Development and Assessment of CACC for Cars and Trucks

Steven E. Shladover, Sc.D.

California PATH Program

University of California, Berkeley

May 24, 2017

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**

CALIFORNIA PATH

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

CALIFORNIA PATH

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

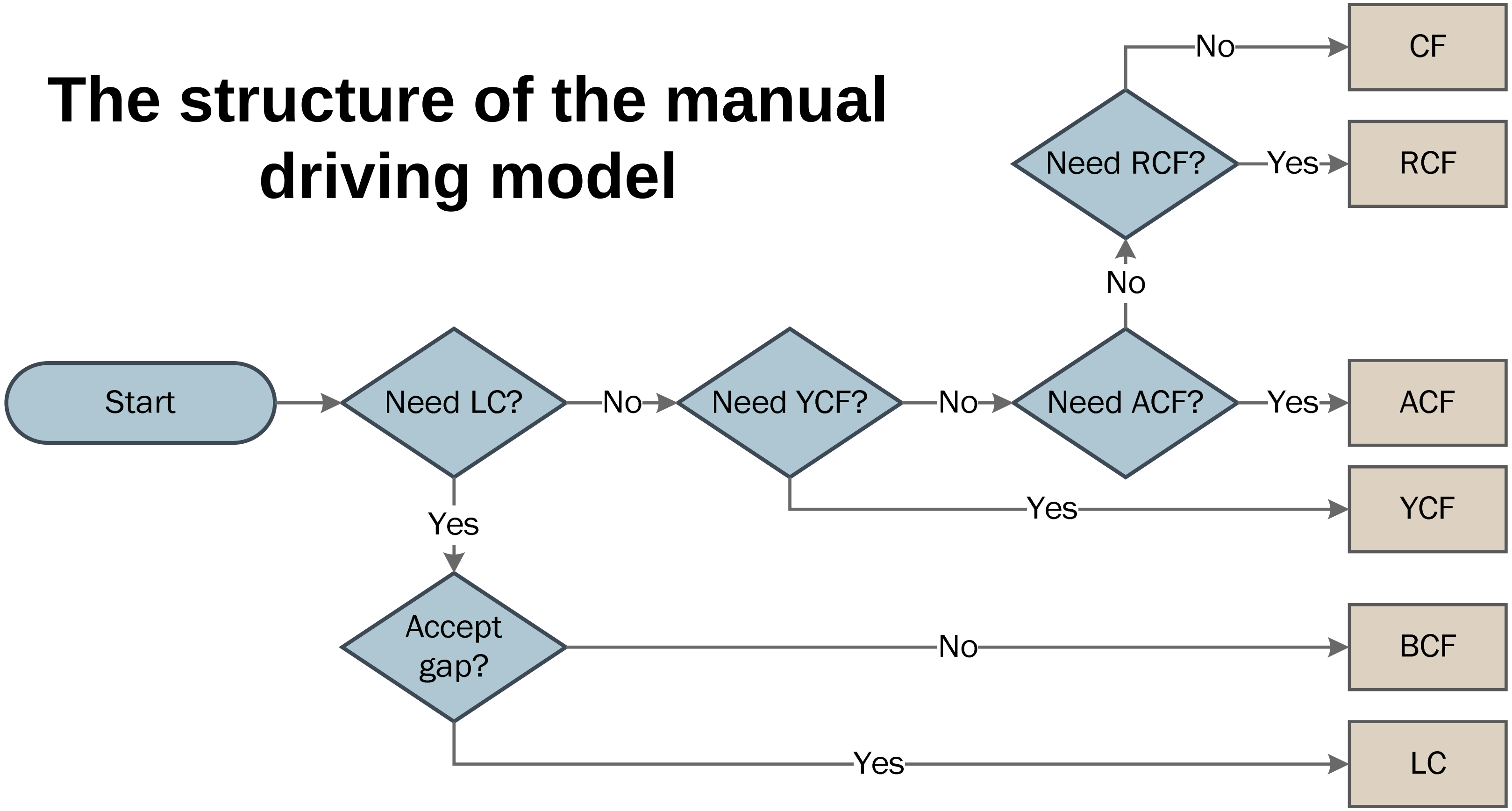
- **Detailed micro-simulations to represent interactions with manually driven vehicles, including lane changing**
- **Baseline manual driving models – NGSIM Oversaturated Flow model (Berkeley) and MOTUS (TU Delft)**
  - **Extensive enhancements to both models to represent detailed vehicle-vehicle interactions 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**

CALIFORNIA PATH

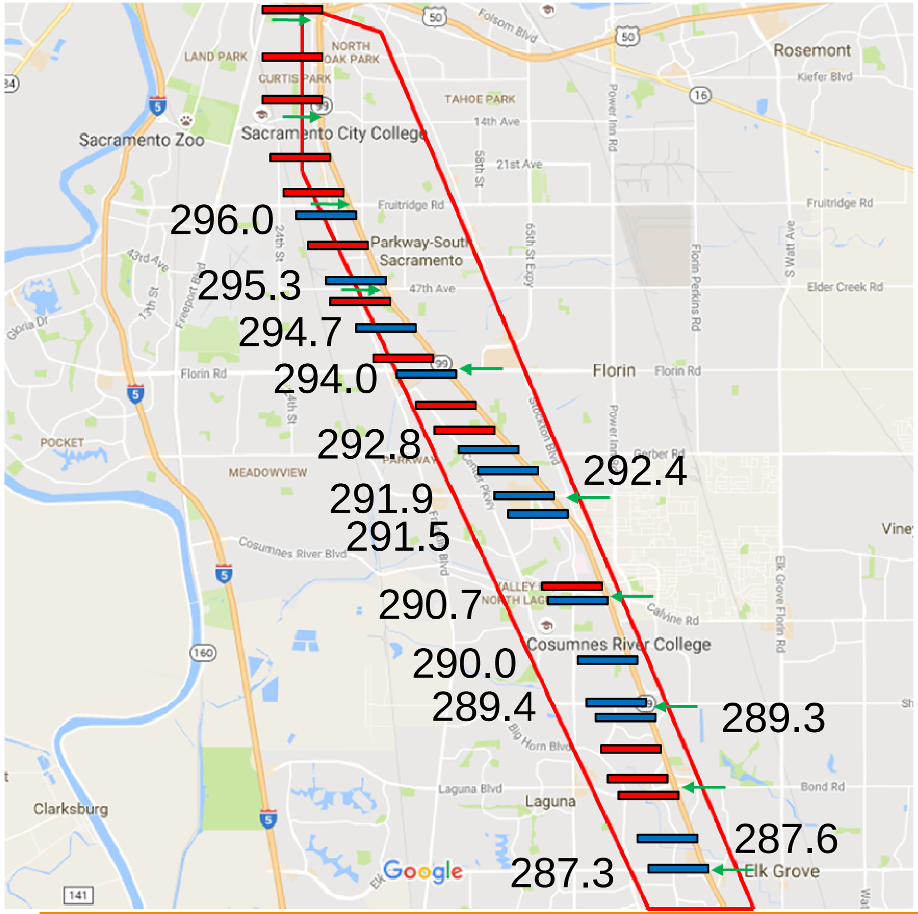
Manual Driving Model

- **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:**
  - ***CF*: Regular car following mode**
  - ***LC*: Lane change mode**
  - ***ACF*: After lane changing car following mode**
  - ***BCF*: Before lane changing car following mode**
  - ***RCF*: Receiving car following mode**
  - ***YCF*: Yielding (cooperative) car following mode**

Manual Driving Model



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***

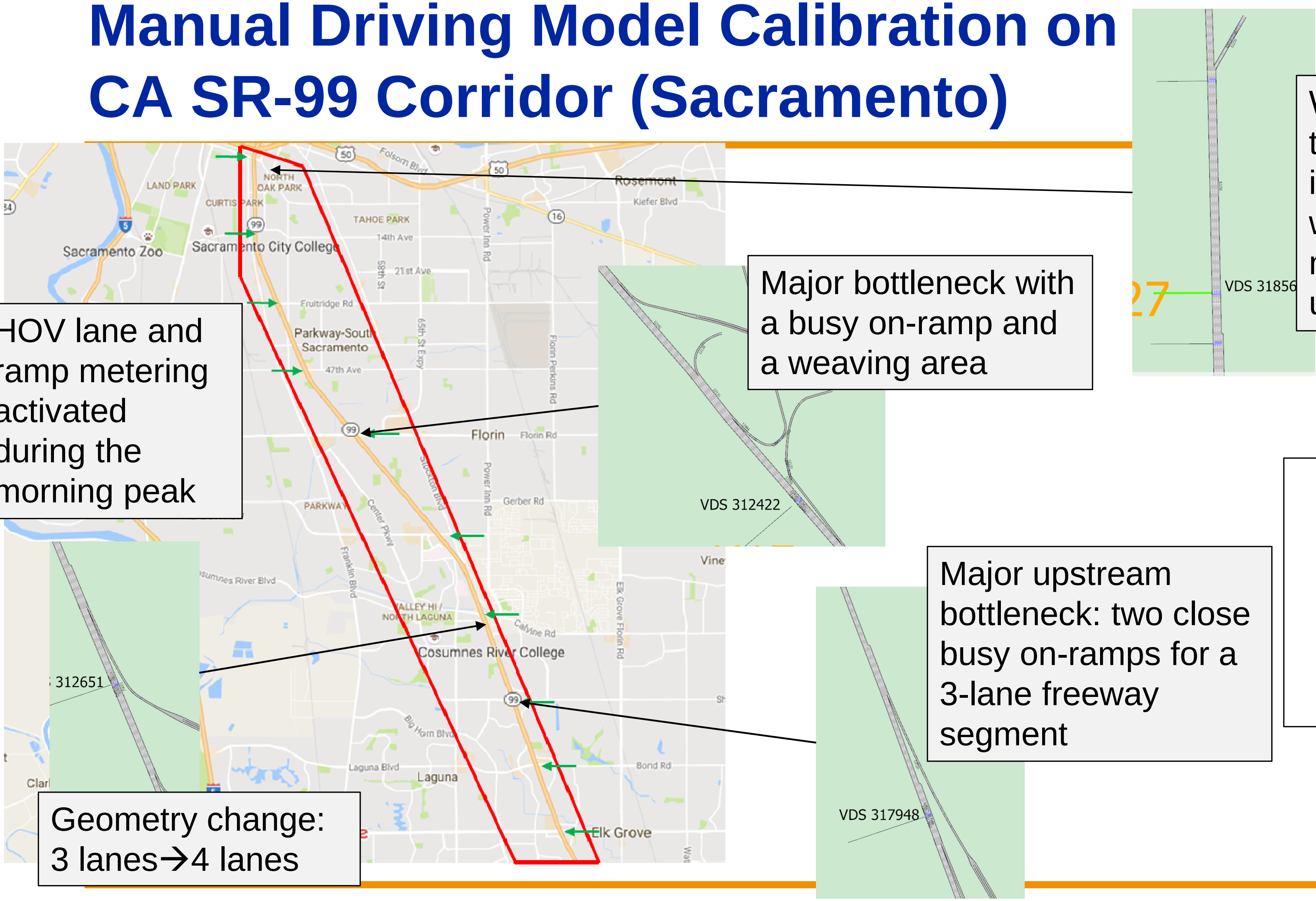
The 5-minute interval vehicle count and speed data observed at reliable detectors are used as the benchmark data.

Detector: not considered in calibration

Detector: considered in calibration

Interchange

Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)



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

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

HOV lane and ramp metering activated during the morning peak

Major upstream bottleneck: two close busy on-ramps for a 3-lane freeway segment

Geometry change: 3 lanes→4 lanes

Modeling the complicated network in Aimsun

CALIFORNIA PATH

Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

Freeway: 5-min flows of SR-99 Northbound					
Detector Location (post-mile)	Target	Cases	Cases Met	% Met	Target Met?
287.3	GEH < 5 for > 85% of *k*	930	921	99.0%	Yes
287.6	GEH < 5 for > 85% of *k*	930	904	97.2%	Yes
289.3	GEH < 5 for > 85% of *k*	930	915	98.4%	Yes
289.4	GEH < 5 for > 85% of *k*	930	914	98.3%	Yes
290.0	GEH < 5 for > 85% of *k*	930	921	99.0%	Yes
290.7	GEH < 5 for > 85% of *k*	930	920	98.9%	Yes
291.5	GEH < 5 for > 85% of *k*	930	870	93.5%	Yes
291.9	GEH < 5 for > 85% of *k*	930	852	91.6%	Yes
292.4	GEH < 5 for > 85% of *k*	930	875	94.1%	Yes
292.8	GEH < 5 for > 85% of *k*	930	887	95.4%	Yes
294.0	GEH < 5 for > 85% of *k*	930	889	95.6%	Yes
294.7	GEH < 5 for > 85% of *k*	930	915	98.4%	Yes
295.3	GEH < 5 for > 85% of *k*	930	909	97.7%	Yes
296.0	GEH < 5 for > 85% of *k*	930	850	91.4%	Yes
Overall	GEH < 5 for > 85% of *k*	13020	12542	96.3%	Yes

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

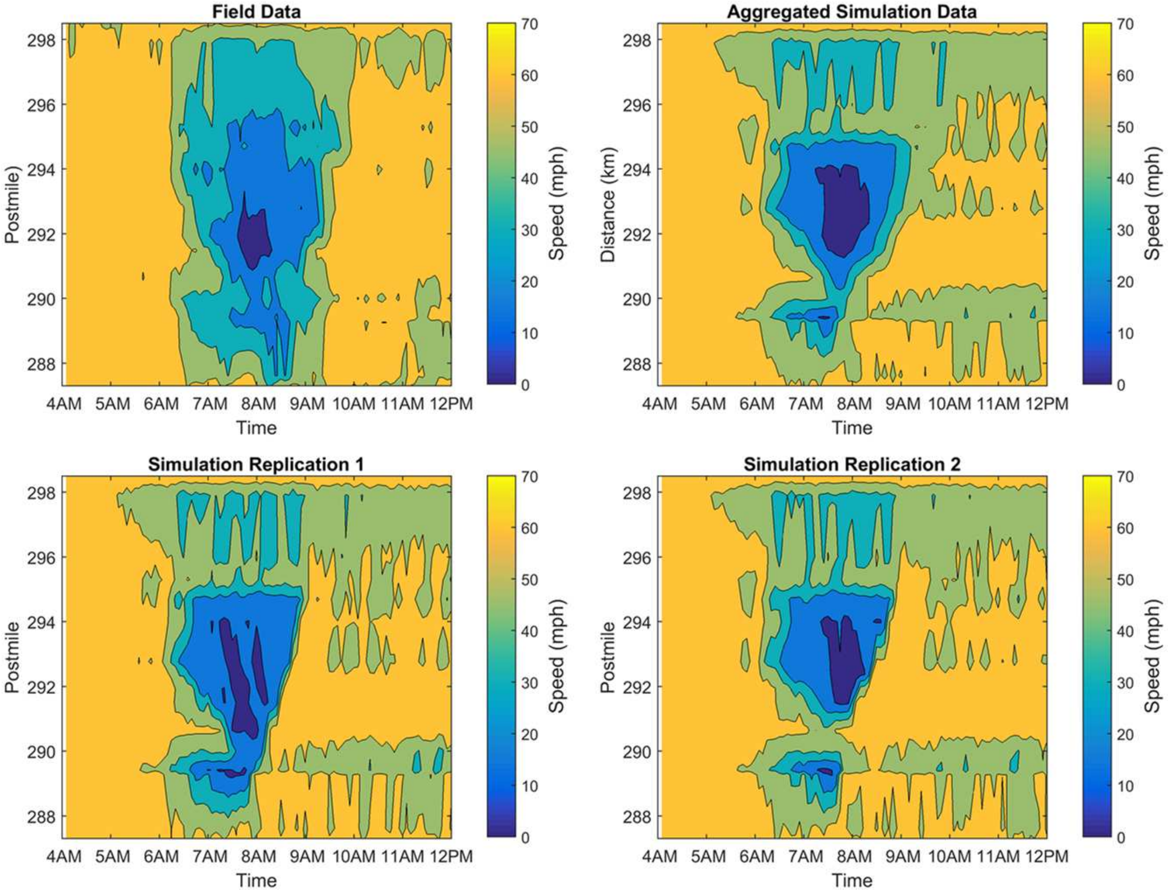
k: ID of the 5-min time interval
M: simulated flow
C: observed flow

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***

CALIFORNIA PATH

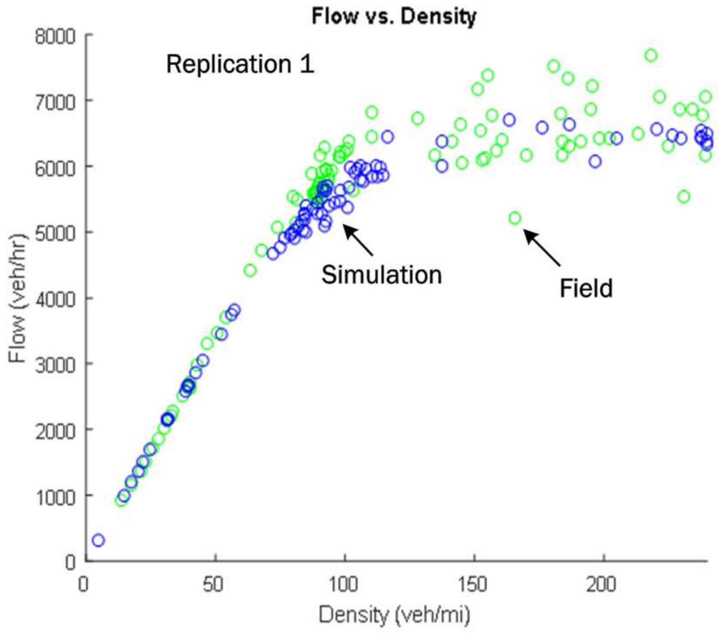
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

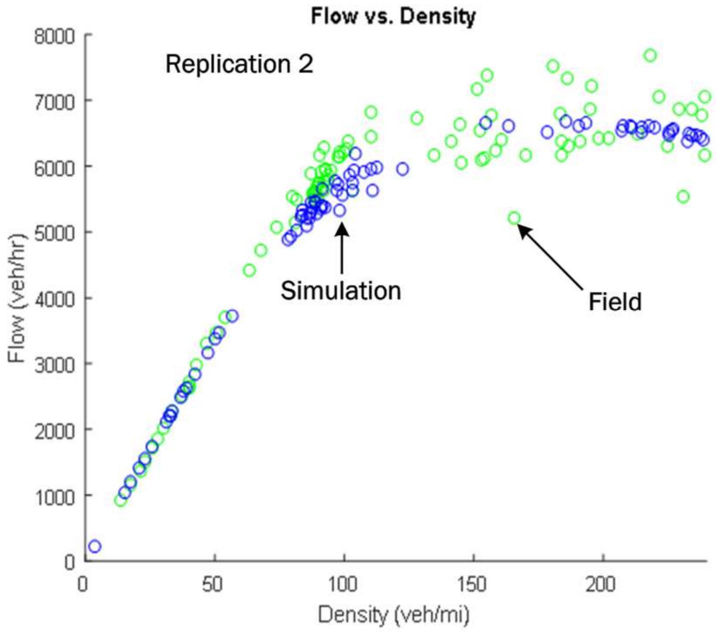


The calibrated model can accurately replicate the spatial and temporal characteristics of the traffic along SR99.

Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

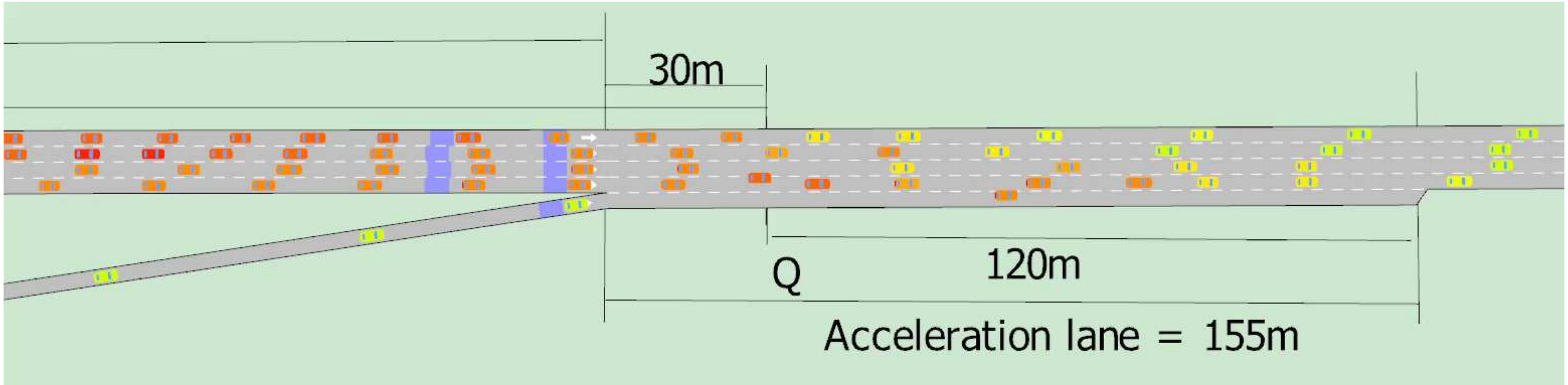
- **Comparison of fundamental diagrams of simulated and field observed flow-density relationships**
- **Two sample replications at Station 292.8**





CALIFORNIA PATH

Animation of Base Case (Manual Driving)



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

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**

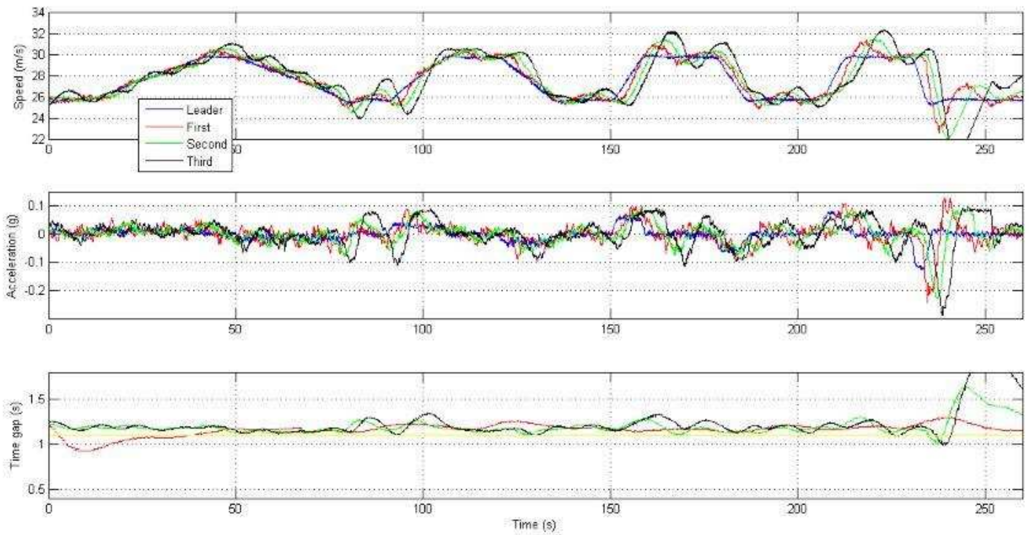
Adaptive Cruise Control with and without V2V Cooperation (AACC and CACC)

Autonomous (no communication) at minimum gap of 1.1 s

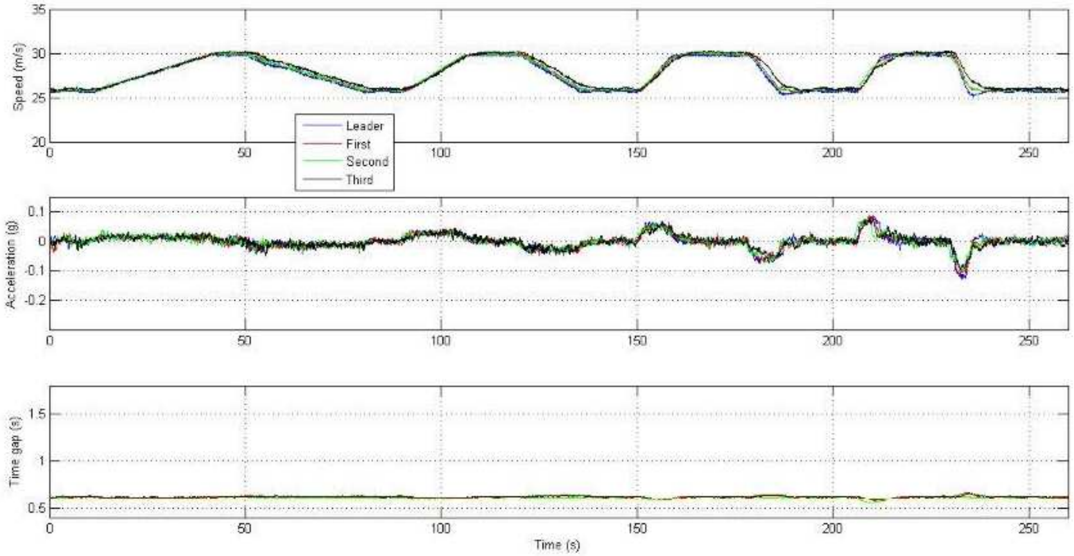
Cooperative (V2V communication) at minimum gap of 0.6 s

Comparison of Performance

Autonomous (no communication)

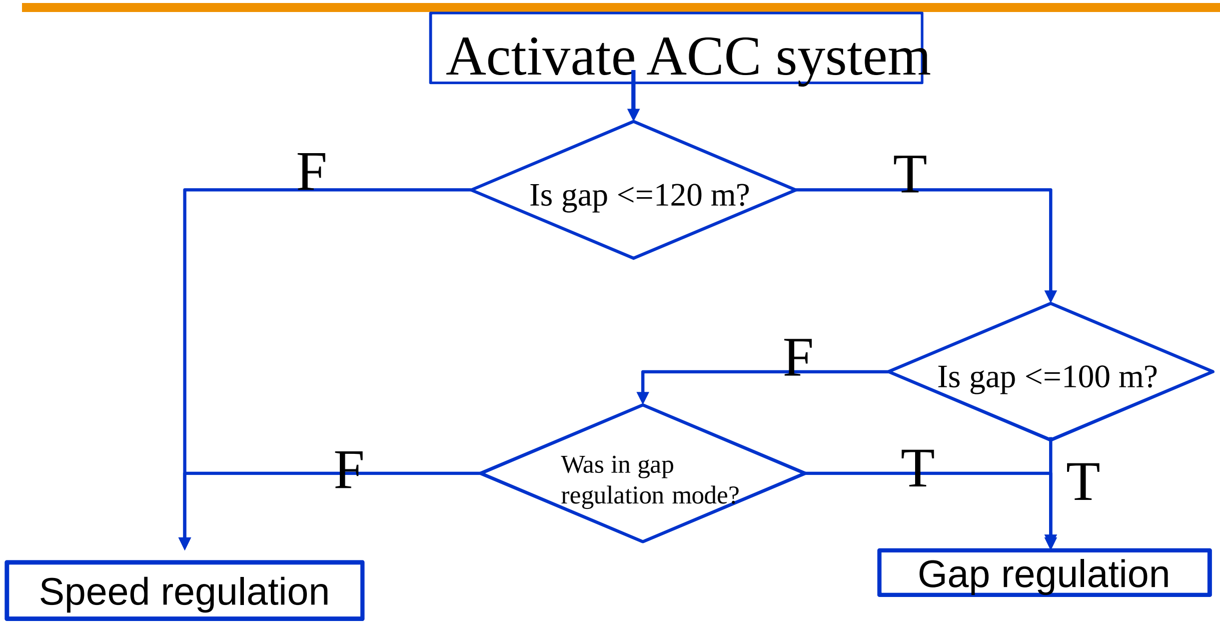


Cooperative (V2V communication)



CALIFORNIA PATH

ACC Model



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

- **Speed regulation**

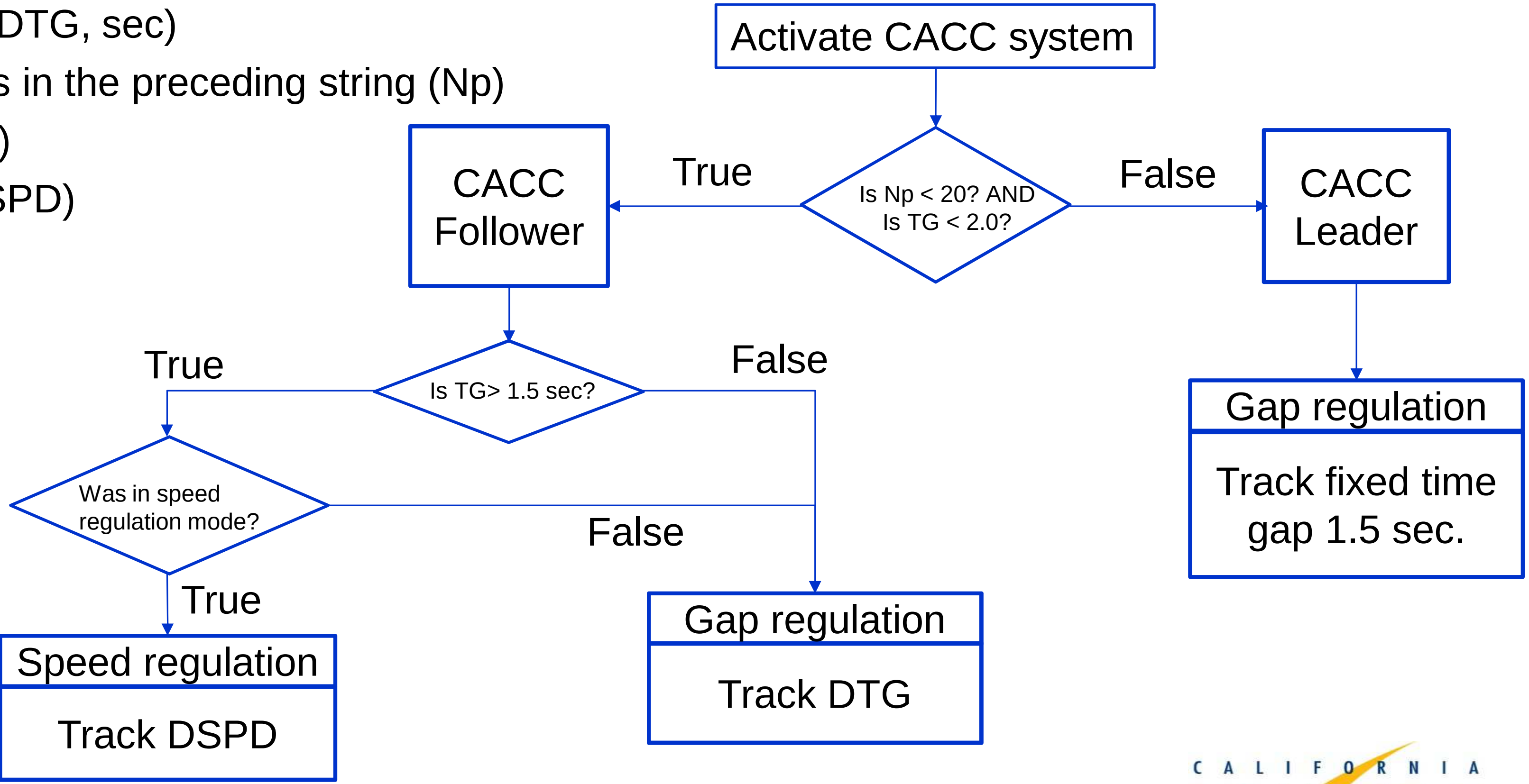
$$a_k = 0.4(v_{k-1} - v_k)$$

- **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)



*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)

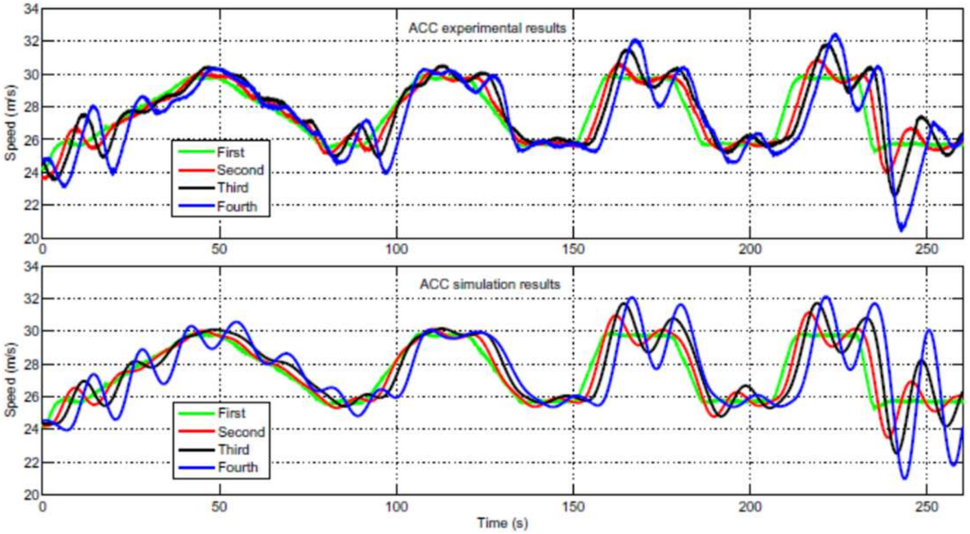
Time gap distribution from field test

- **0.6 sec 50%**
- **0.7 sec 25%**
- **0.9 sec 10%**
- **1.1 sec 15%**

AACC Model Predictions and Test Results

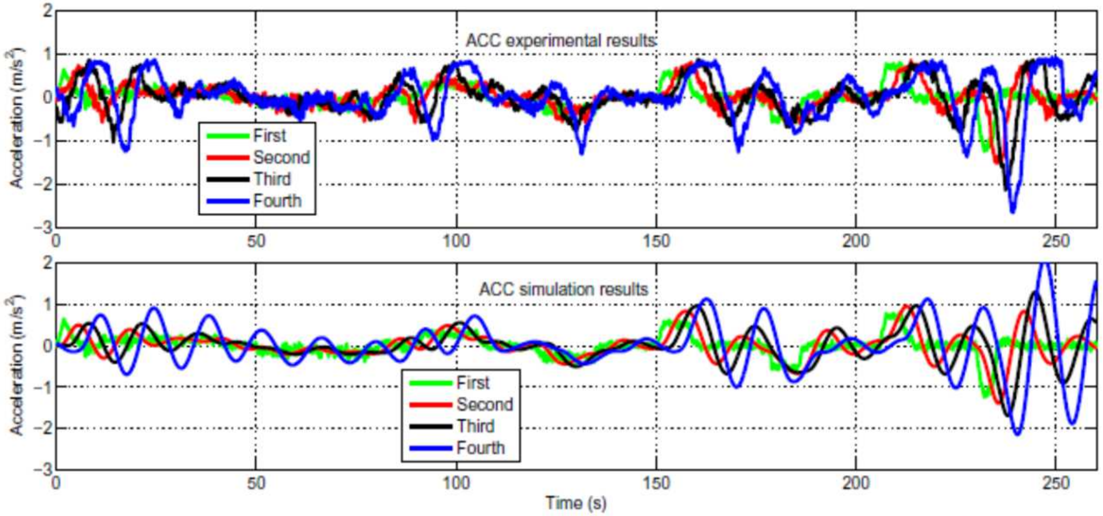
Speeds

(Test above, model below)



Accelerations

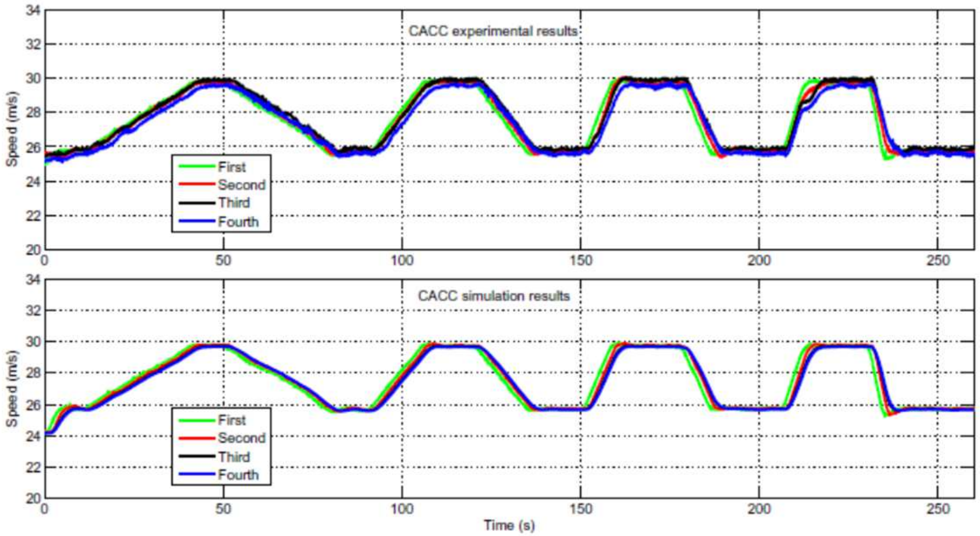
(Test above, model below)



CACC Model Predictions and Test Results

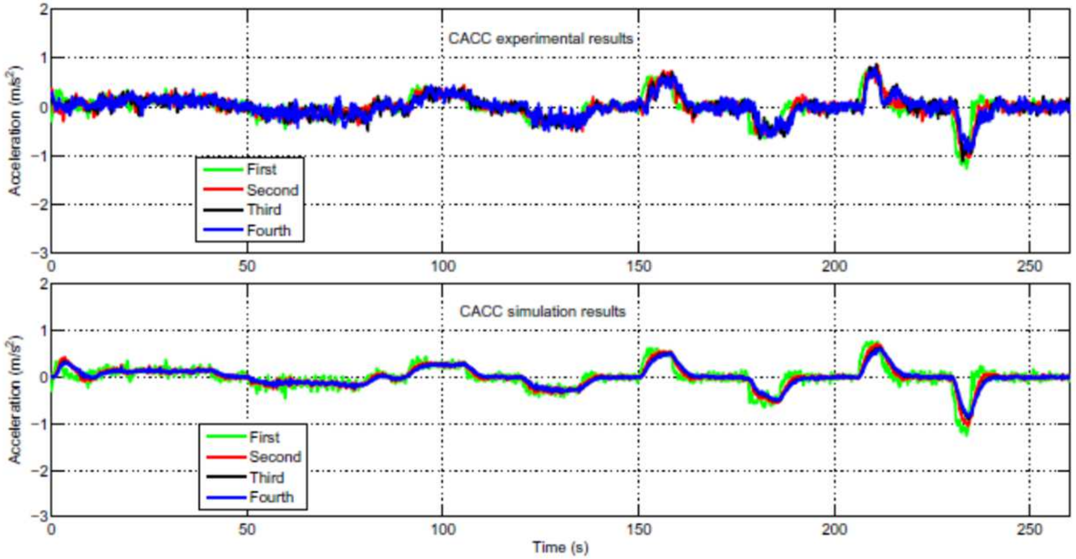
Speeds

(Test above, model below)



Accelerations

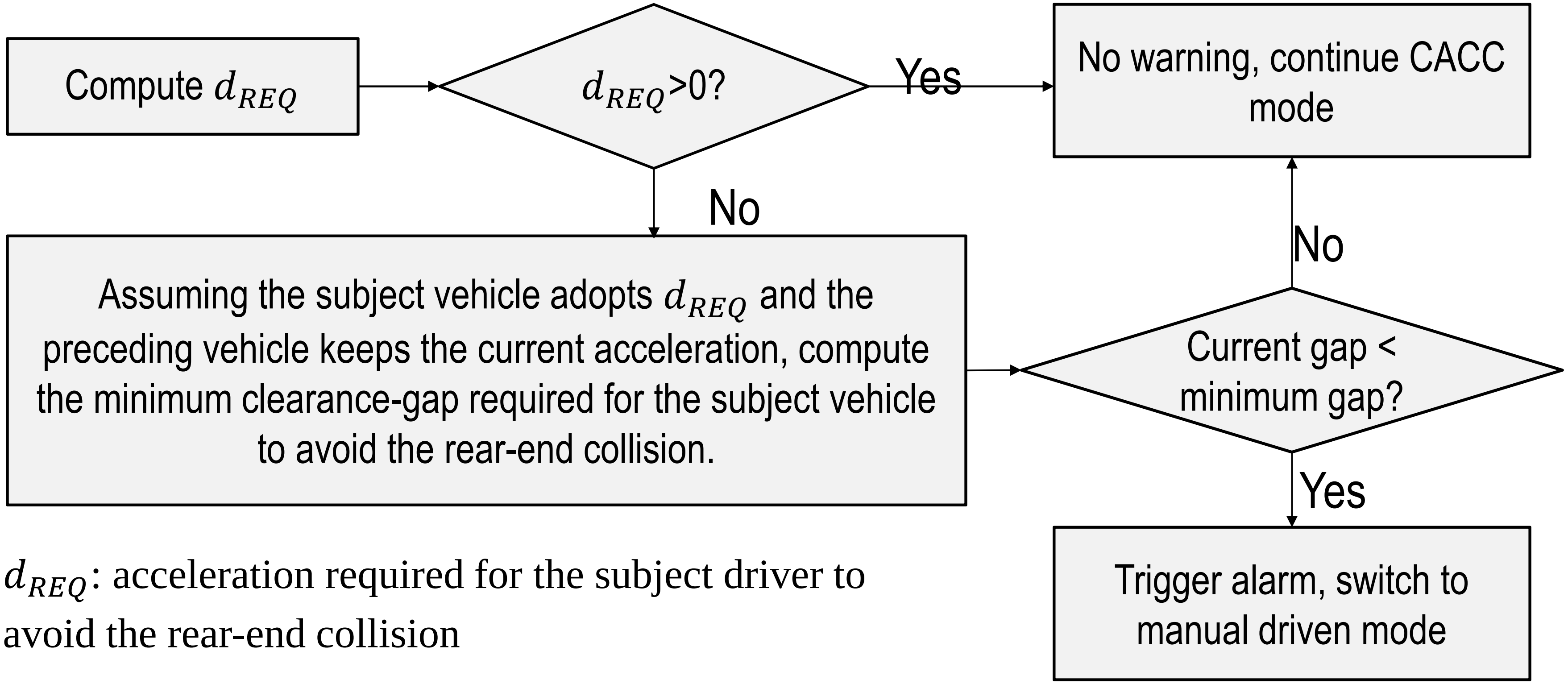
(Test above, model below)



CALIFORNIA PATH

Additional Collision Avoidance Logic

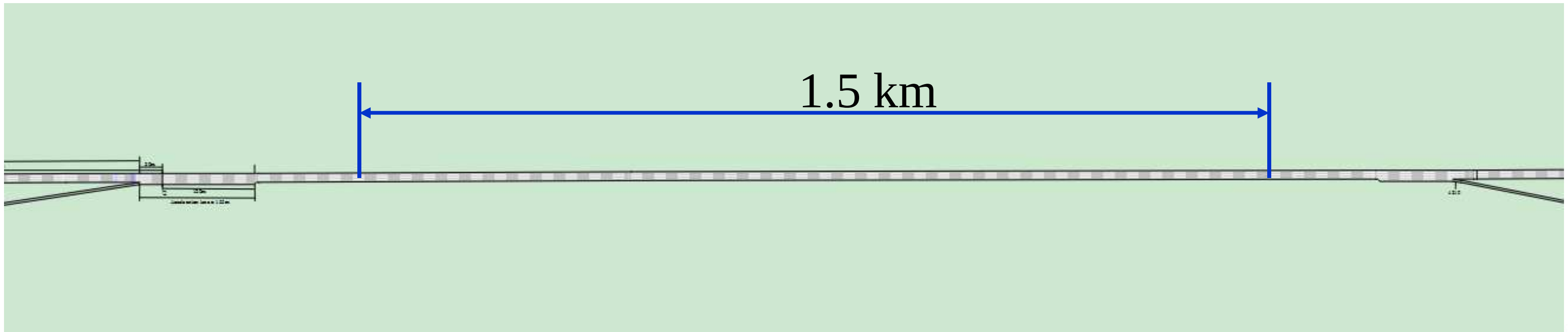
- **CAMP forward collision warning algorithm**



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

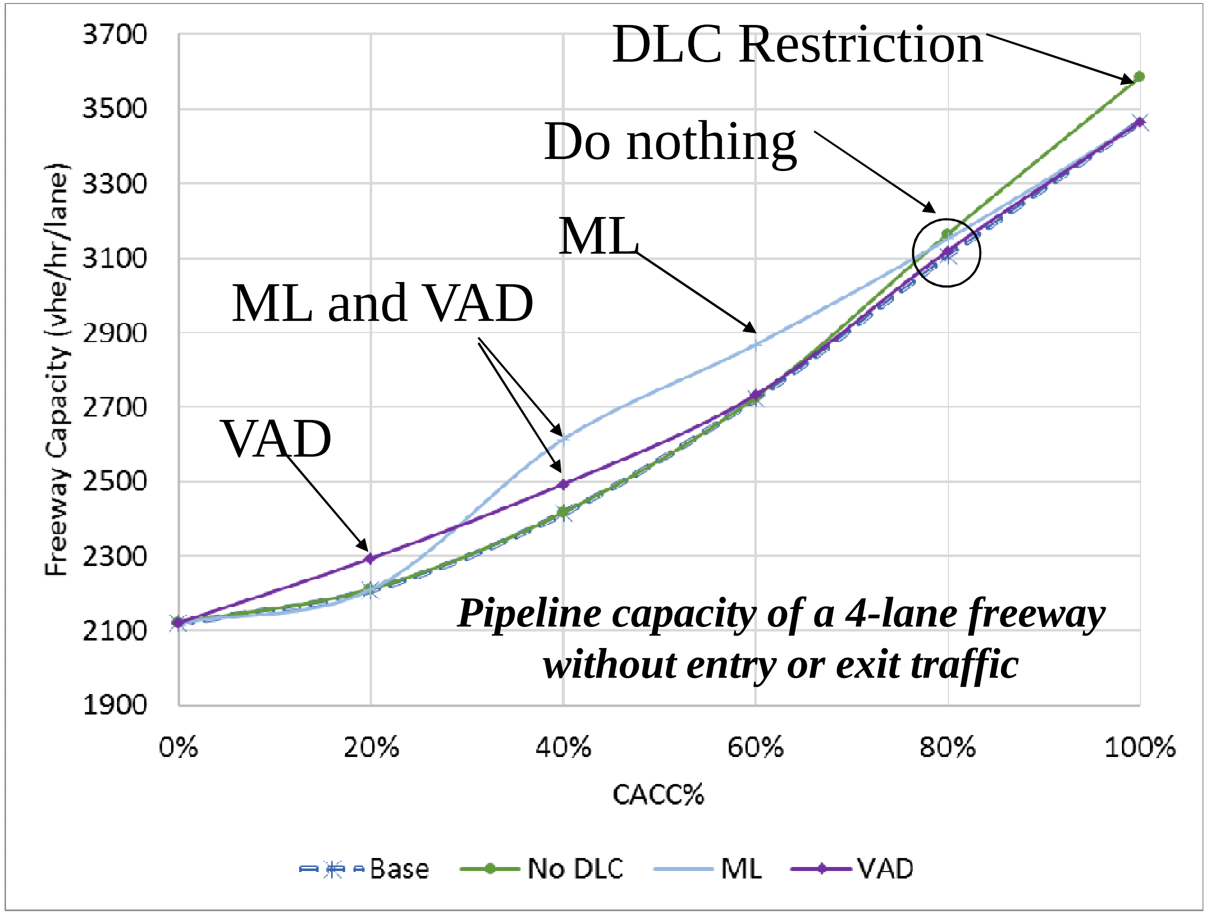
- **Freeway capacity increases because of CACC string operation**
  - **Small probability of forming CACC strings under low CACC market penetration**
  - **CACC strings are often interrupted by lane change maneuvers in the traffic stream and interactions with heterogeneous traffic**
- **Traffic management 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***

CALIFORNIA PATH

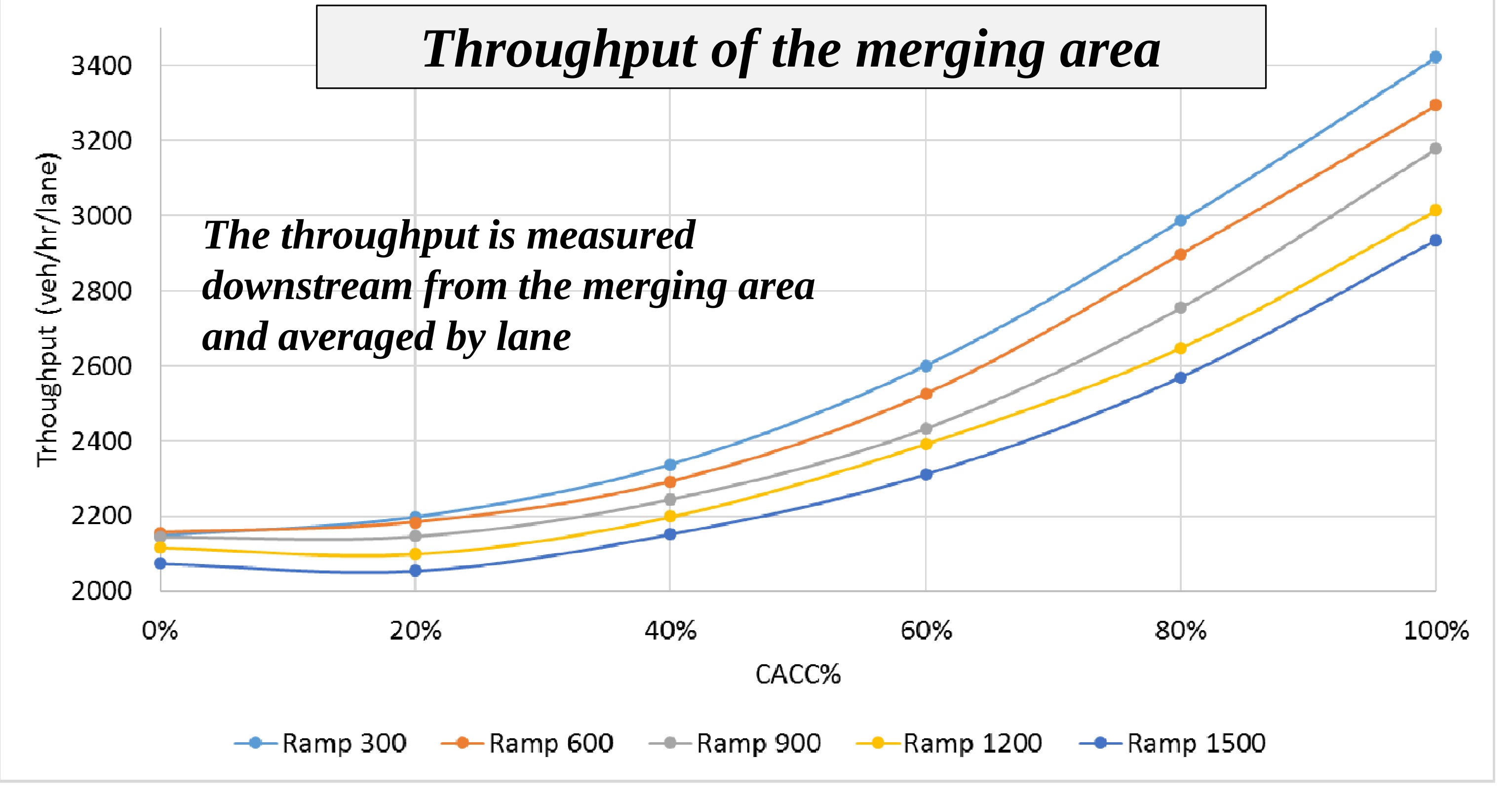
Lane Capacity Increases for Different Strategies



- **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**

CALIFORNIA PATH

Throughput Limitations as On-Ramp Volume Grows



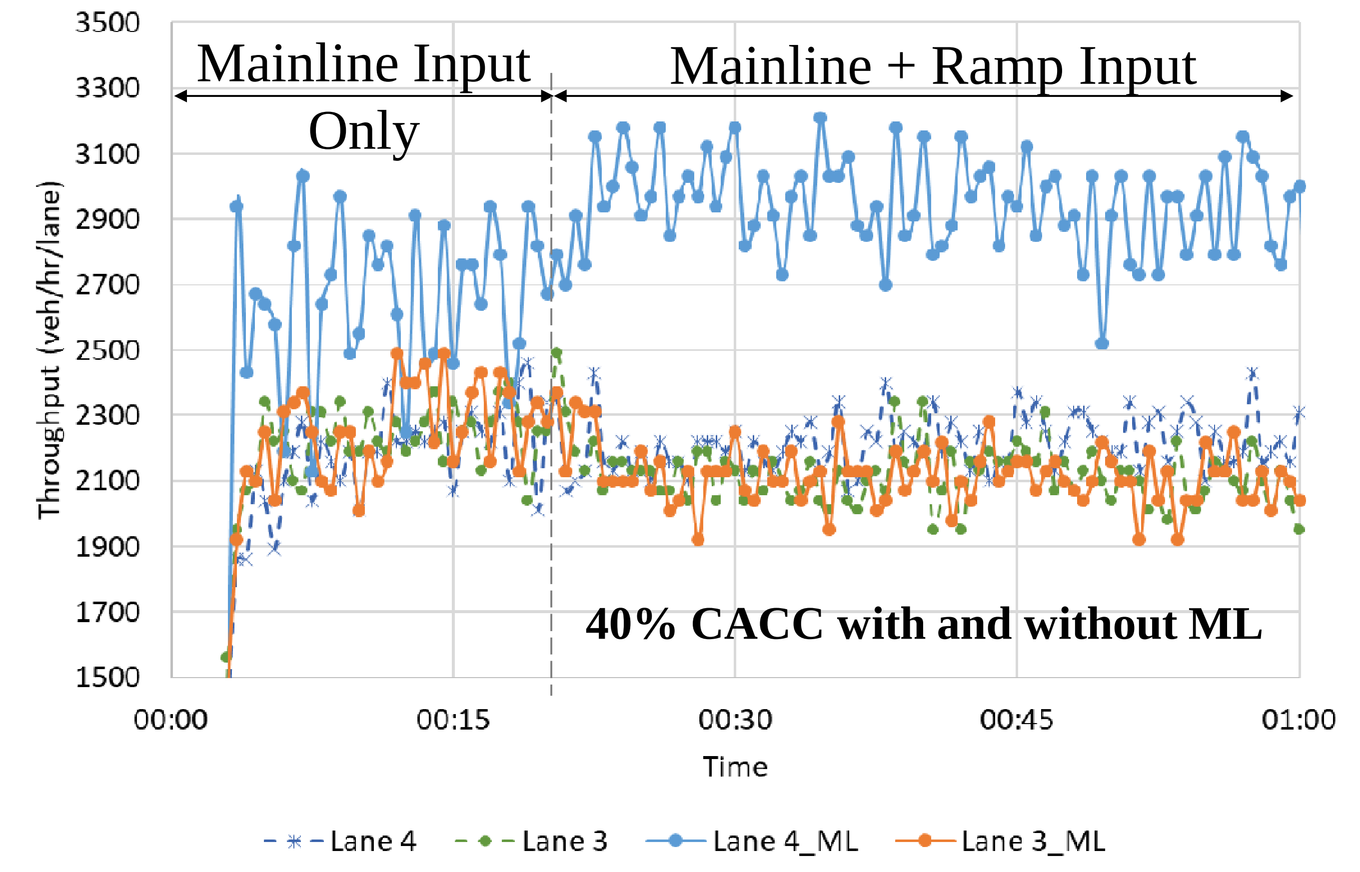
- **Downstream throughput reduces as on-ramp traffic increases**
- **It maintains quadratic trend with CACC market penetration**

Ramp traffic in veh/hr/lane
Mainline traffic volume equals the base case pipeline capacity shown in the previous slide

CALIFORNIA PATH

Managed Lane Throughput Advantage

Time series of output flow from the merging area

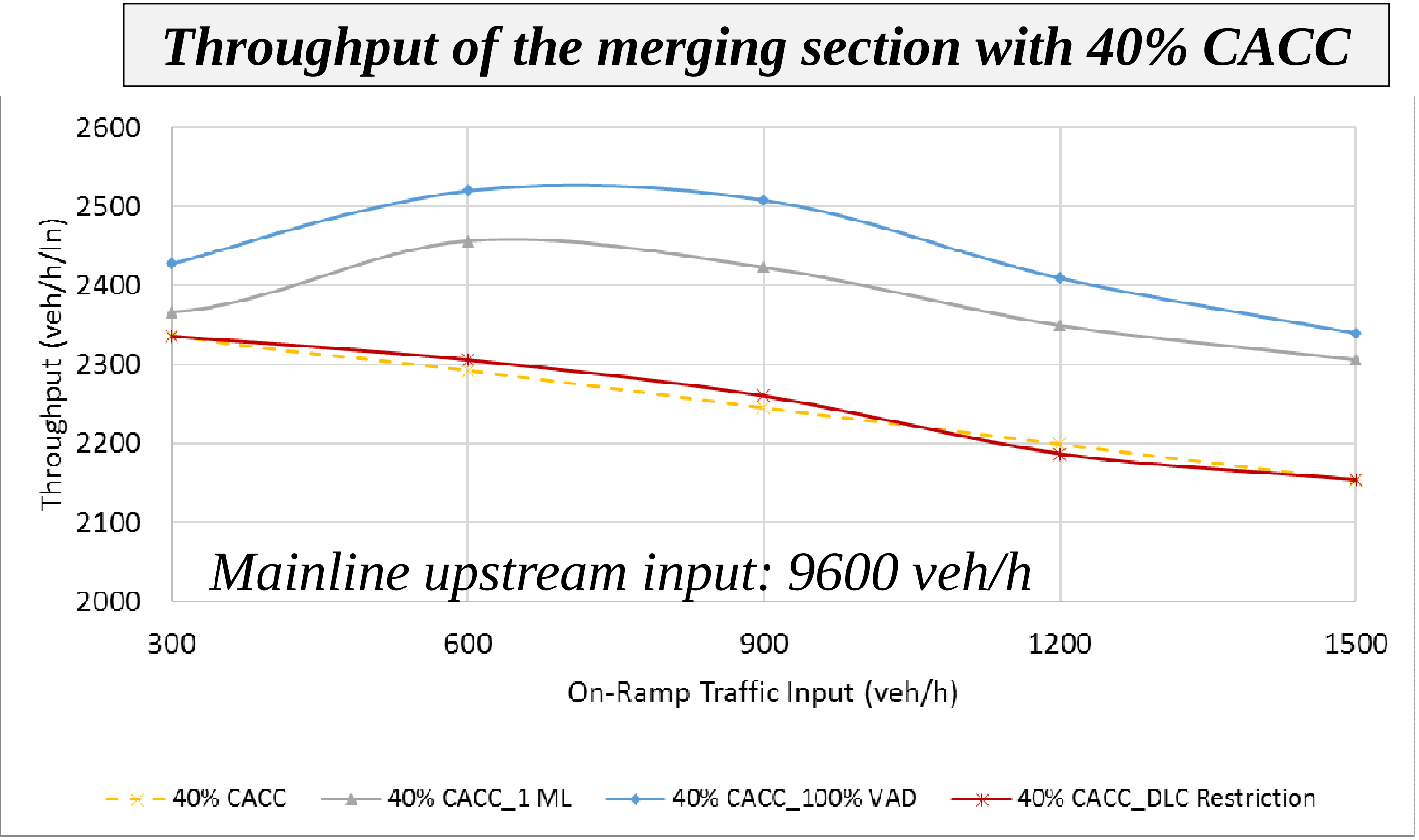


The ML strategy increases the capacity of the merging area

- **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**

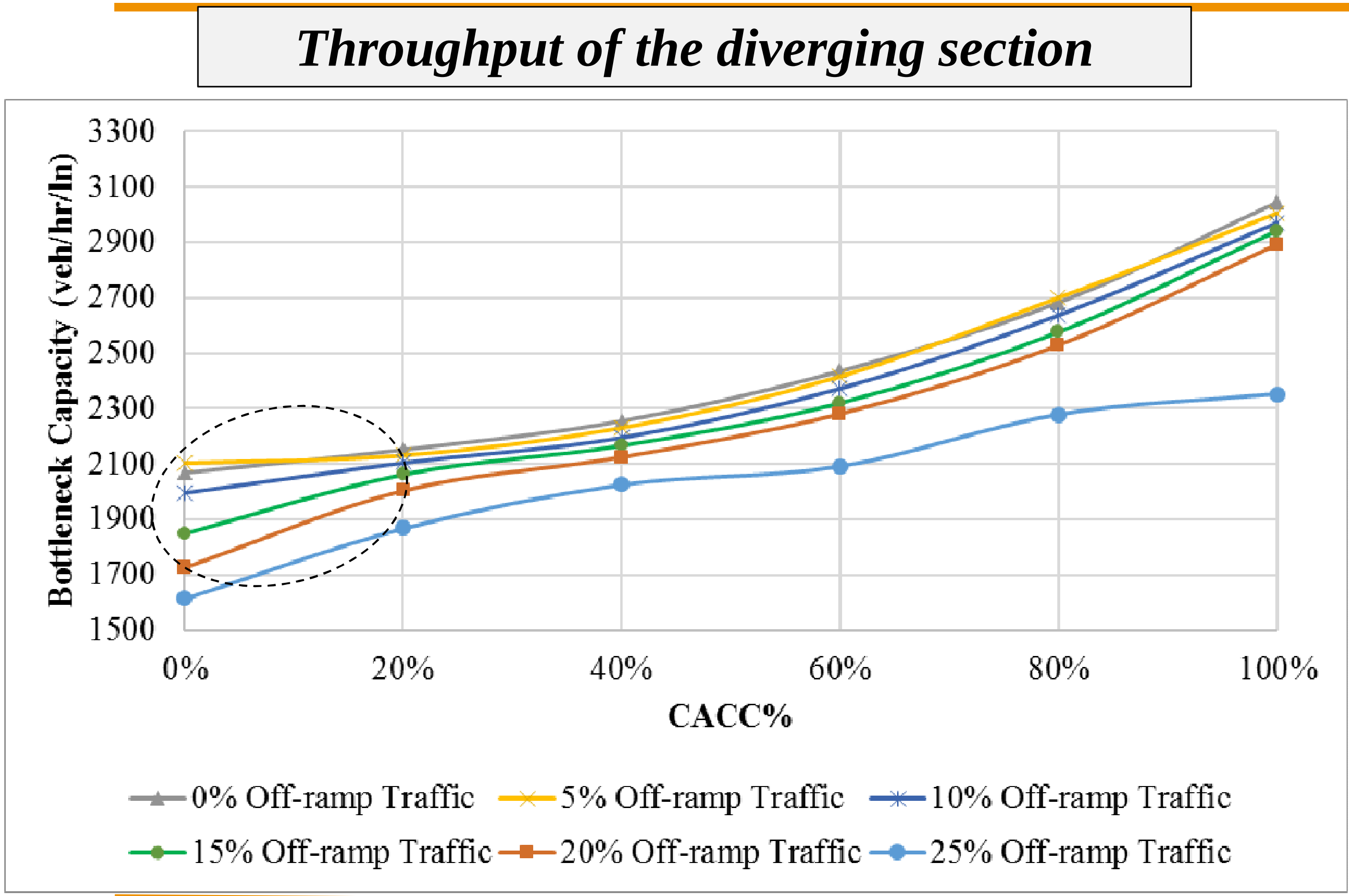
Mainline input: 9600 veh/h, on-ramp input: 1500 veh/h
Lane 4 is the managed lane in the ML case
Results for Lane 1 and 2 are similar to those of lane 3

Effects of Management Strategies on Throughput at Merging Section



- **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**

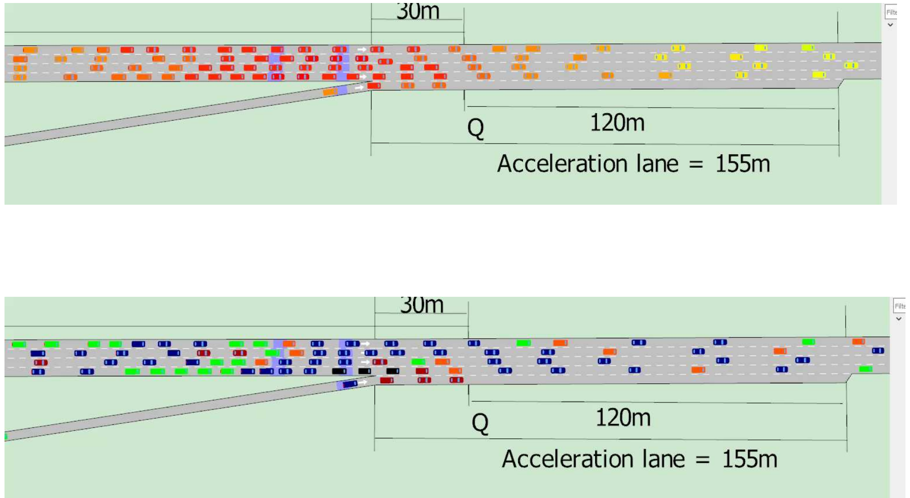
Higher Exiting Traffic Impacts on Throughput



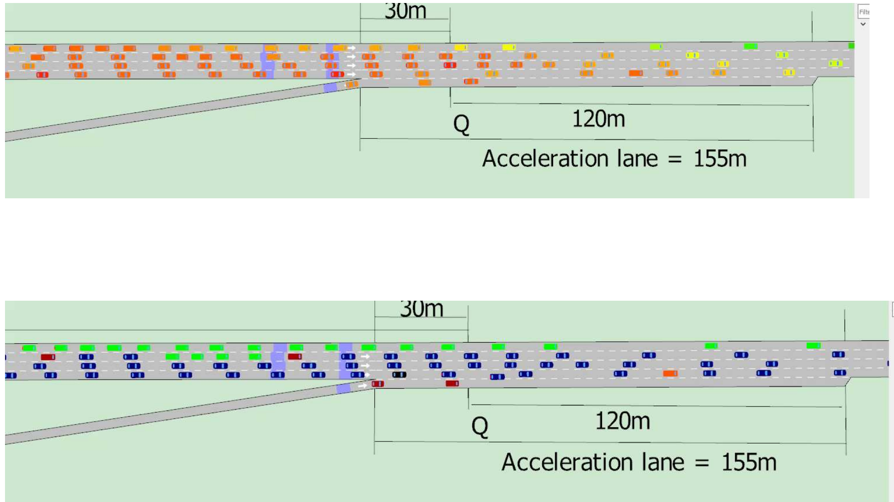
- **Increase of capacity when CACC grows from 0% to 20% and off-ramp traffic > 15%**
- **When off-ramp traffic is more than 20% of mainline volume, traffic management strategy is needed to address the large exiting flow, especially for the 80% and 100% CACC market penetration cases.**

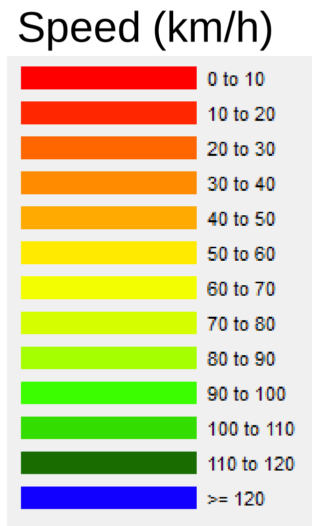
Simulation Animations

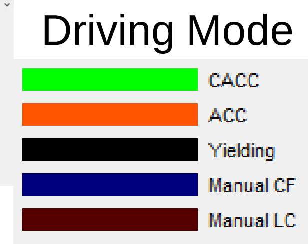
40% CACC



40% CACC with ML







In both cases: mainline input—9600 veh/h, on-ramp input—1200 veh/h

CALIFORNIA PATH

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**

CALIFORNIA PATH

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)**

CALIFORNIA PATH

VOLVO
Volvo Group North America

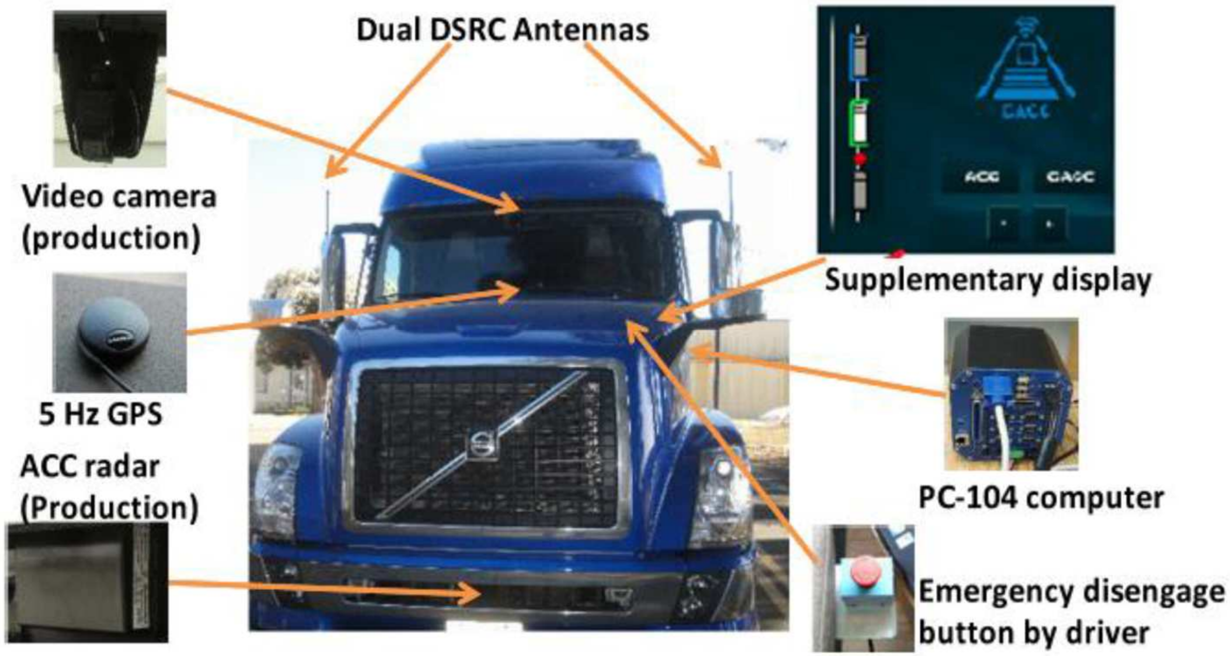
U.S. Department of Transportation
Federal Highway Administration

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**

Transport Canada Transports Canada

Environment and Climate Change Canada Environnement et Changement climatique Canada

PMG www.pmgtest.com

PIT Group by FPInnovations

cftr

NRC·CNRC

- **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**

PATH

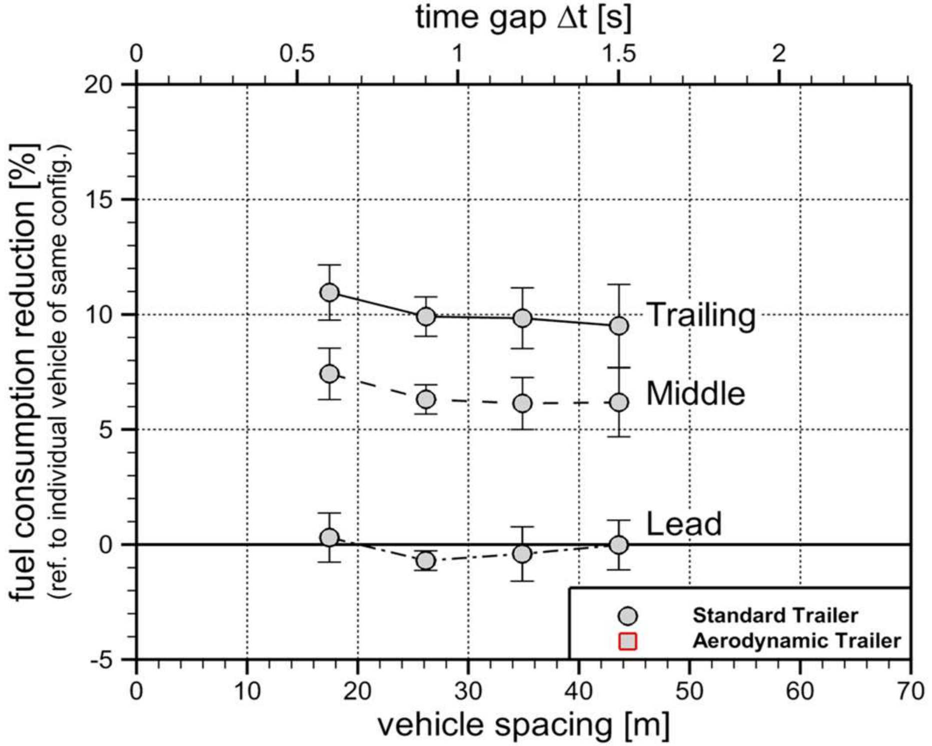
Testing Procedures

CALIFORNIA PATH

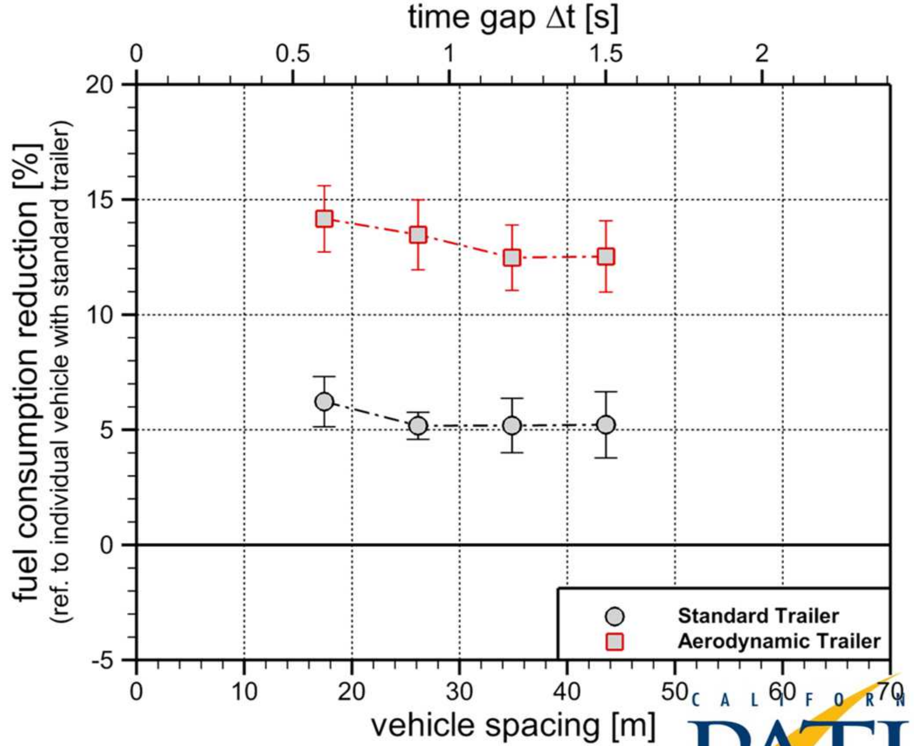
Testing at 0.6 s Time Gap in Blainville

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



CALIFORNIA PATH

Main Experimental Findings

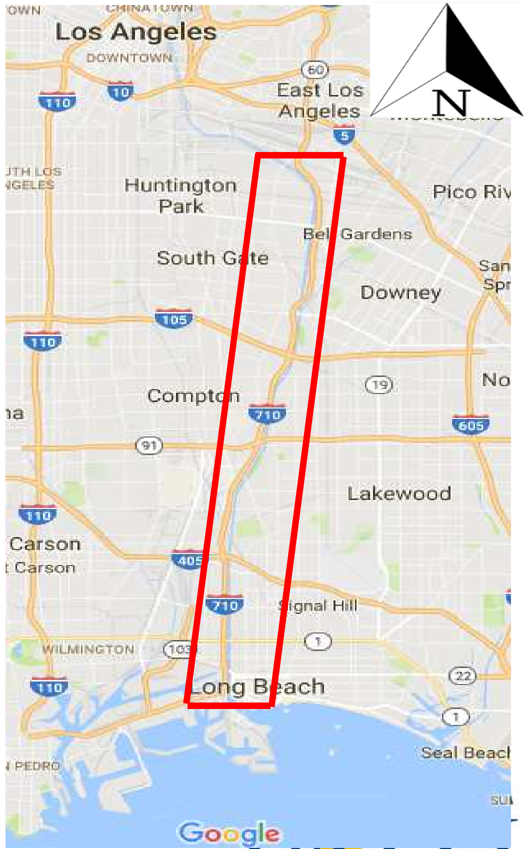
- **With standard trailers, trucks can save 5% energy on average in a three-truck CACC string**
- **With aerodynamic trailers, these savings grow to 12-14% compared to standard-trailer solo driving**
- **Drag savings not very sensitive to time gap values from 0.6 s to 1.5 s (57 to 143 ft. at 65 mph)**
- **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**

CALIFORNIA PATH

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**

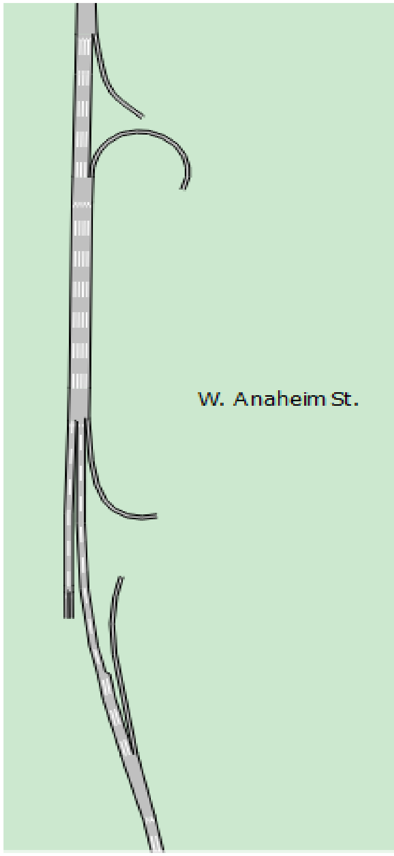
(models will be published later)

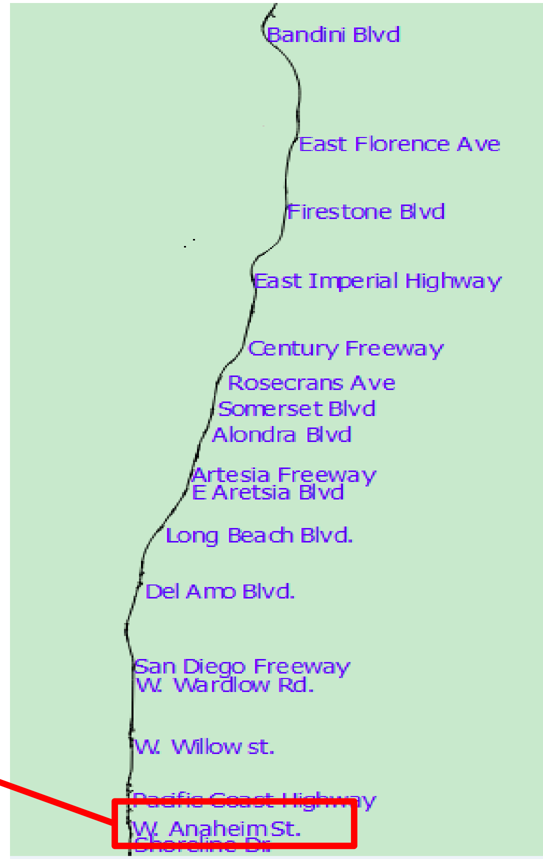


Modeling I-710 Corridor in Aimsun

Example of restricted geometric conditions

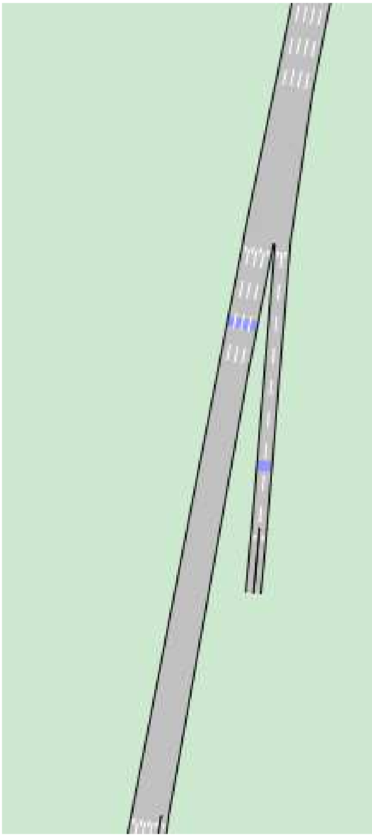
Traffic direction

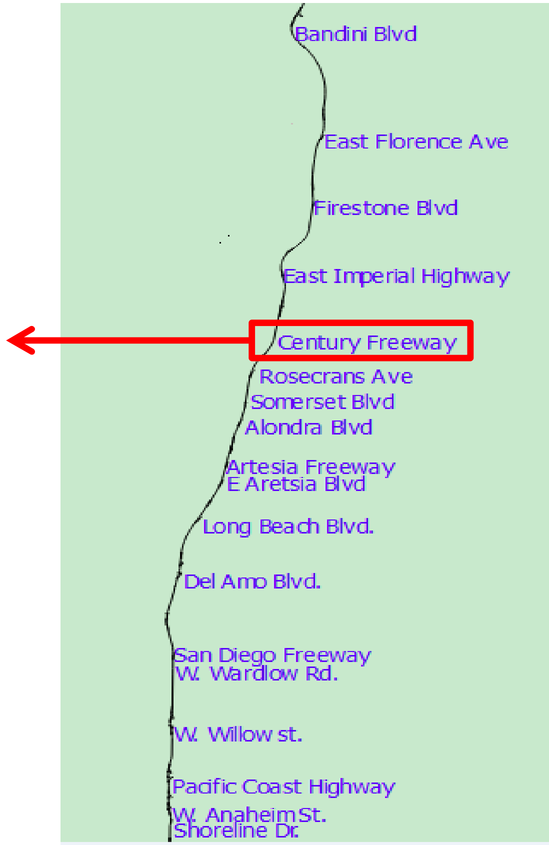




Modeling I-710 Corridor in Aimsun

Example of a major on-ramp from I-105



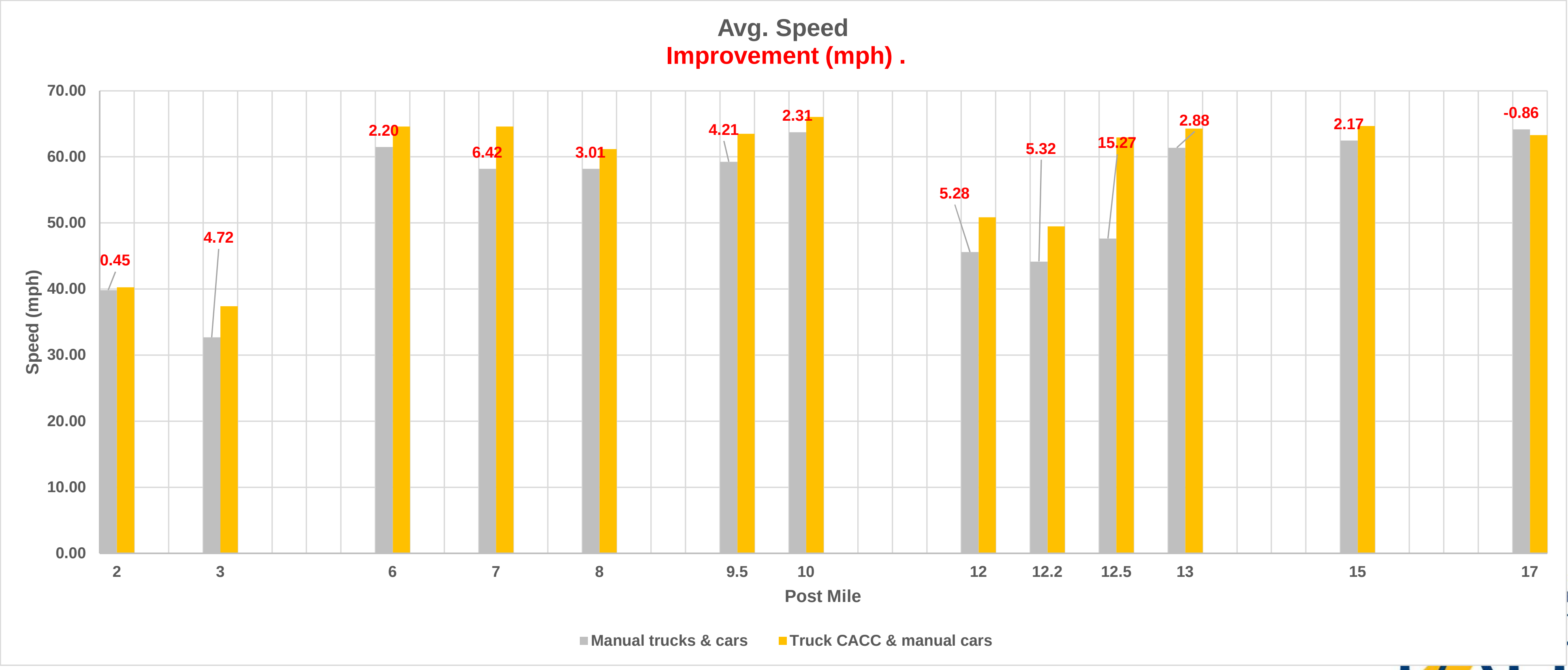


Simulation Conditions

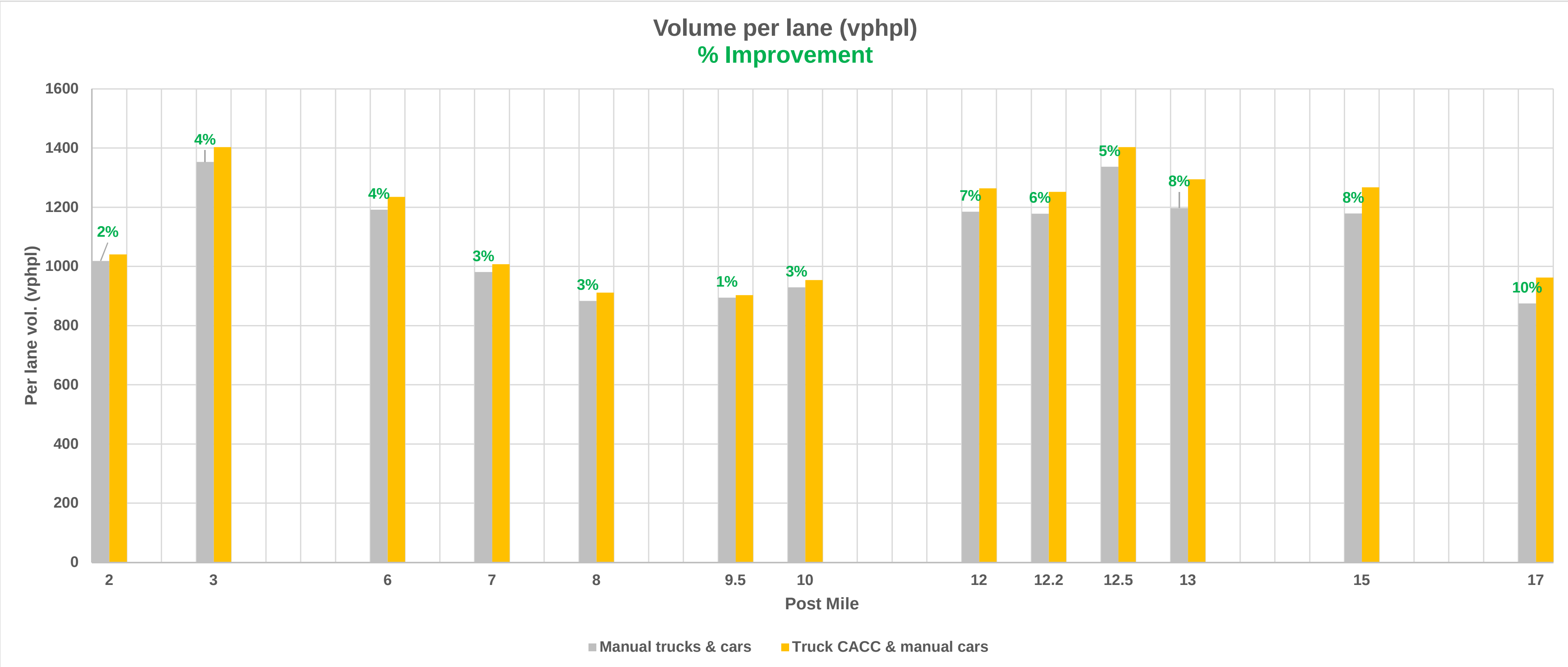
- **Shortest desired gap for truck CACC: 0.6 sec**
- **100% penetration rate for truck CACC, with cars all manual**
- **No lane change cooperation by trucks in CACC string**
- **Desired gap for trucks in manual mode : 1.5 sec**
- *Effects of desired gap & penetration rate, among other factors, will be studied*

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

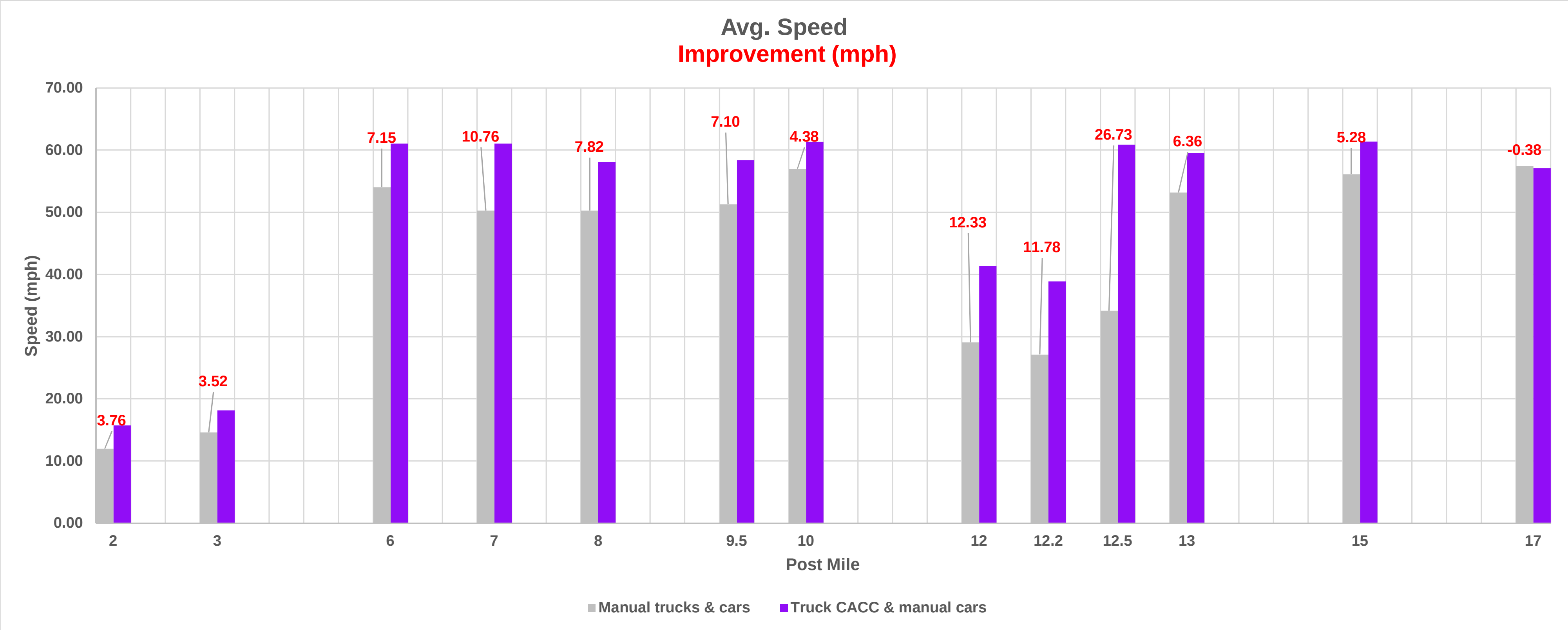
Average speeds at 13 detector stations



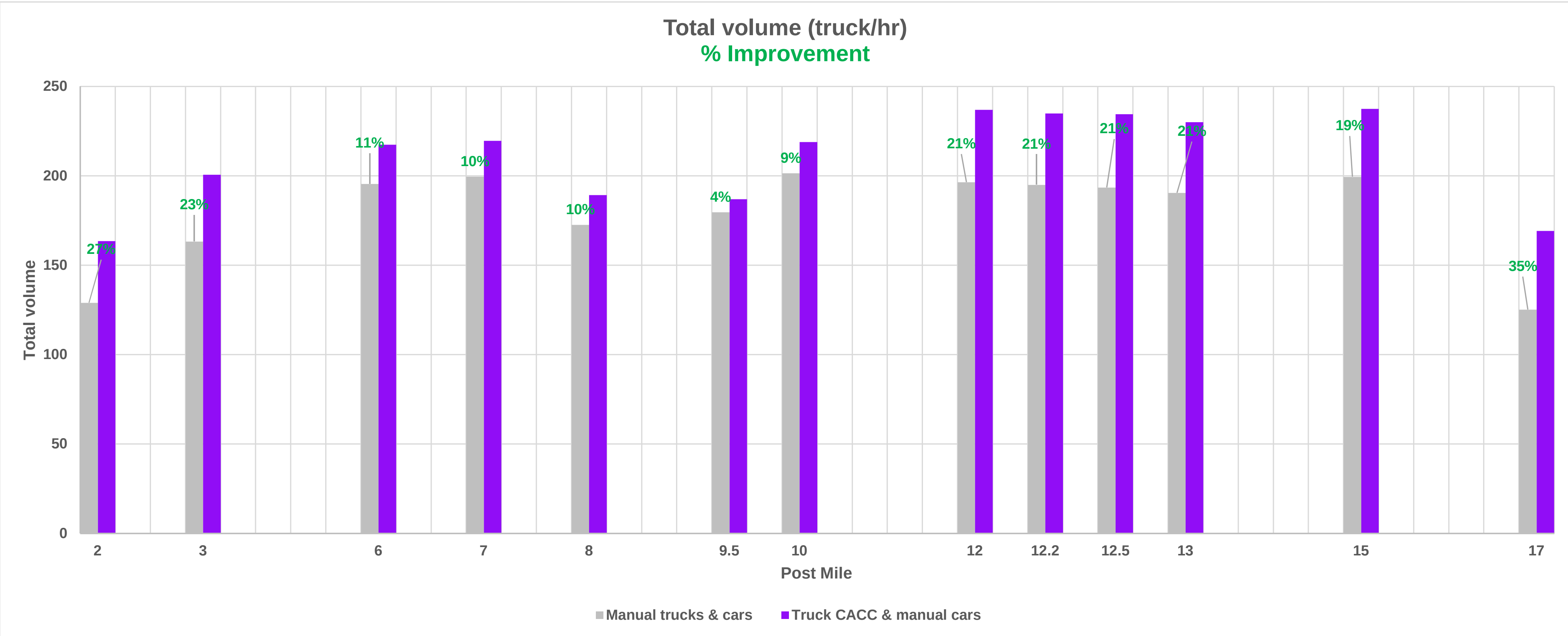
Simulation Results: Total Traffic Volume



Simulation Results: 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)

CALIFORNIA PATH

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**

CALIFORNIA PATH

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