Assessing the Traffic and Energy Impacts of Connected and Automated Vehicles (CAVs)

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Impact Assessment Challenges

- Traffic and energy impacts scale strongly with market penetration of CAVs
- Large numbers of CAVs are not available for full-scale testing, and such testing would be very expensive even if they were available

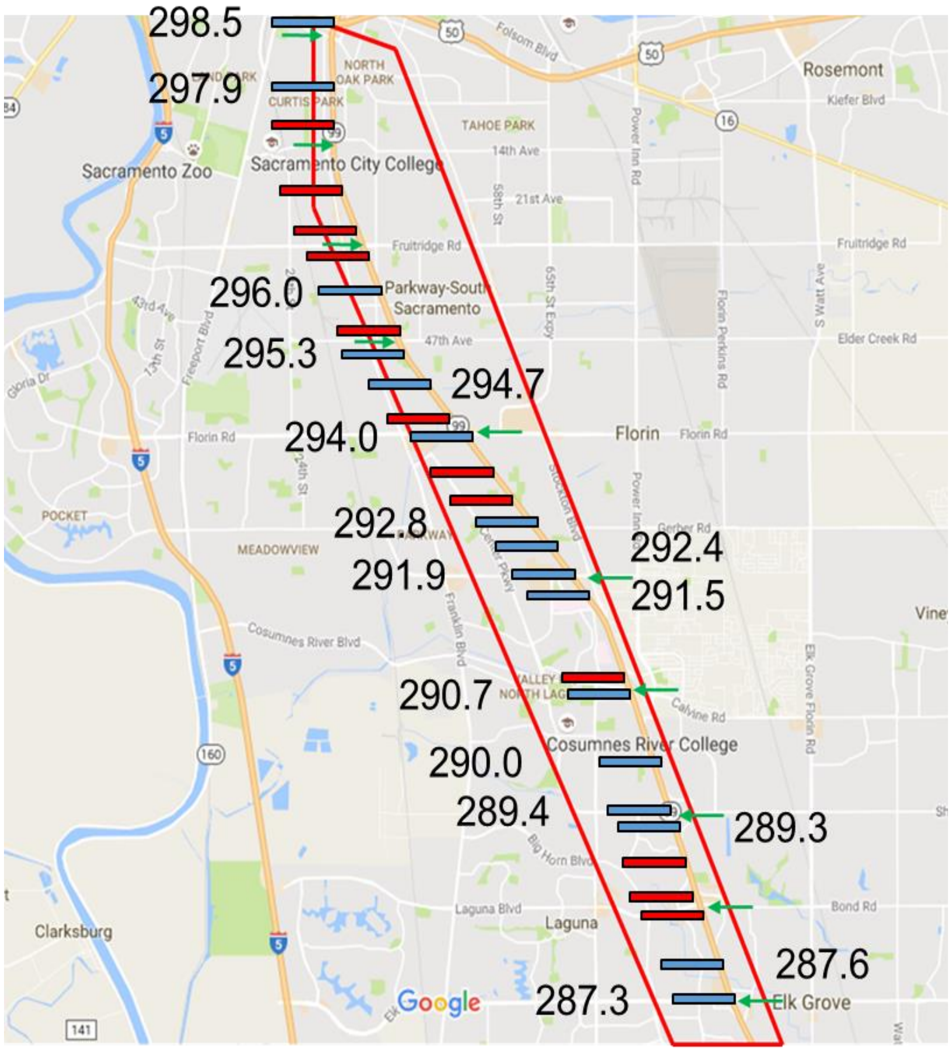
→ Must rely on microscopic computer simulations to estimate these impacts

- Needs high-fidelity, well calibrated models of normal driving behavior
- Needs high-fidelity models of CAV behavior, derived from vehicle testing

Traffic Microsimulations of CAVs

- **Start from high-fidelity representations of human driver car following and lane changing**
- **Calibrate human driver model to traffic data from a real freeway corridor**
- **First, model ACC and CACC car following based on full-scale vehicle experimental data**
- **Model traffic management strategies for taking advantage of CAV capabilities**
- **Analyze simulated vehicle speed profiles to estimate energy consumption**
- ***Results for Level 1 automation are relevant for higher levels of automation***

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



- **Length: 13 miles = 21 km**
- **Morning peak: 6-9 AM**
- **16 on-ramps**
- **11 off-ramps, metered**
- **Recurrent delay mainly caused by high on-ramp demand**

5-minute interval vehicle count and speed data at reliable detectors are used for calibration

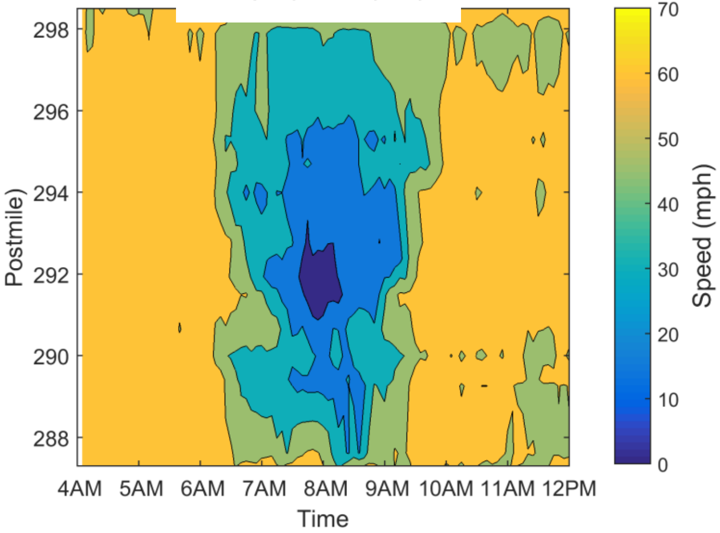
🟥 ***Unreliable Detector: not considered in calibration***

🟦 ***Reliable Detector: considered in calibration***

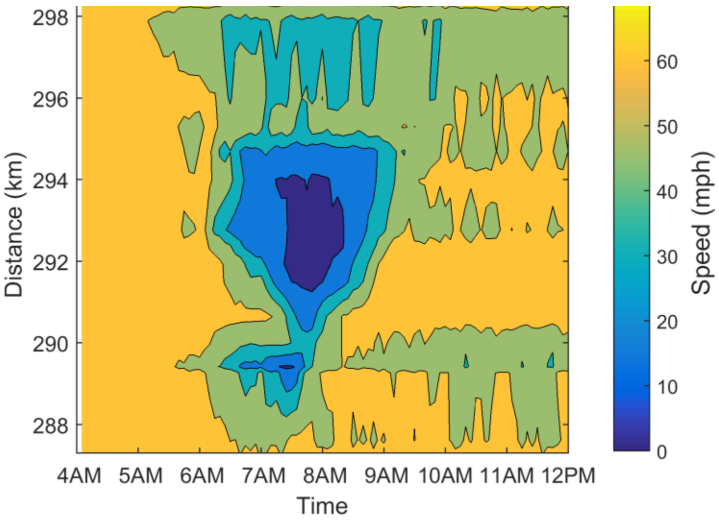
← ***Interchange***

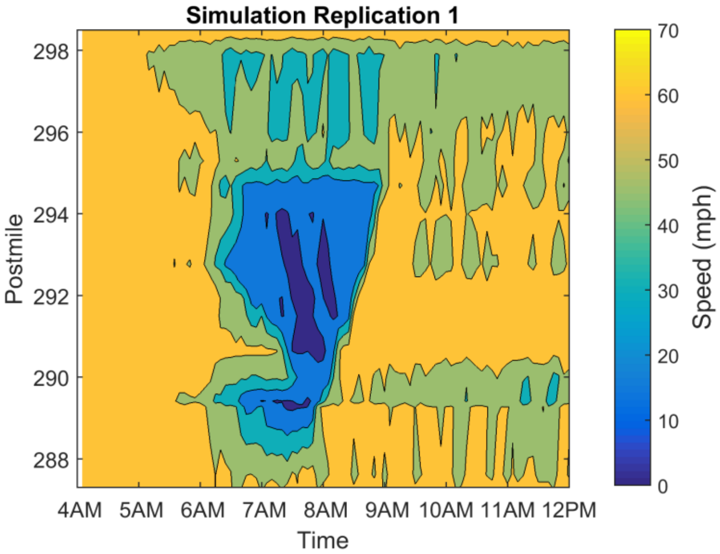
Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

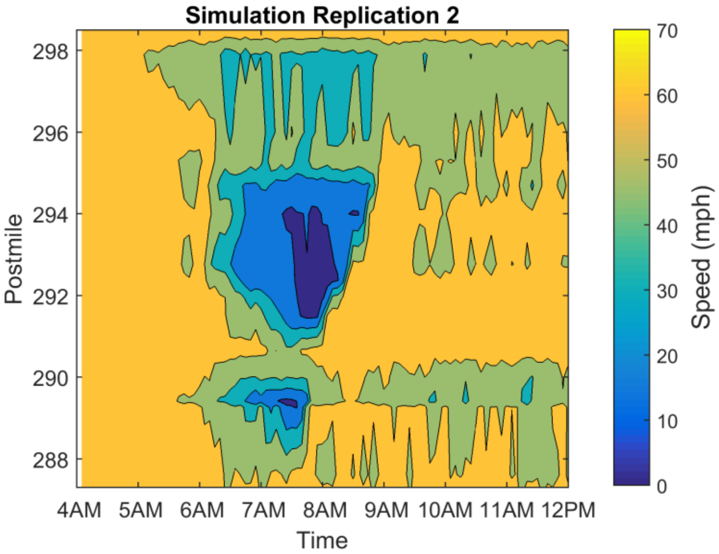
Field Data



Averaged Simulation Data

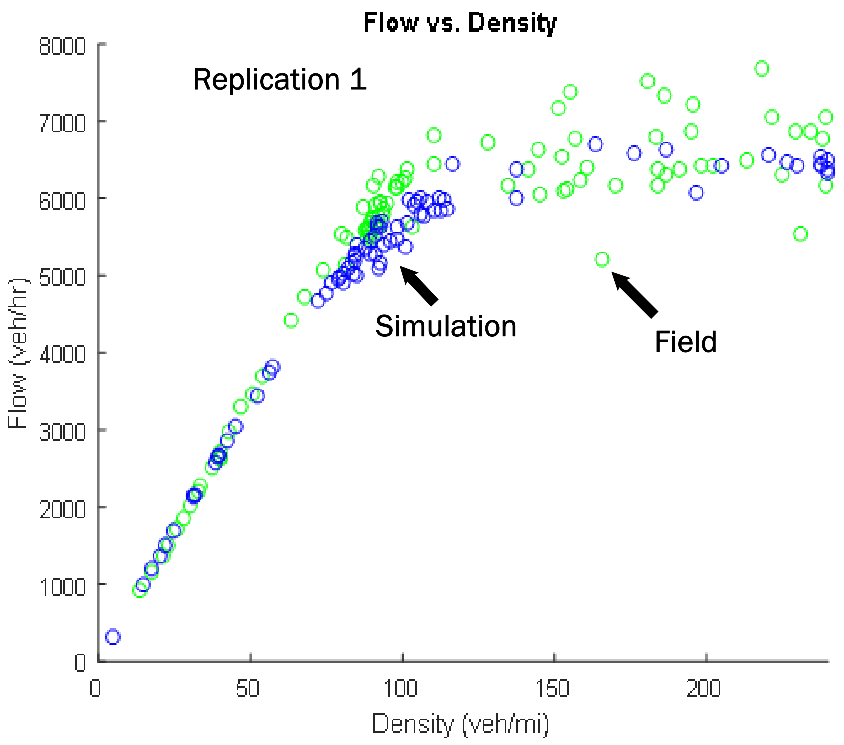


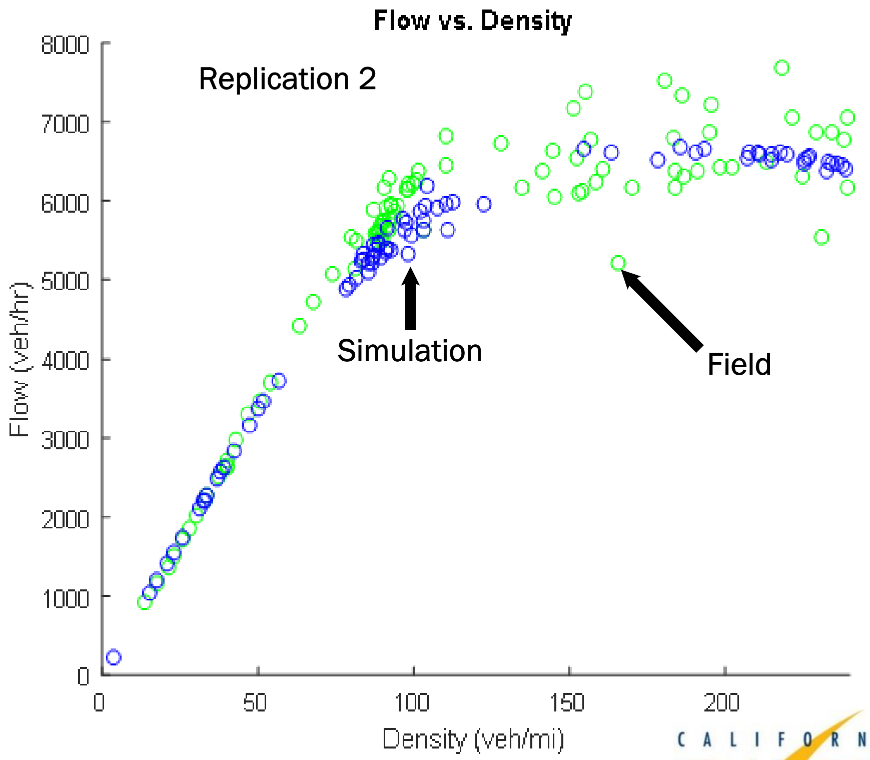




Manual Driving Model Calibration on CA SR-99 Corridor (Sacramento)

- **Comparison of fundamental diagrams of simulated and field observed flow-density relationships**
- **Two sample replications at one detector location**

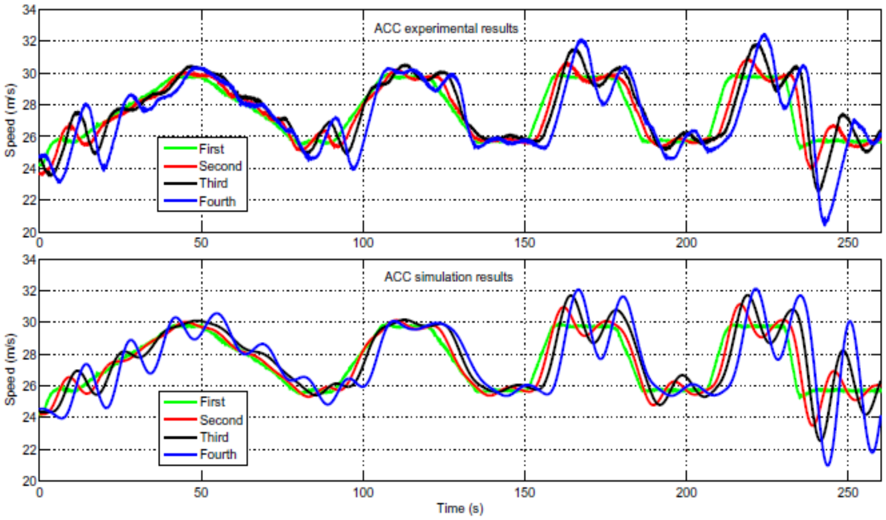




AACC Car-Following Model Predictions Compared to Calibration Test Results

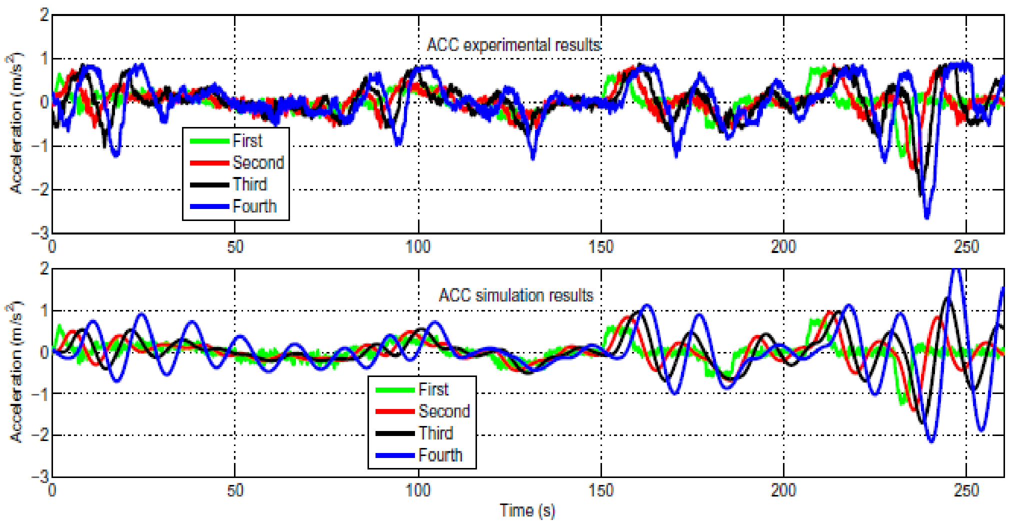
Speeds

(Test above, model below)



Accelerations

(Test above, model below)



Note string instability (amplification of disturbance)

CACC Car-Following Model Predictions Compared to Calibration Test Results

Speeds

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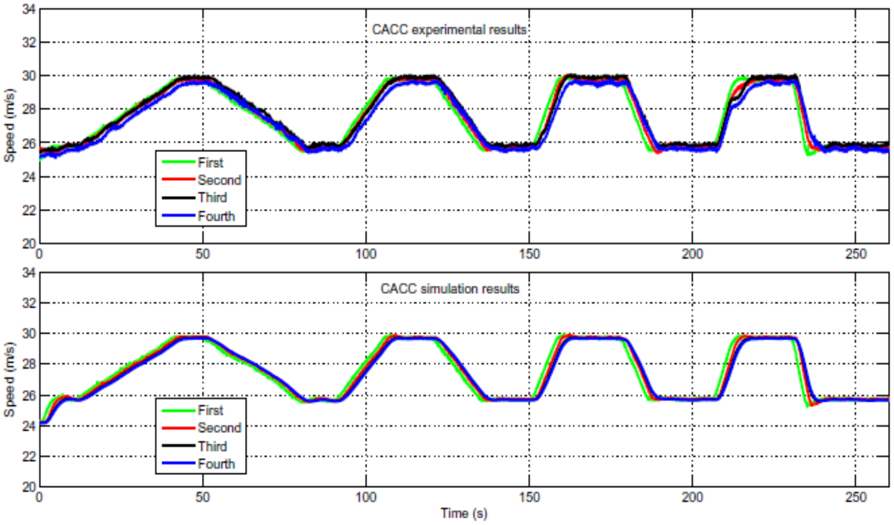

Accelerations

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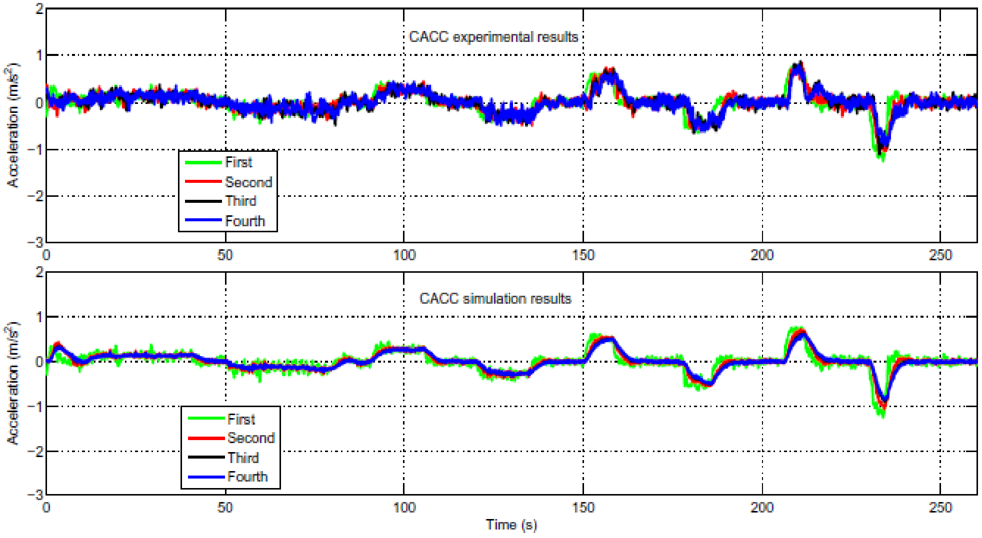
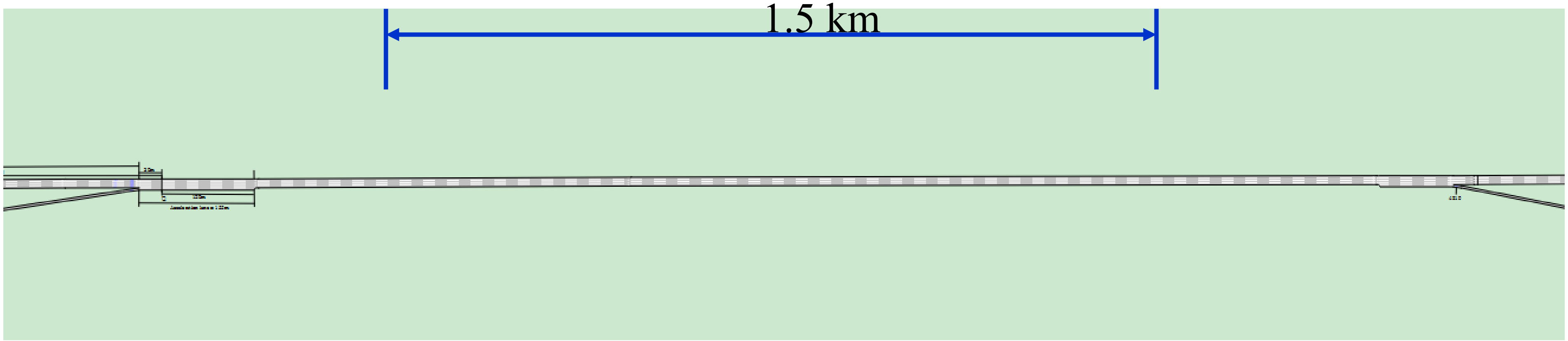


Simple Highway Network Layout for Simulating Key Performance Trends

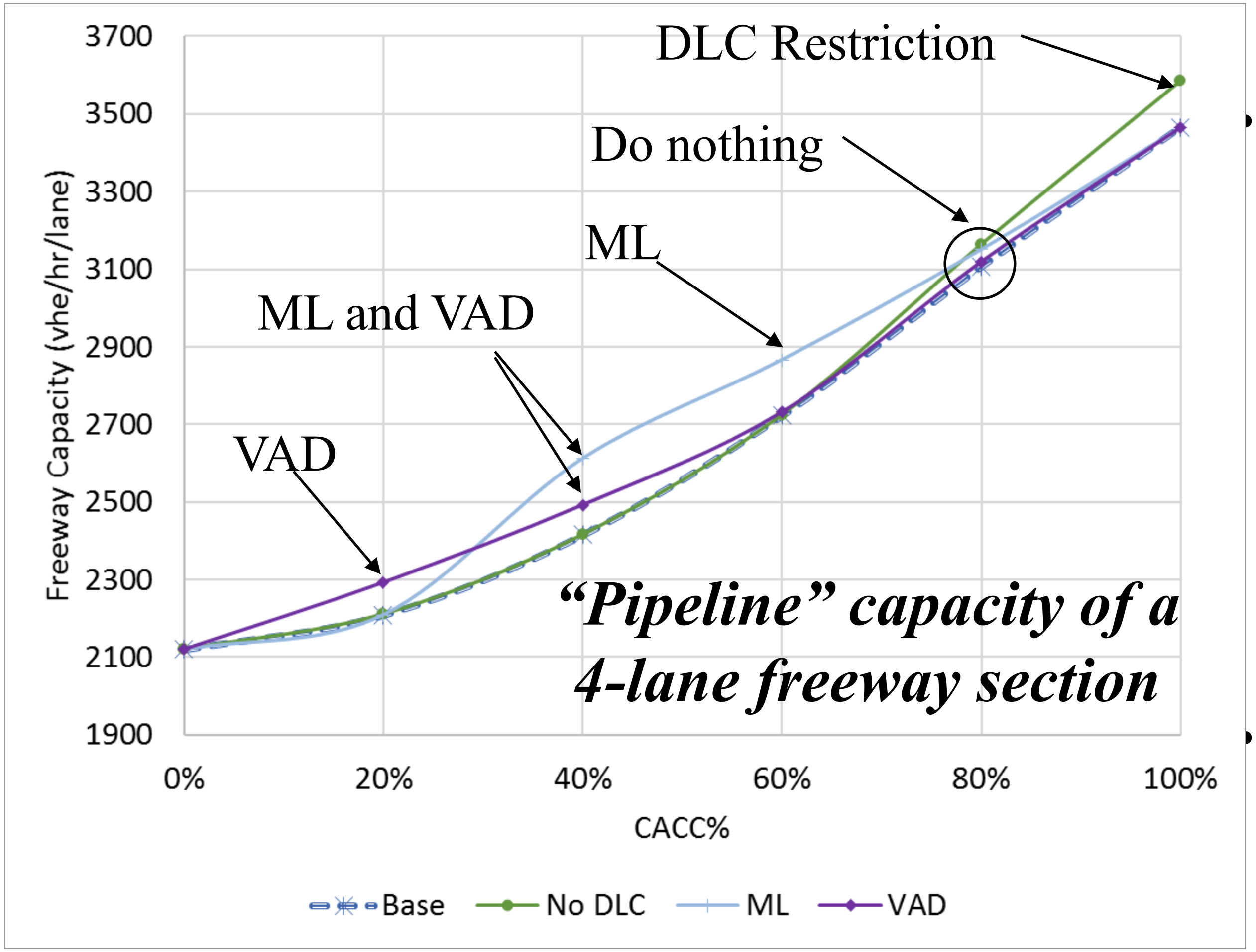
- Four-lane mainline highway, traffic generated further upstream
- One-lane on-ramp, volumes from 300 to 1200 veh/hr
- One-lane off-ramp, volume from 5% to 25% of mainline
- On-ramp and off-ramp are 1.5 km apart
- Simulate far enough upstream and downstream to stabilize results



Aspects of Performance Evaluated in Simulations

- **Maximum downstream throughput achievable**
- **Travel times and delays traversing test section**
- **Energy consumption**
- **Effects of variations in:**
  - **AACC, 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**

Lane Capacity Increases for Different Management Strategies with CACC

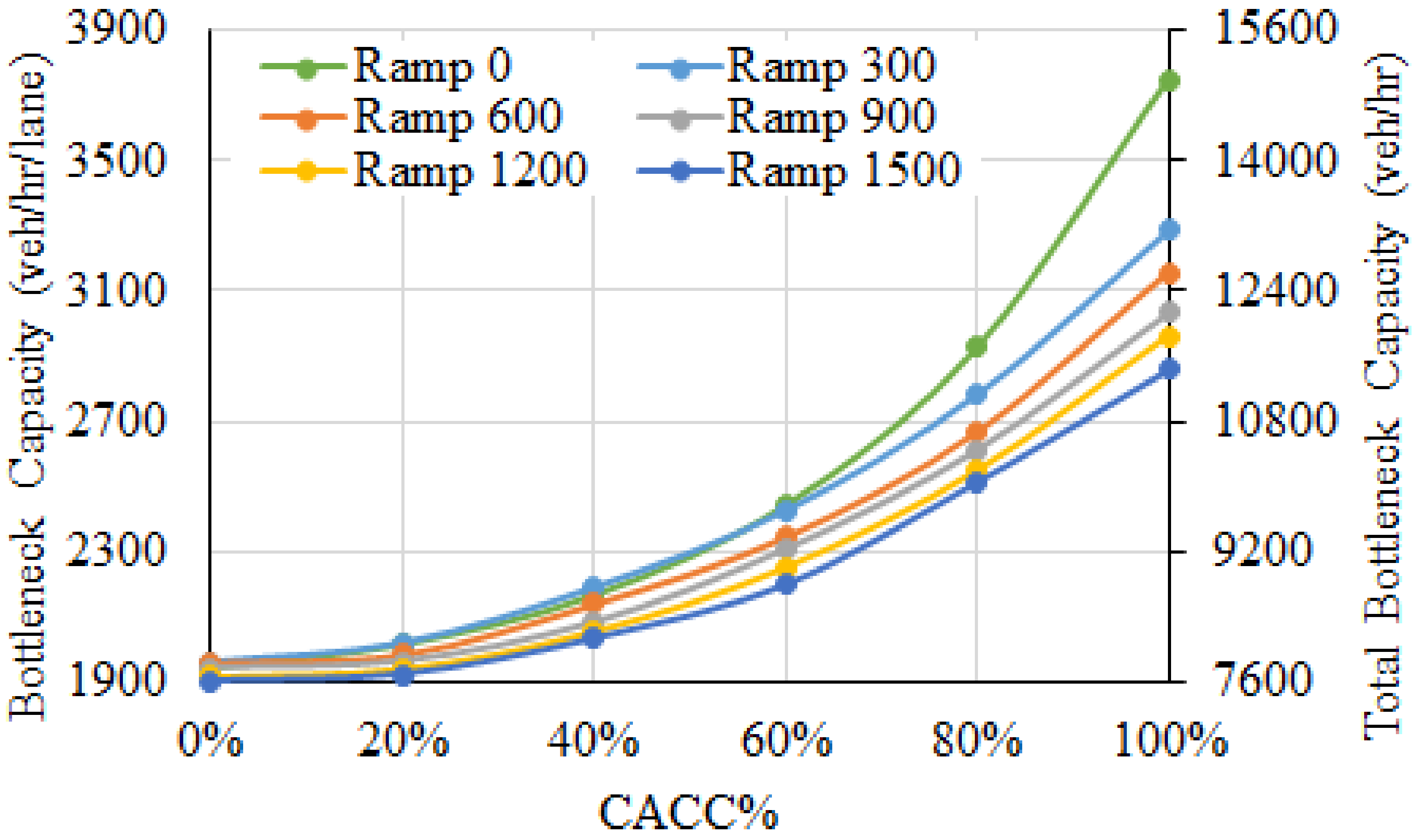


"Pipeline" capacity of a 4-lane freeway section

- Strong increase with CACC market penetration
- Managed lane (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 for different CACC market penetrations

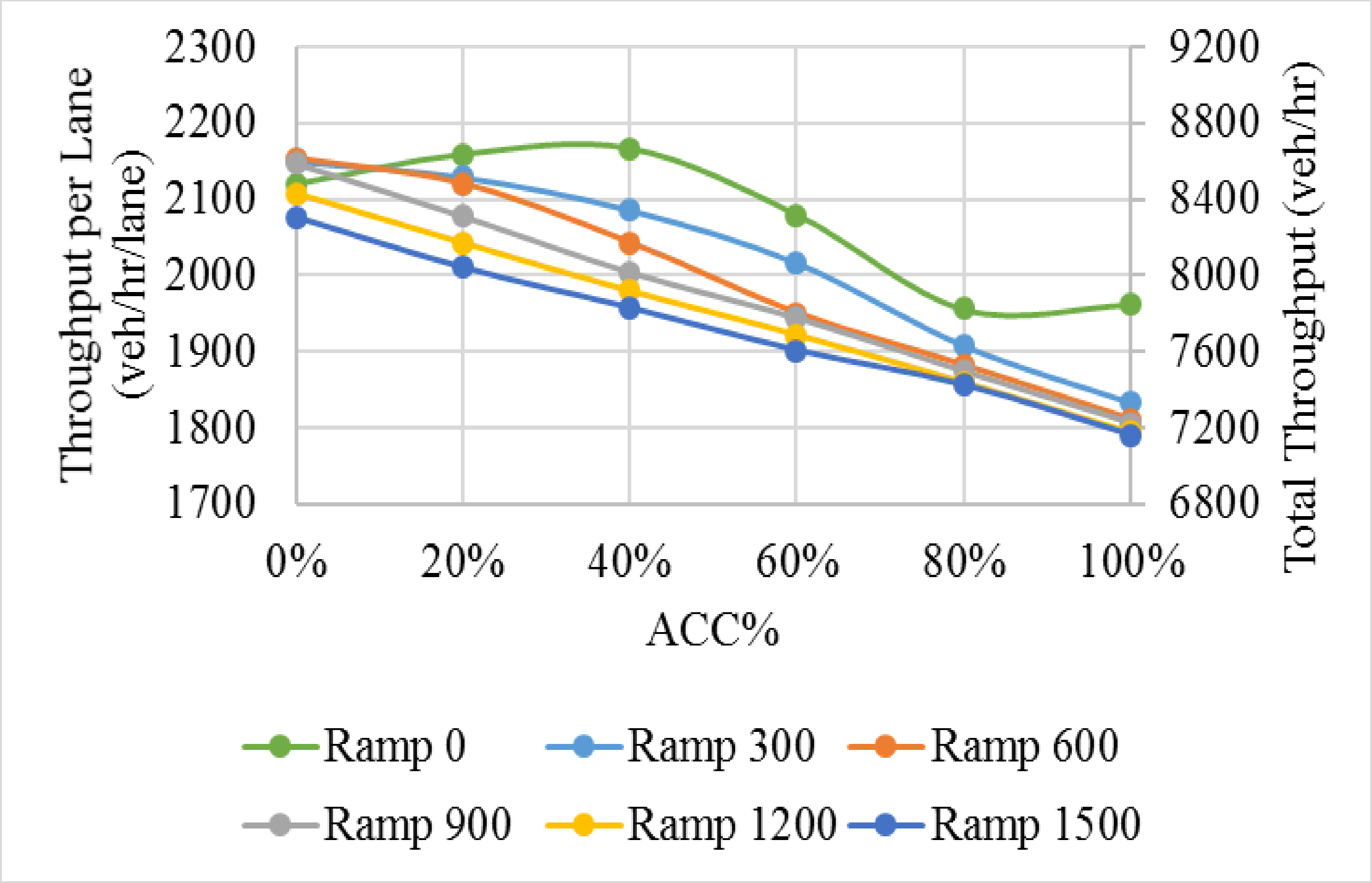
CACC Throughput with Varying On-Ramp Volumes

Ramp traffic entering in veh/hr
Mainline input traffic volume is at pipeline capacity for that market penetration



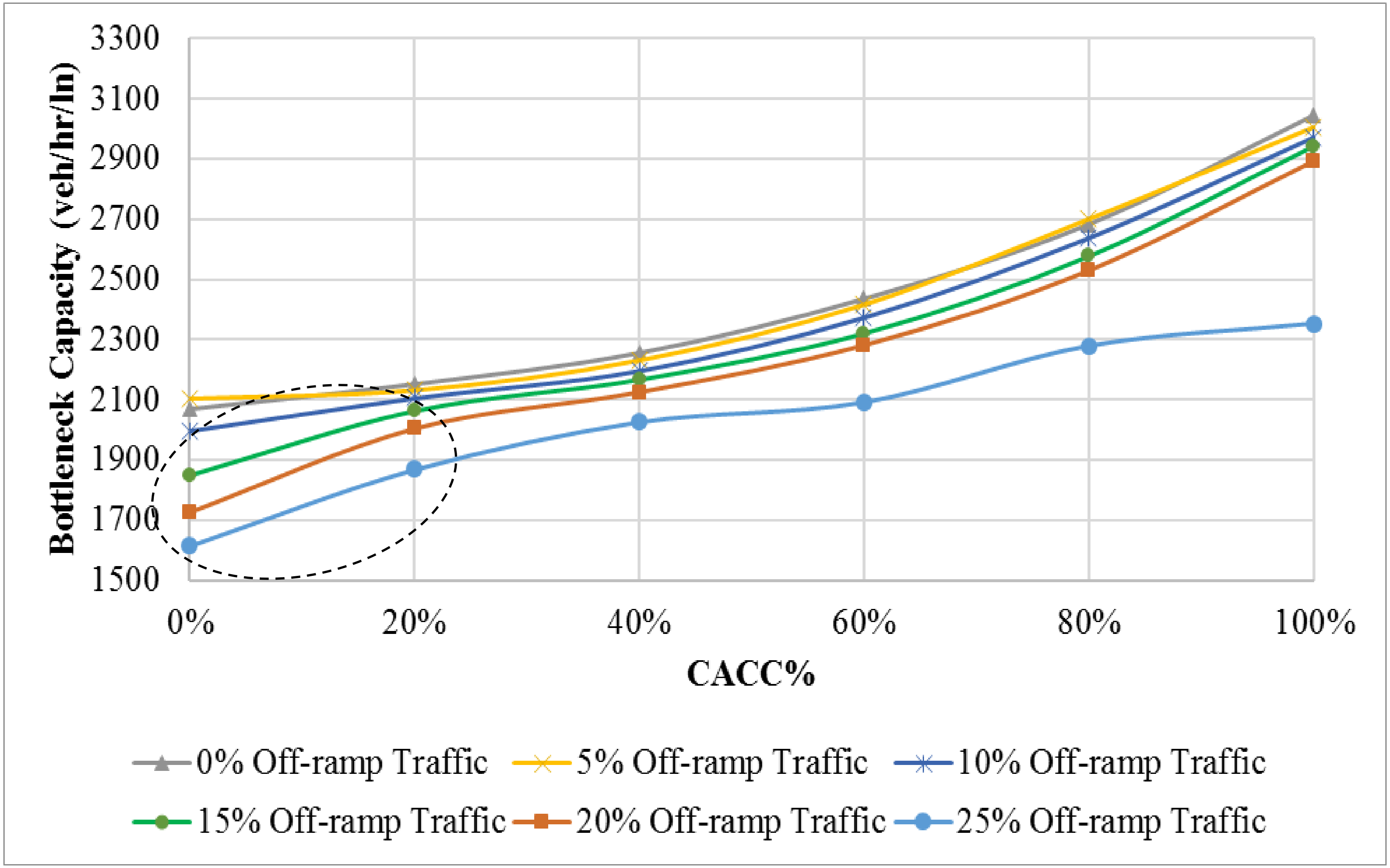
Downstream throughput reduces as on-ramp traffic increases

AACC Throughput with Varying On-Ramp Volumes



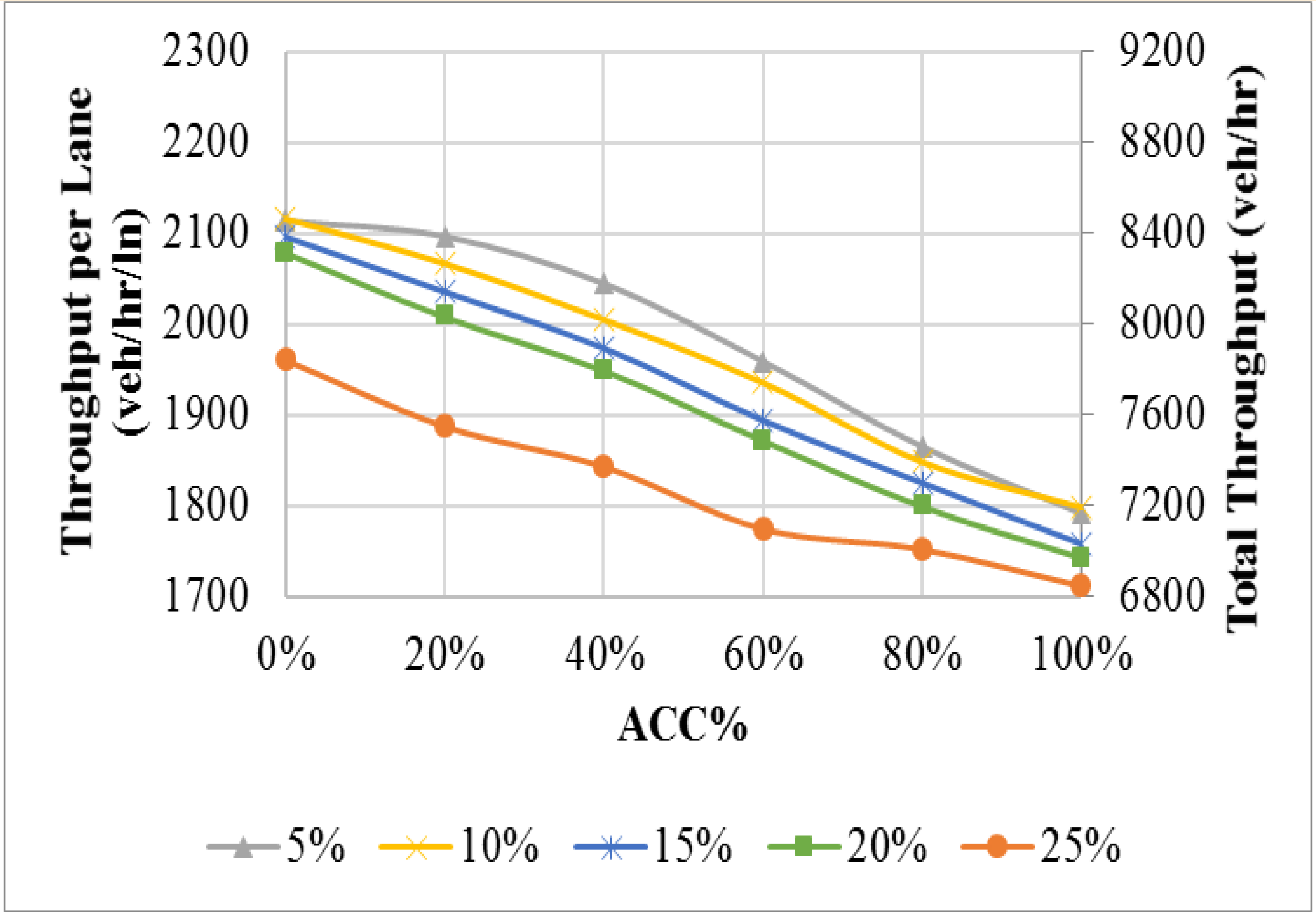
Traffic flow instability with more AACC (lacking V2V communication capability)

CACC Throughput for Various Exiting Traffic Volumes



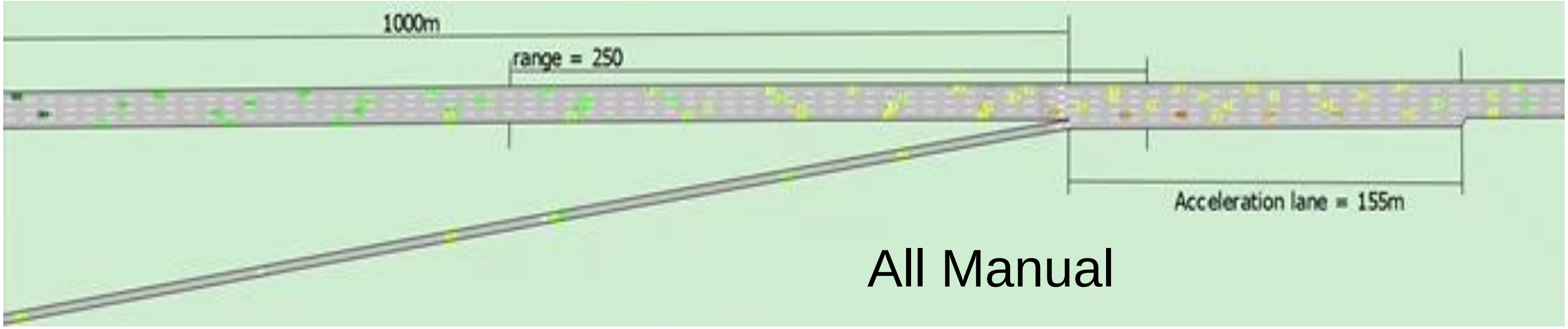
- When off-ramp traffic exceeds 20% of mainline volume, traffic management strategies are needed

AACC Throughput for Various Exiting Traffic Volumes

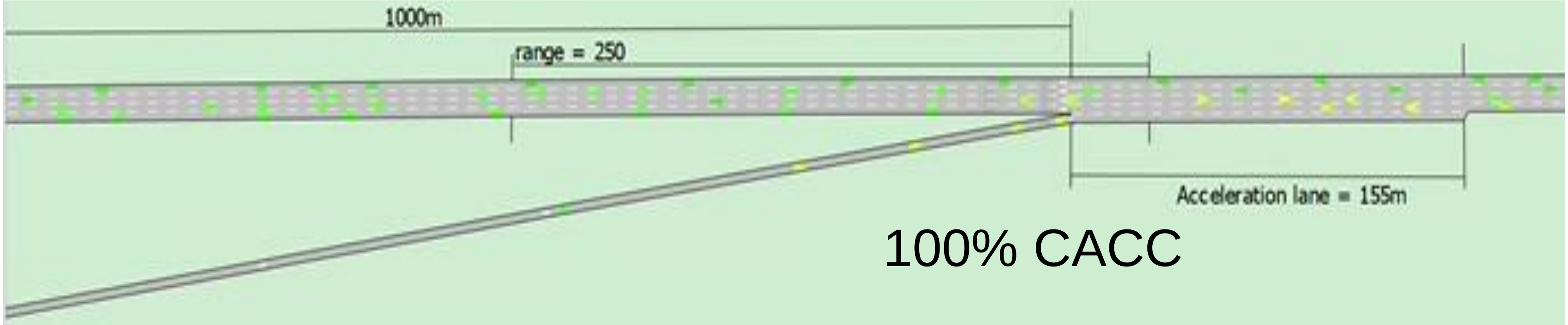


Traffic flow instability with more AACC (lacking V2V communication capability)

Animations Comparing Manual and CACC Driving at a Merge Junction for the Same Traffic Volume



All Manual



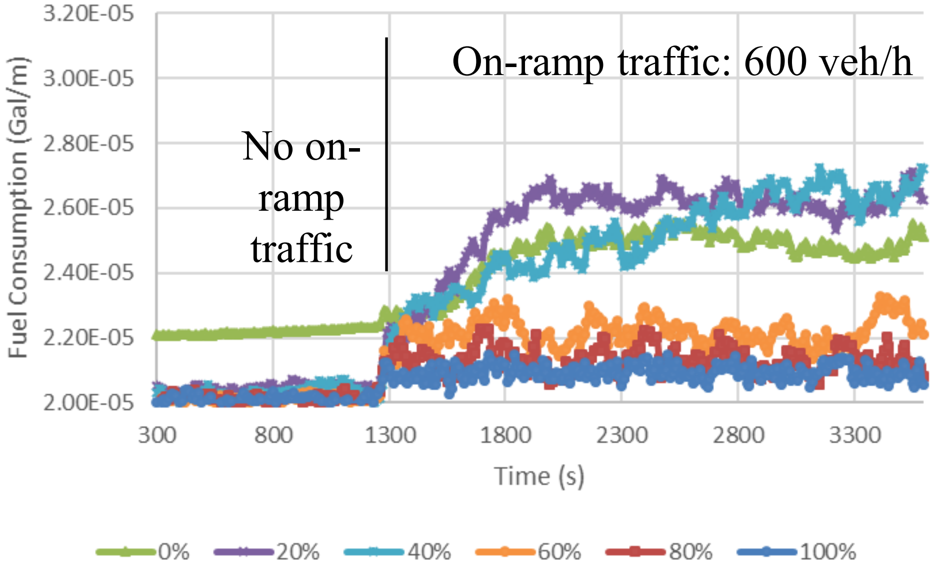
100% CACC

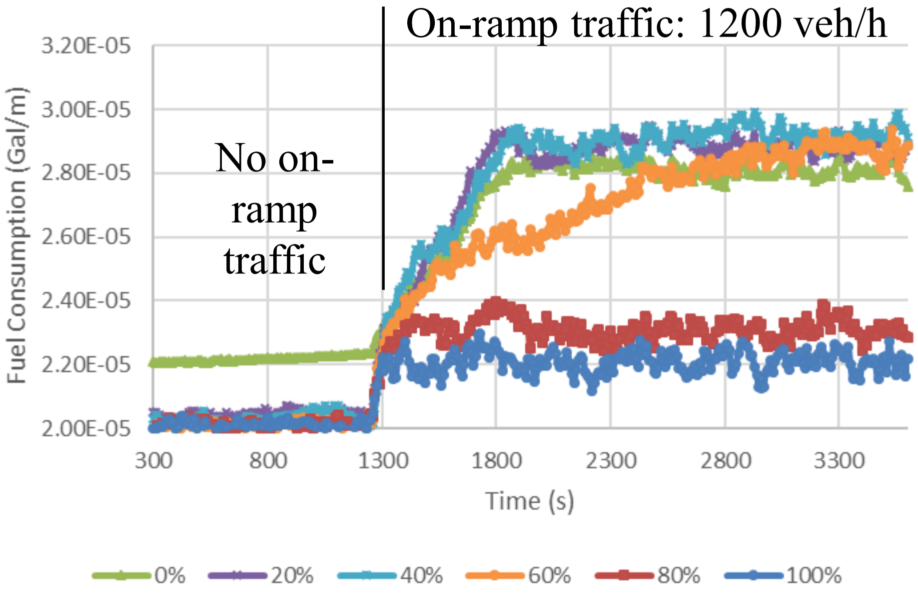
Mainline input: 7500 veh/hr On-ramp input: 900 veh/hr

Fuel Consumption Comparisons

- **Mainline upstream input: fixed as the pipeline capacity achievable with all-manual driving**
- **On-ramp input: 300 to 1500 veh/hr**
- **CACC market penetration: 20% to 100%**
- **CACC operation strategies: CACC with Managed Lanes (ML) and Vehicle Awareness Devices (VAD)**
- **AACC also compared (without cooperation)**

Fuel Consumption vs. Time with Addition of On-Ramp Traffic

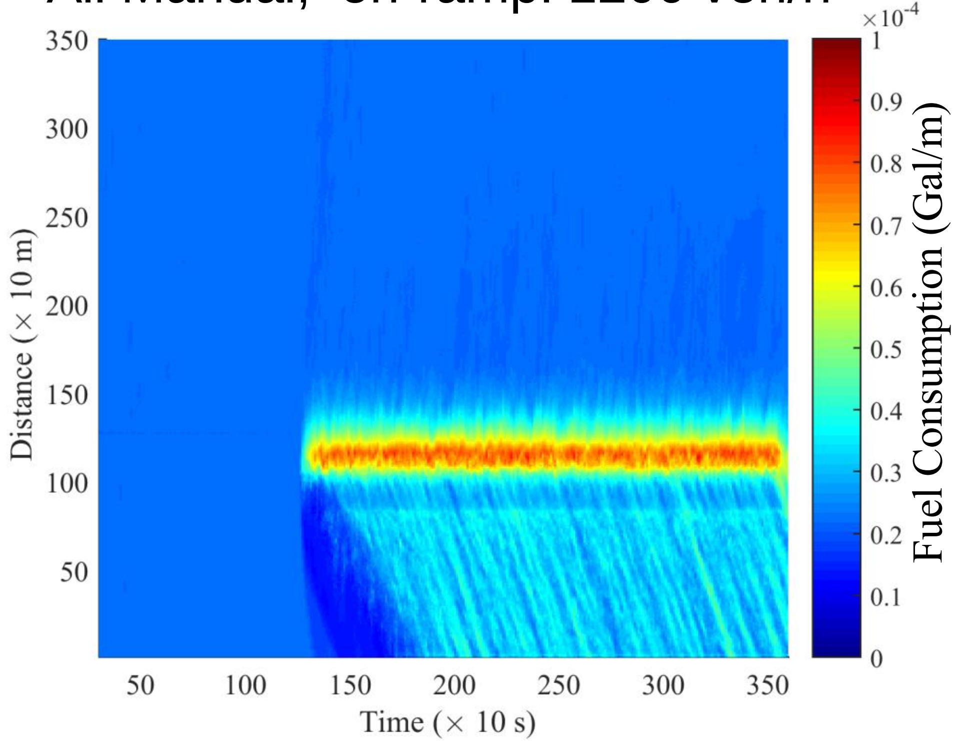




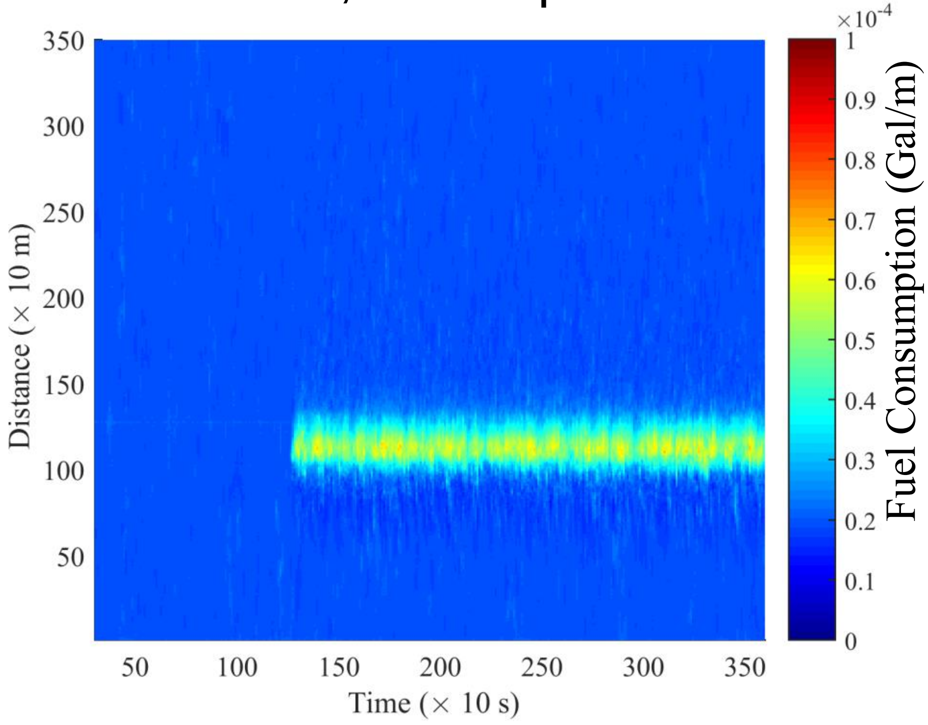
- **CACC from 0% to 100%, in 20% increments**
- **Lower % CACC cases are worse than the all-manual case due to the negative impact of the ACC controller on the lead vehicle.**
- **Above a critical CACC market penetration, traffic becomes free flow, reducing fuel consumption.**

Fuel Consumption: Spatiotemporal Pattern

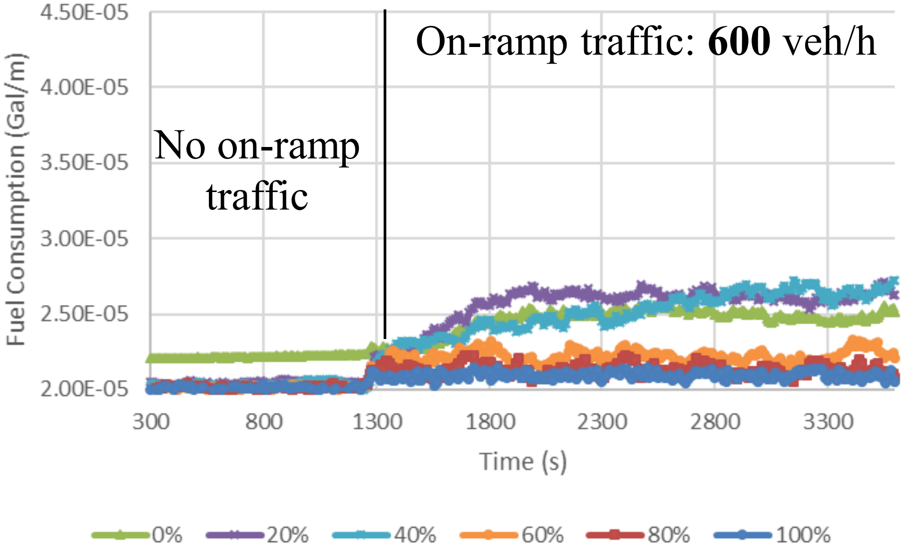
All Manual, on-ramp: 1200 veh/h



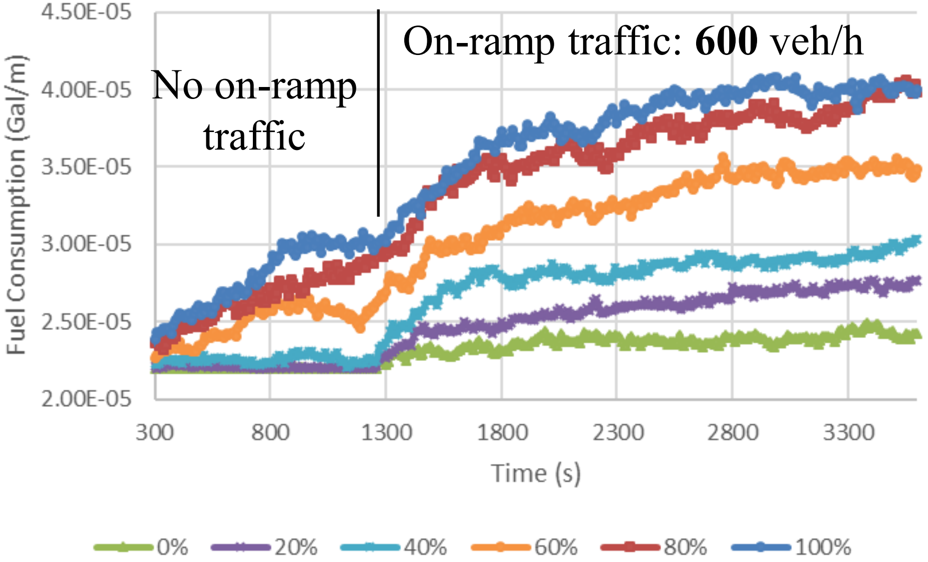
100% CACC, on-ramp: 1200 veh/h



Fuel Consumption: ACC vs. CACC



CACC

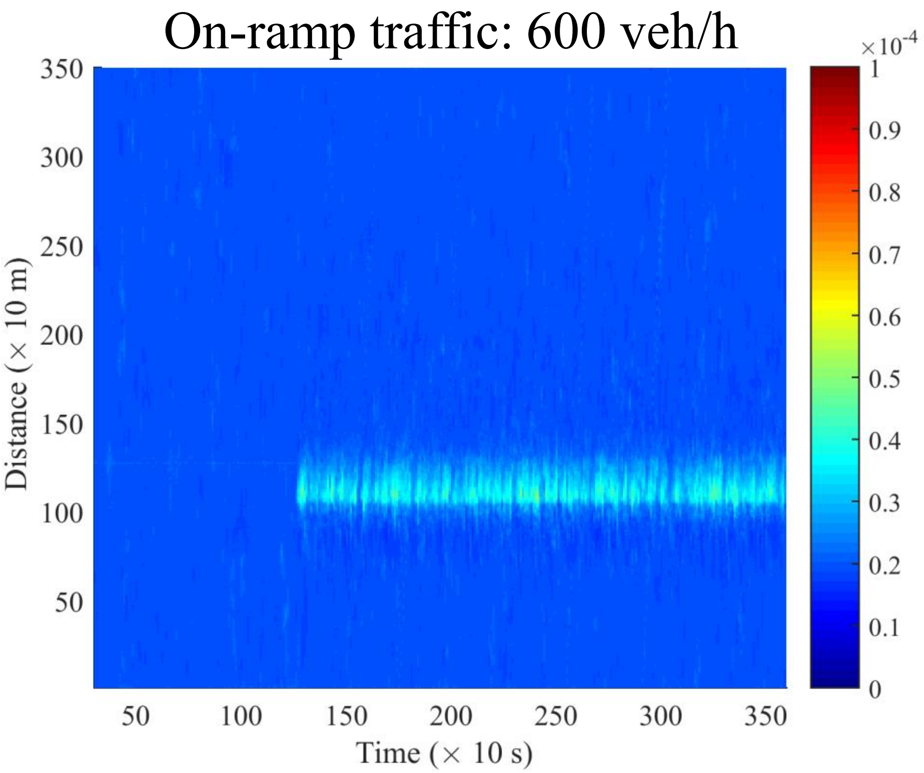


ACC

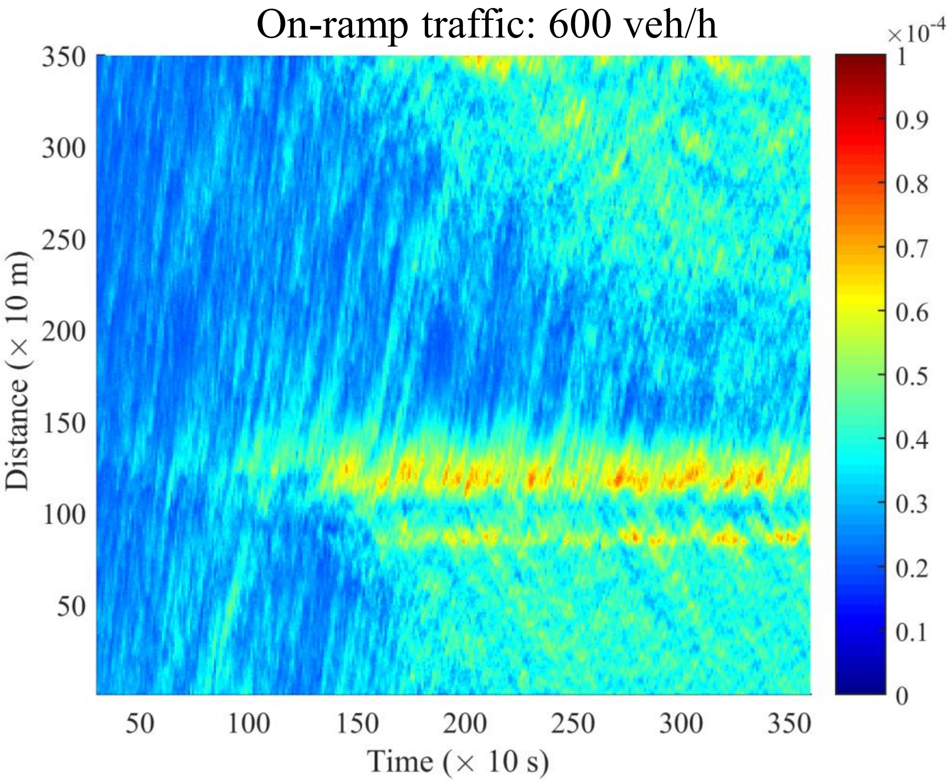
- **When the mainline and on-ramp traffic volumes are the same, the fuel consumption rate is almost twice as much in the 100% ACC case as in the 100% CACC case.**

Fuel Consumption: ACC vs. CACC

100% CACC



100% ACC



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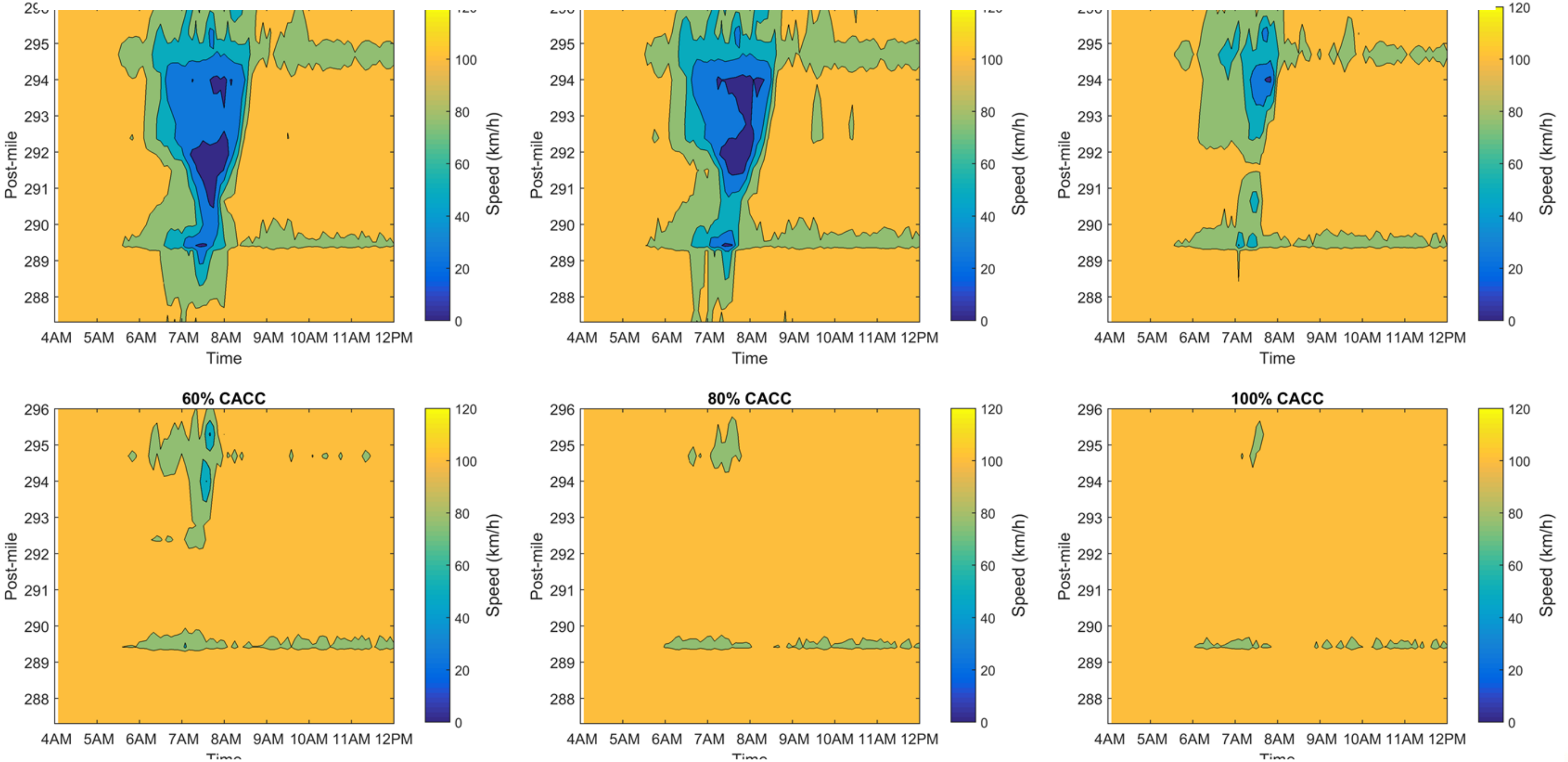
Effects of CACC Market Penetration on SR-99 Corridor Congestion

Traffic speeds from 4 am to 12 noon at current traffic volume

All manual (today) **20% CACC** **40% CACC**



60% CACC **80% CACC** **100% CACC**

Primary Findings from ACC/CACC Simulation Evaluations (1/2)

- Automation without cooperation reduces traffic throughput and energy efficiency because of unstable car following
- Throughput improvement grows quadratically with cooperative vehicle following market penetration
- If cooperative automation string (platoon) length is not limited, strings grow very long, interfering with lane changing (recommend limiting to 10 cars)
- Choose gap between strings (platoons) to balance between efficient use of space and leaving gaps to permit lane changing (1.5 s looks reasonable)

Primary Findings from ACC/CACC Simulations (2/2)

- **Performance is sensitive to assumptions about desire of drivers to change lanes to go faster (discretionary lane changing -- DLC)**
- **Managed lanes for CACC can improve traffic conditions in certain cases (when CACC market penetration and number of managed lanes are well matched)**
- **With CACC gap preferences of drivers in our field test, highway throughput could increase about 50% when all drivers use CACC**
- **Additional throughput increases will need active control of merging and lane changing**