To analyze fuel savings impact with simulation for a traffic network involving freeway and arterial corridors with integrated traffic control

RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

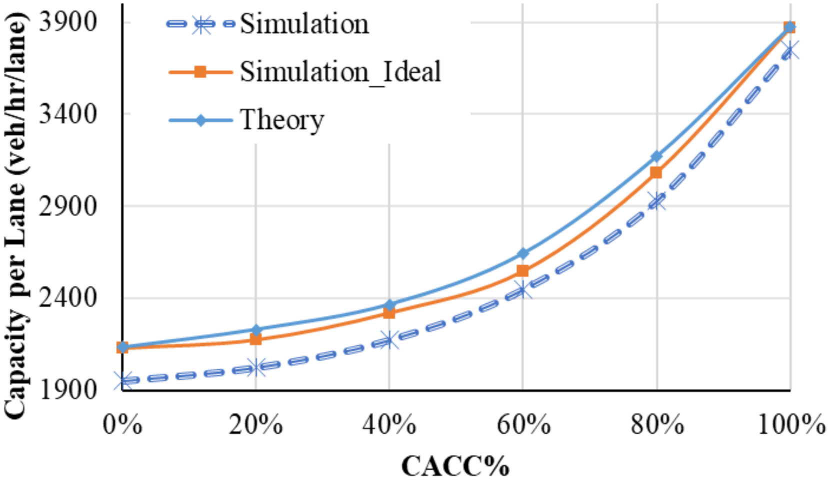
This project was not reviewed last year.

QUESTIONS?

BACKUP: PIPELINE CAPACITY IMPACT – FY17

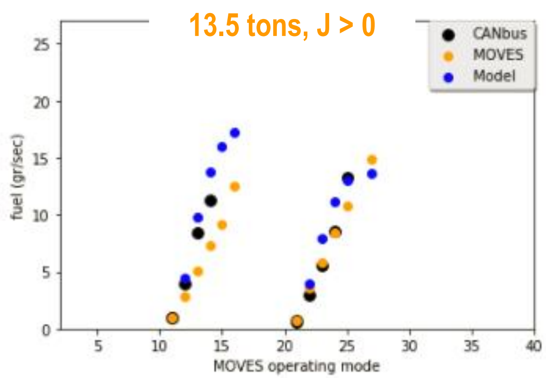


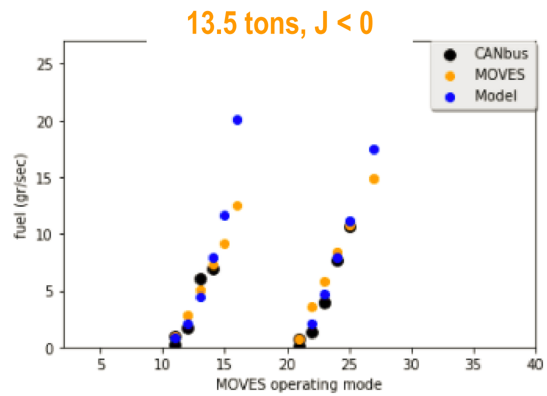
- Theory: calculated capacity
- Simulation_Ideal: simulated capacity for no lane changes and no randomness in drivers' behaviors
- Simulation: simulated capacity

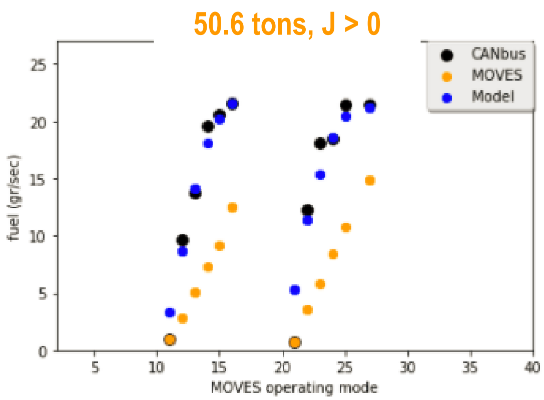


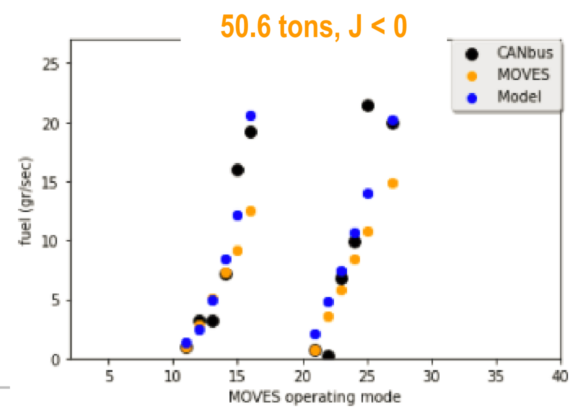
BACKUP: TRUCK FUEL CONSUMPTION MODEL: MOVES – FY17

$$fuel\_model = A + B * M + C * MOVES + D * MOVES^2$$



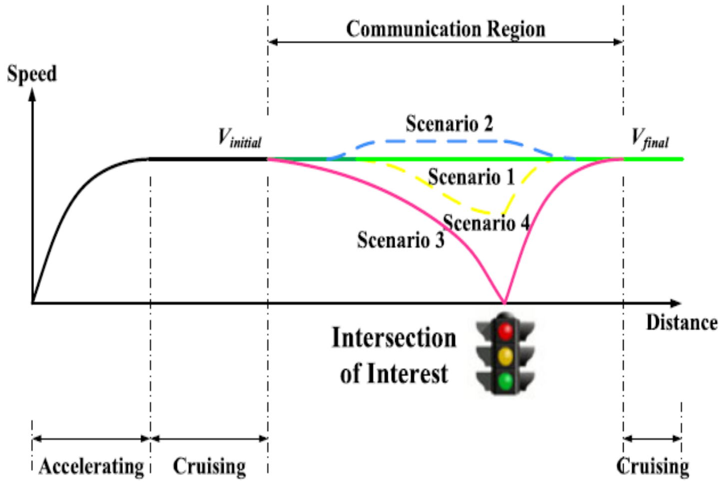


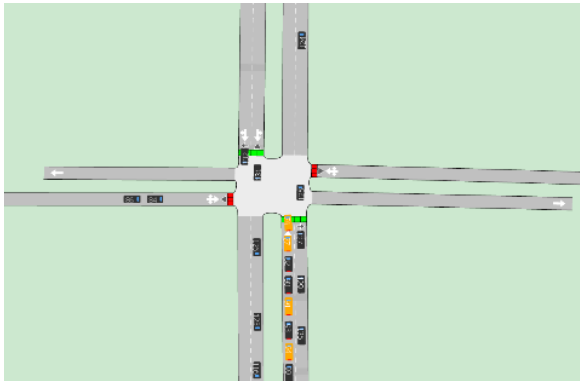




BACKUP: SIMPLE SIGNALIZED INTERSECTION – FY17

Speed profile scenarios





BACKUP: PUBLICATIONS – FY17

- F.-C. Chou, H. Ramezani, X. Y. Lu, and S. Shladover , Modeling Vehicle-Following Dynamics of Heavy Trucks under Automatic Speed Control Based on Experimental Data, *TRB Annual Meeting*, Washington D. C., Jan 7-11 2018
- H. Ramezani, S. E. Shladover, X. Y. Lu, and O. D. Altan, Ph.D., Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study, TRB Annual Meeting, Washington D. C., Jan 7-11 2018; accepted for publication by *TRB Journal of Transportation Research Record*
- H. Liu, D. Kan, S. E. Shladover, X. Y. Lu, R. Ferlis, Impact of Cooperative Adaptive Cruise Control (CACC) on Multilane Freeway Merge Capacity, *J. of Intelligent Transportation System*, DOI: 10.1080/15472450.2018.1438275
- H. Liu, S. Shladover, X. Y. Lu, and D. Kan, Vehicle Fuel Efficiency Improvement via Cooperative Adaptive Cruise Control Vehicle String Operations in Freeway. Accepted to *Transportation Research Part D (2017)*

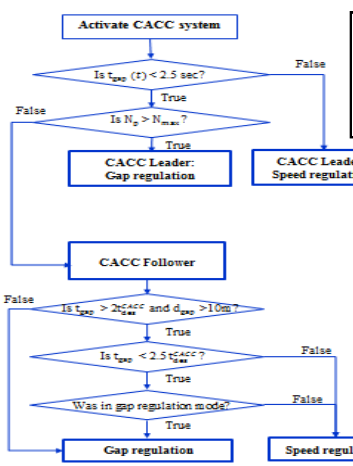
Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study

H. Ramezani, S. E. Shladover, X. Y. Lu, California PATH Program, University of California, Berkeley
O. D. Altan, Federal Highway Administration

ABSTRACT

- Objective: Developed a micro-simulation model of heavy truck CACC when trucks share a freeway with manually driven passenger cars.
- Car following models: Developed for CACC, ACC, and CC
- Other behavioral models: Implemented lane changing, lane change cooperation, lane use restrictions, and switch from automated mode to manual mode
- Case study: Calibrated Aimsun model for a 15-mile corridor
  Studied effect of penetration rate on speed and VMT

MECHANISM OF AUTOMATIC VEHICLE FOLLOWING



Glossary:
$t_{gap}(t)$: Time gap at time t
d_{gap}: Distance gap
t_{des}^{CACC}: Desired time gap in CACC
N_{max}: Maximum number of vehicle in a platoon
N_p: Position in platoon

CAR FOLLOWING MODEL

$$a_{target}(t) = Max(b_f, Min(a_F(t), a_m(t), a_G(t)))$$

b_f: Max braking rate
$a_F(t)$: Acc. rate to reach free flow speed
$a_G(t)$: Gipps deceleration component
$a_m(t)$: Acc. rate for a given driving mode. For manual mode, the Newell model is used. For automated modes the following models are used.

Vehicle Following Model (Cont.)

For Cruise Control (CC) mode:

$$a_m(t+1) = 0.3907(v_{ref}(t) - v(t))$$

$v_{ref}(t)$: Reference speed
$v(t)$: Speed of the subject vehicle

For Adaptive CC (ACC) mode:

$$a_m(t+1) = 0.0561[d(t) - t_{des}^{ACC} v(t)] + 0.3393[v_{prec}(t) - v(t)]$$

$d(t)$: Distance gap
t_{des}^{ACC}: Desired time gap, selected to be 2.2 sec
$v_{prec}(t)$: Speed of the preceding vehicle

For Cooperative ACC (CACC) mode:

$$a_m(t+1) = 0.0074\,[d(t) - t_{des}^{CACC} v(t)] + 0.0805\,[v_{prec}(t) - v(t) - t_{des}^{CACC} a(t)]$$

t_{des}^{CACC}: Desired time gap, evenly distributed between 1.2 sec and 1.5 sec

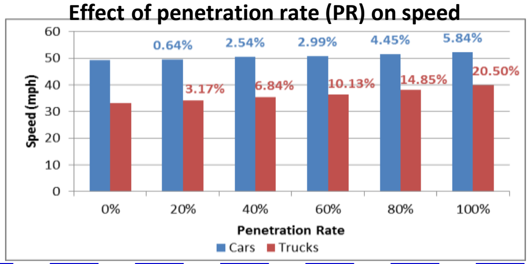
CASE STUDY: I-1710 NB

15-mile corridor with loop detector locations

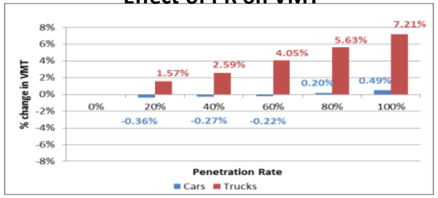
Calibrated parameters

Parameter	Calibrated value
Reaction time	1.3 sec
Gap for manual trucks	2.4 sec
Gap for manual cars	1.25 sec
Theta in Gipps model	$0.2^* \tau_r$
Max Acc. for cars	$2.5\ m/s^2$
Max Dec. for cars	$3\ m/s^2$
Min. speed difference to consider friction	10 m/s

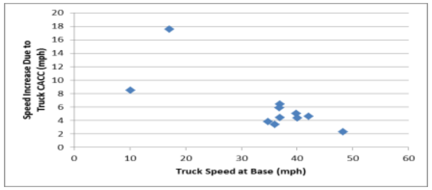
Effect of penetration rate (PR) on speed



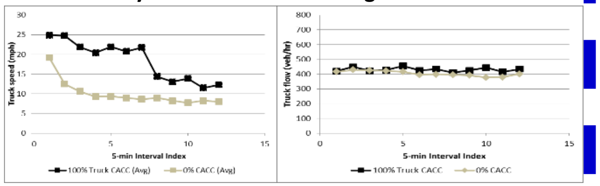
Effect of PR on VMT



Effect of 100% PR on speed at detector locations:



Traffic dynamic at the most congested detector:



CONCLUDING REMARKS

- Developed a framework to simulate automated truck platoon, manual passenger cars and manual trucks
- Comparison of 0% penetration rate vs. 100%:
  For trucks: Speed and VMT increased by 20.5 % and 7.2%, respectively
  For cars: Speed increased by 5.8%; marginal effect on VMT

ACKNOWLEDGMENT

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