A Hardware-in-the-Loop Simulation System for Assessing Intersections with Cooperative Traffic Signal Control and Connected Automated Vehicles

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November 16-18, 2020

Background

- Rapid evolution of connected automated vehicles (CAV) allows
  - Advanced intersection traffic management
  - Maximization of **intersection mobility** and **energy efficiency**
- Performance evaluation of new technologies
  - Require quantitative approach
  - Need to address the uncertainty under **different market penetrations of CAV**

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Research Objectives

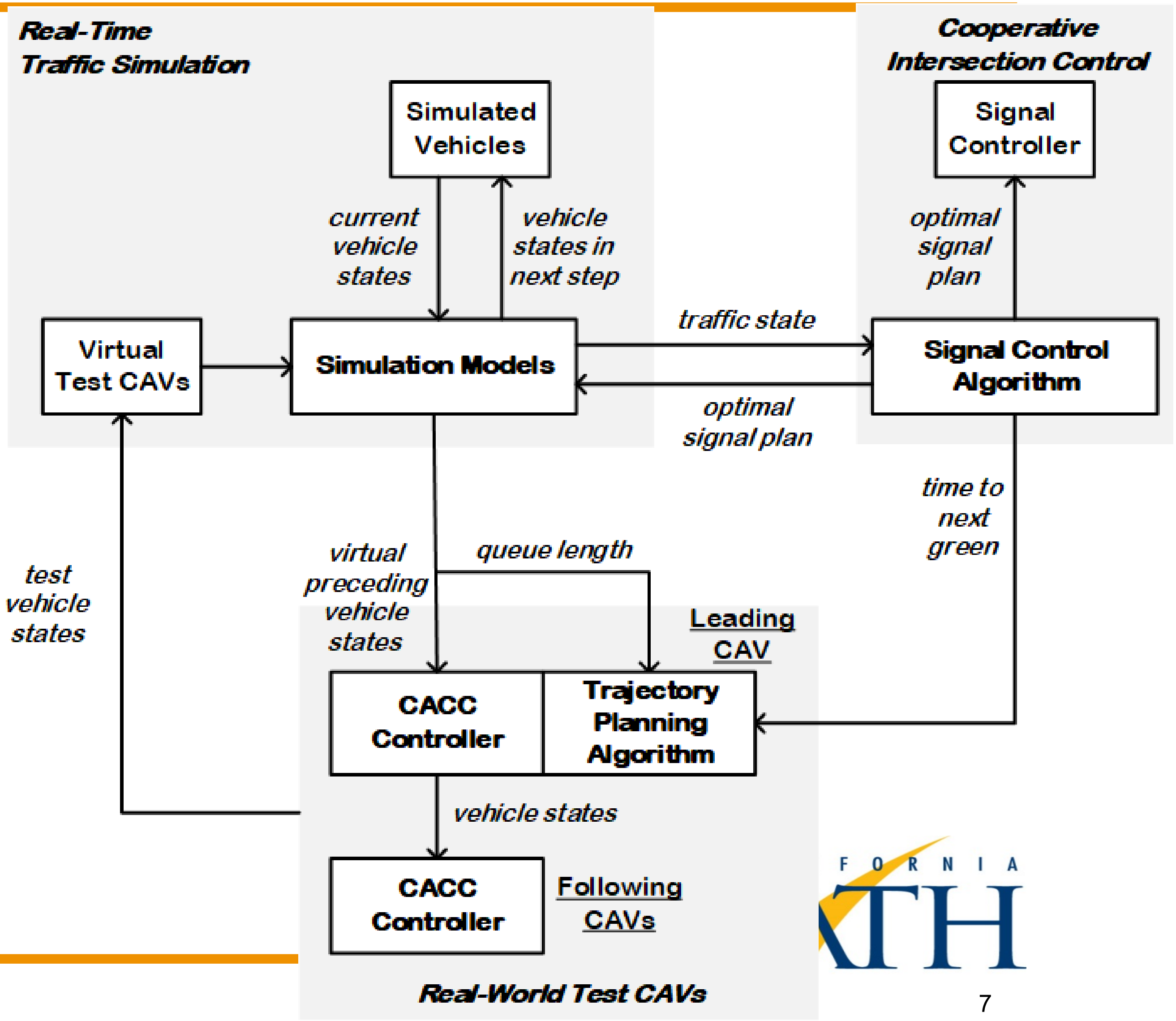
- Developing an intersection control algorithm that:
  - Relies on **CAV capabilities**
  - Maximizes the **intersection mobility**
  - Improves the **vehicle energy efficiency**
- Building a **hardware-in-the-loop (HIL)** system to test the effectiveness of the intersection control
  - Realistic system evaluation **using physical CAVs** and **signal controllers** instead of simulated systems
  - **Multiple system implementation cases** and **repeatable test runs** for statistical analysis
  - Safe test environment

Research Overview

- Intersection control algorithm:
  - **Cooperative signal control algorithm** that generates signal phasing and time (SPaT) to maximize throughput based on CAV information
  - **Trajectory planning algorithm** that provides energy efficient trajectories for CAVs based on the SPaT information
- HIL system:
  - **Real-time simulation** for generating virtual traffic streams
  - **Traffic controller** for implementing the cooperative signal control algorithm
  - **Test CAVs** that implement the trajectory planning and react to the virtual traffic and signal control

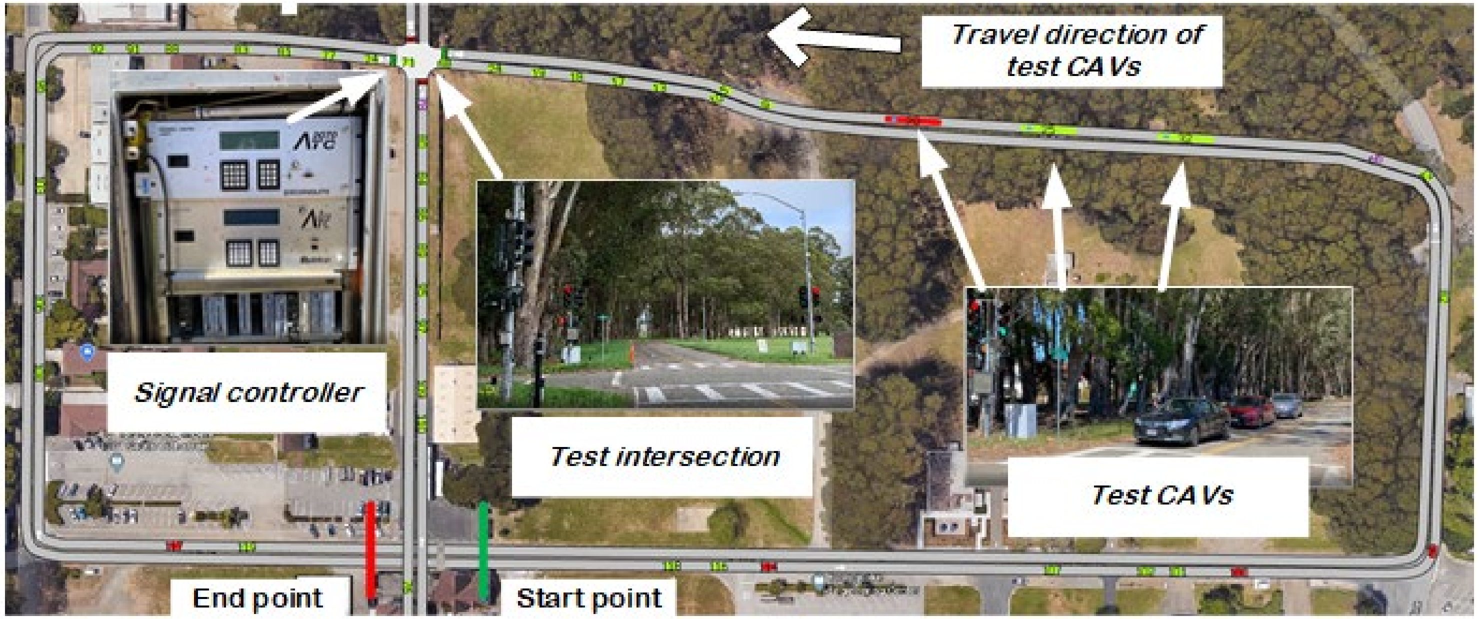
HIL System Development

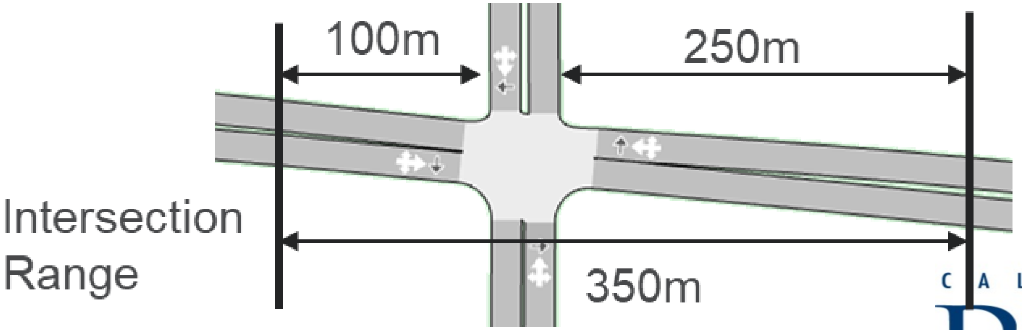
- System components:
  - **Real-time simulation**: generating virtual traffic streams
  - **Cooperative intersection control**: implementing the signal control algorithm
  - **Real-world test CAVs**: implementing trajectory planning, responding to traffic signals and the virtual traffic
- Data flow enabled by a HIL control tool



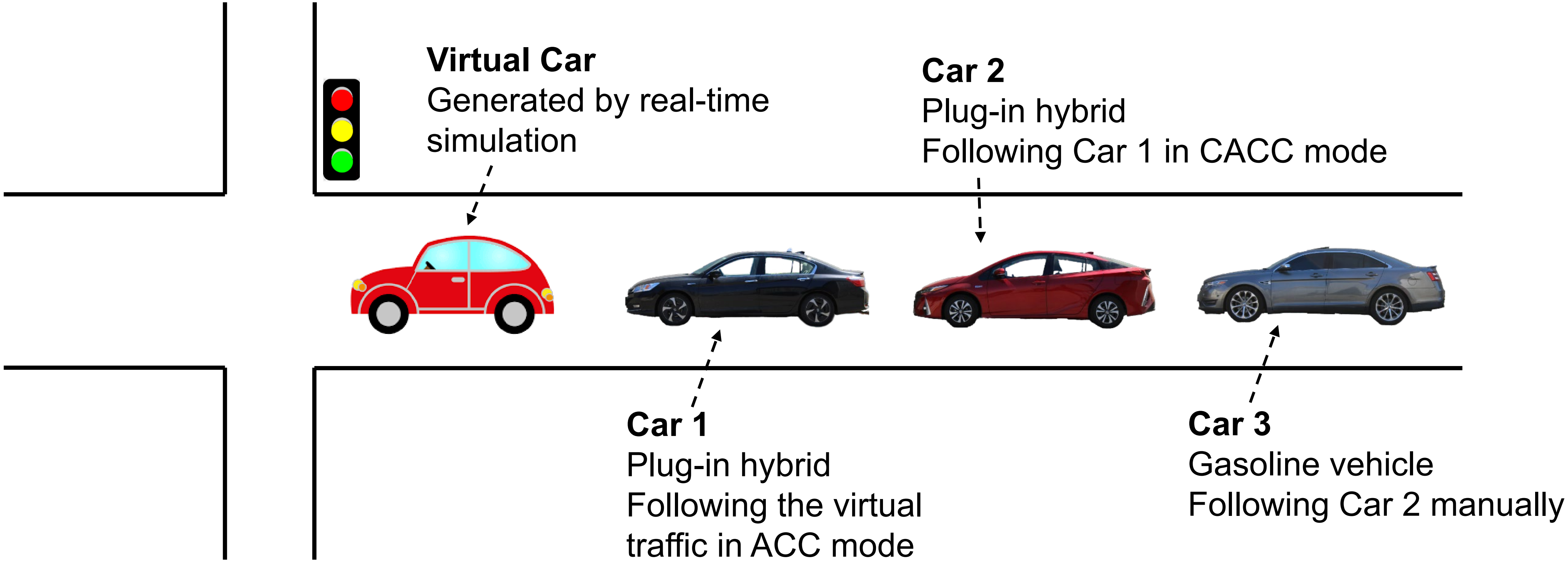
Algorithm Tests

- Test cases:
  - Fixed signal control (FS), 53 laps
  - Fixed signal + trajectory planning (FS+TP), 50 laps
  - Cooperative signal (CS) , 98 laps
  - Cooperative signal + trajectory planning (CS+TP), 101 laps
- Traffic inputs:
  - Major road—800 veh/hr
  - Minor road—350 veh/hr
  - 50% CAV market penetration





Tests Vehicles



- *Car 1 and 2 have different battery capacity and powertrain architecture*
- *Car 1 and 2's batteries were never charged during the tests*
- *All used power was based on fuel*
- *PHEV's advantage comes from regenerative braking*

Test Results: Descriptive Statistics

Car 1

	Speed (m/s)	Fuel (g)	Idling Time (s)
FS	5.07	20.61	22.50
FS+TP	5.14 (+1.4%)	20.48 (-0.6%)	3.61 (-84.0%)
CS	5.21 (+2.8%)	17.15 (-16.8%)	22.19 (-1.4%)
CS+TP	5.52 (+8.9%)	17.50 (-15.1%)	4.07 (-81.9%)

Car 2

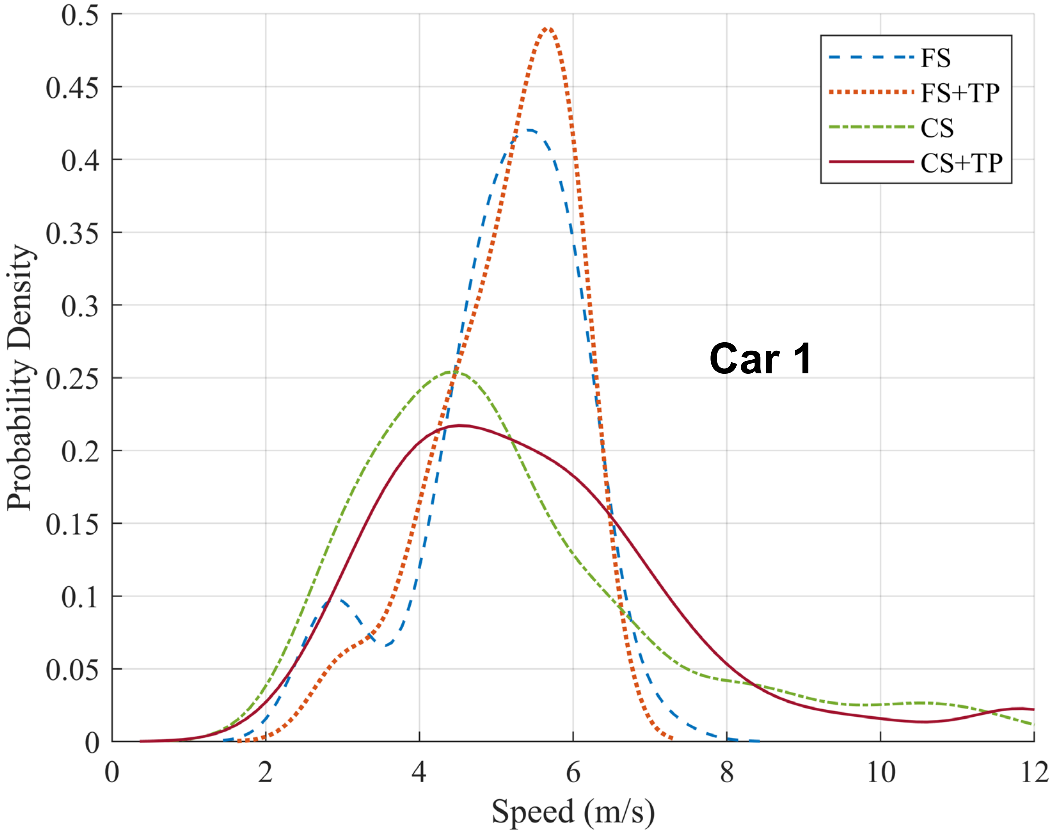
	Speed (m/s)	Fuel (g)	Idling Time (s)
FS	5.08	12.73	24.08
FS+TP	5.15 (+1.4%)	11.50 (-9.6%)	4.52 (-81.2%)
CS	5.18 (+1.8%)	10.56 (-17.0%)	23.58 (-2.1%)
CS+TP	5.55 (+9.2%)	10.03 (-21.2%)	5.50 (-77.2%)

Car 3

	Speed (m/s)	Fuel (g)*	Idling Time (s)
FS	5.01	38.14	24.27
FS+TP	5.05 (+0.8%)	30.04 (-21.2%)	6.93 (-71.5%)
CS	5.10 (+1.8%)	34.72 (-9.0%)	23.88 (-1.6%)
CS+TP	5.46 (+9.0%)	28.88 (-24.3%)	7.66 (-68.5%)

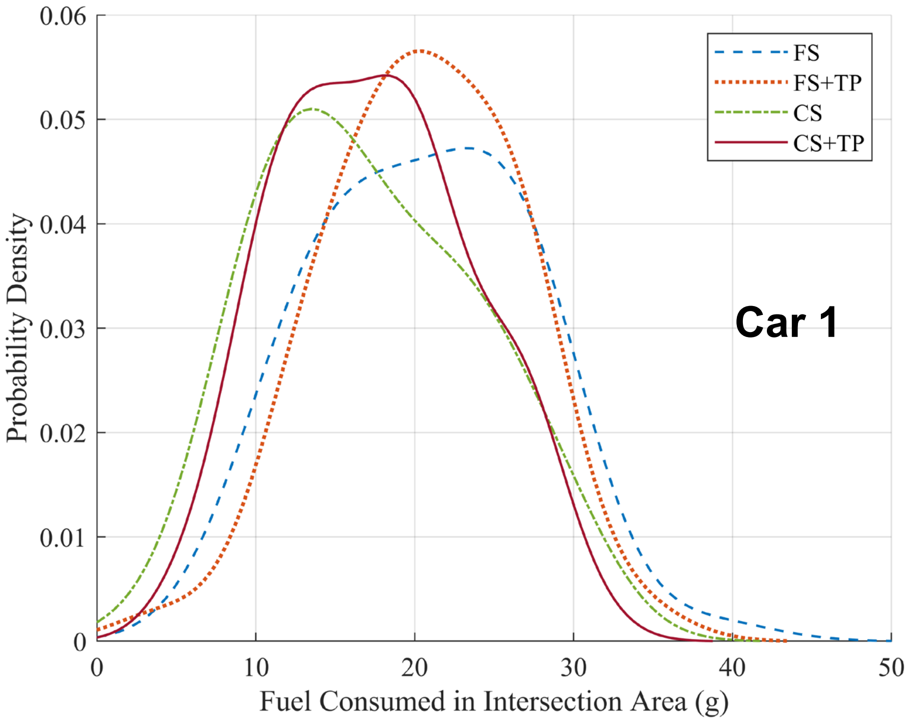
- Largest speed increase with CS+TP scenario
- Car 1's fuel consumption did not benefit from TP
- Car 3's fuel efficiency improved greatly with TP
- TP significantly reduced idling time, while CS has little impact

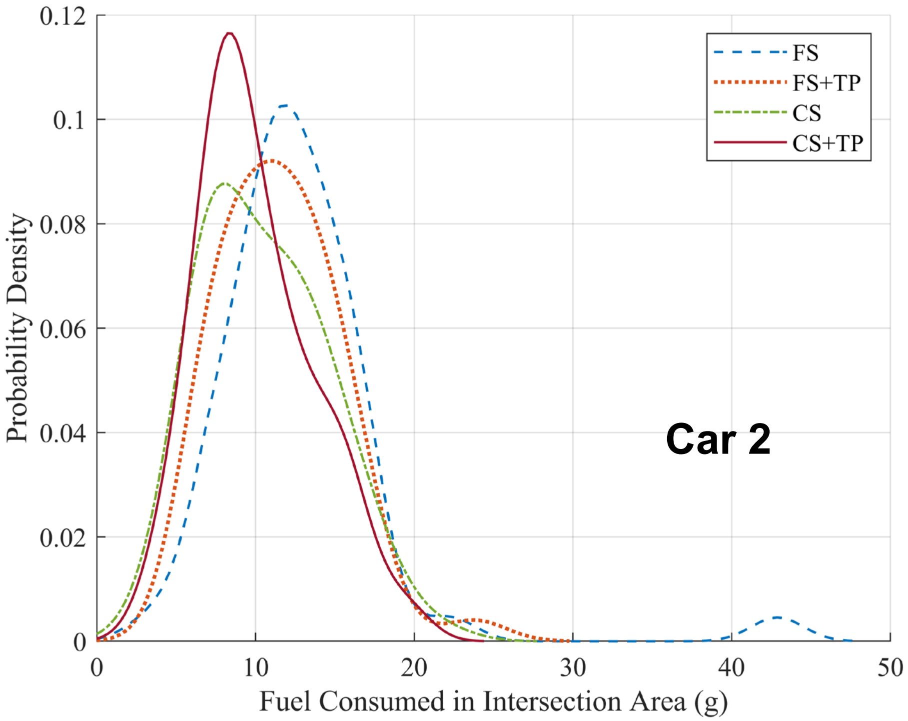
Test Results:
Comparison of Speed Distributions



- Distributions of the average speeds per lap
- Probability density curve estimated based on the measured data
- Similar curves for the 3 cars
- TP removes the peak at the low speed range and shifts the curve to the right
- CS flats the curve and increases the high-speed area

Test Results:
Comparison of Fuel Consumption Distributions

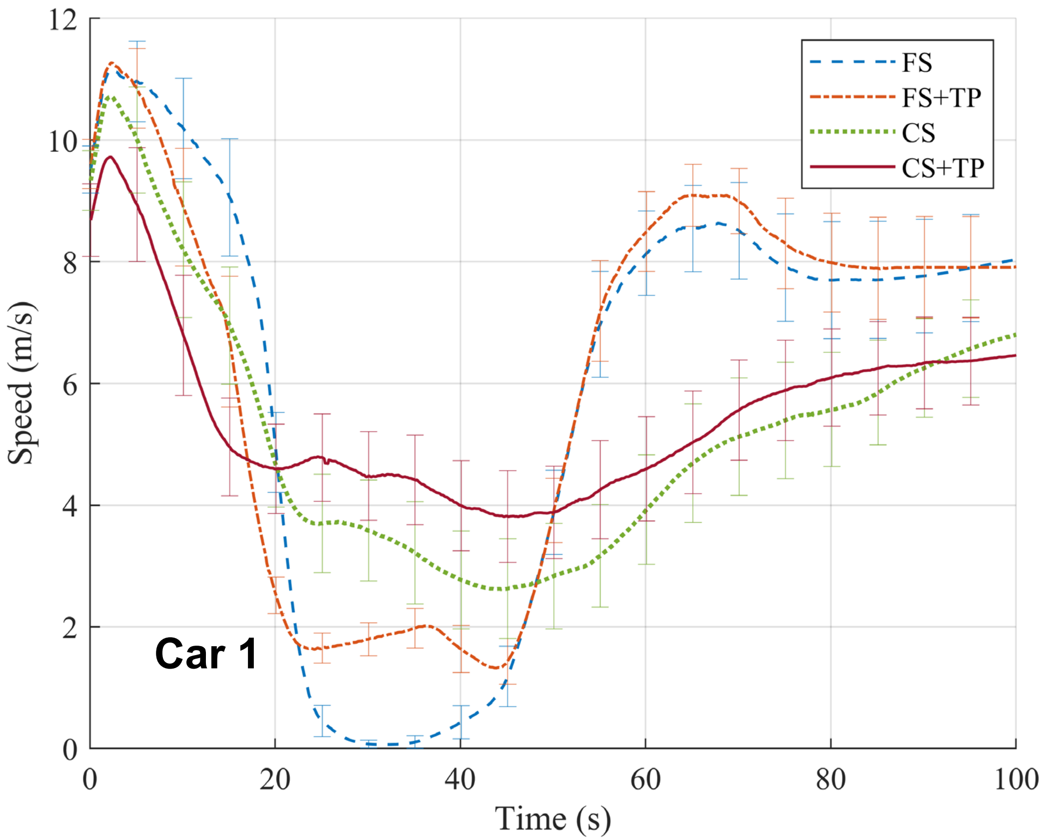




- Car 1 curve shapes differently from Car 2, possibly caused by different powertrain features
- Both TP and CS reduce upper tail of fuel consumption
- Both TP and CS shift curves to the left

12

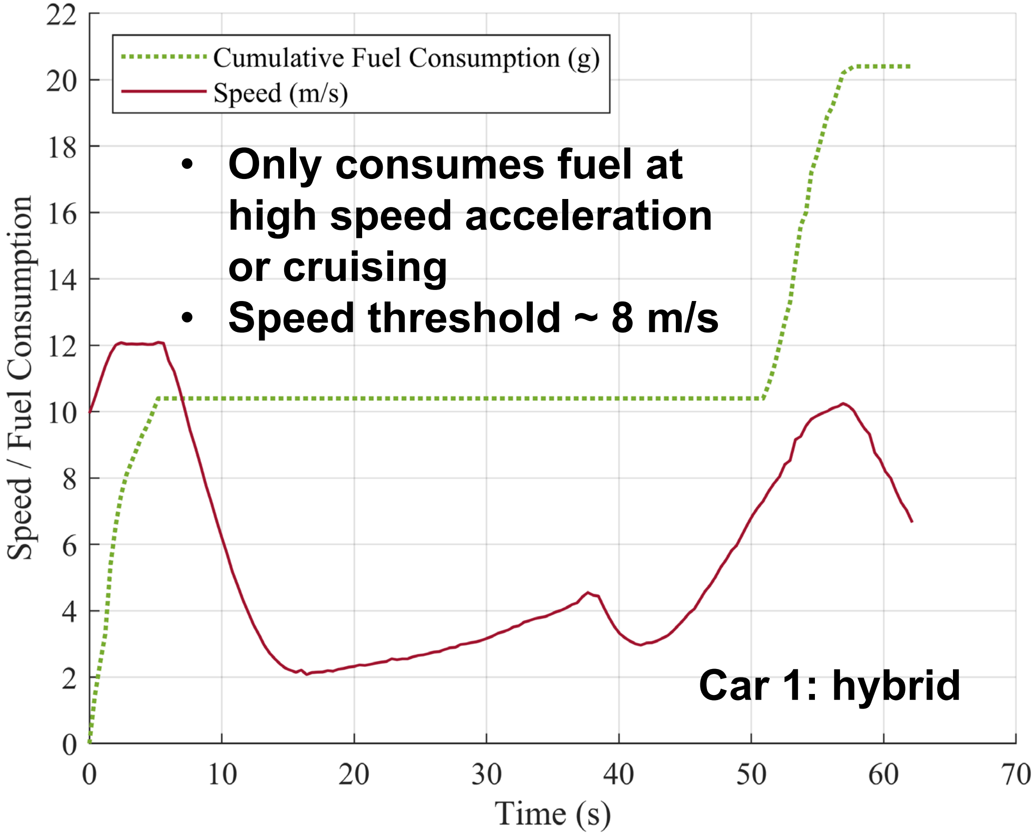
Test Results: Speed Patterns

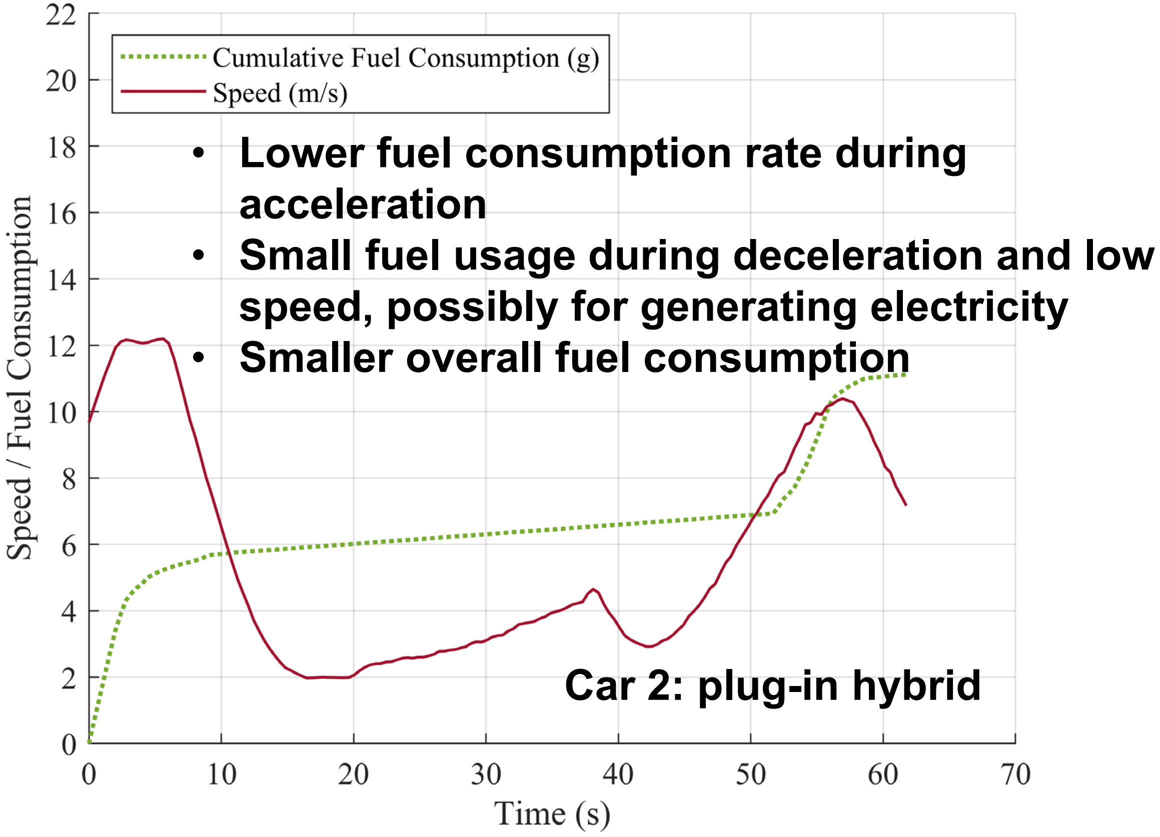


- **Speed increase** at the intersection due to TP and CS
- With TP, vehicles reduce speed in advance, but pass the stop bar at **a higher speed**
- CS increases the cases where vehicles pass the intersection with **little speed reduction**
- With CS, TP can start at a longer distance from the intersection, leading to **lower speed reductions**

Test Results:
Speed and Fuel Consumption for HEV and PHEV

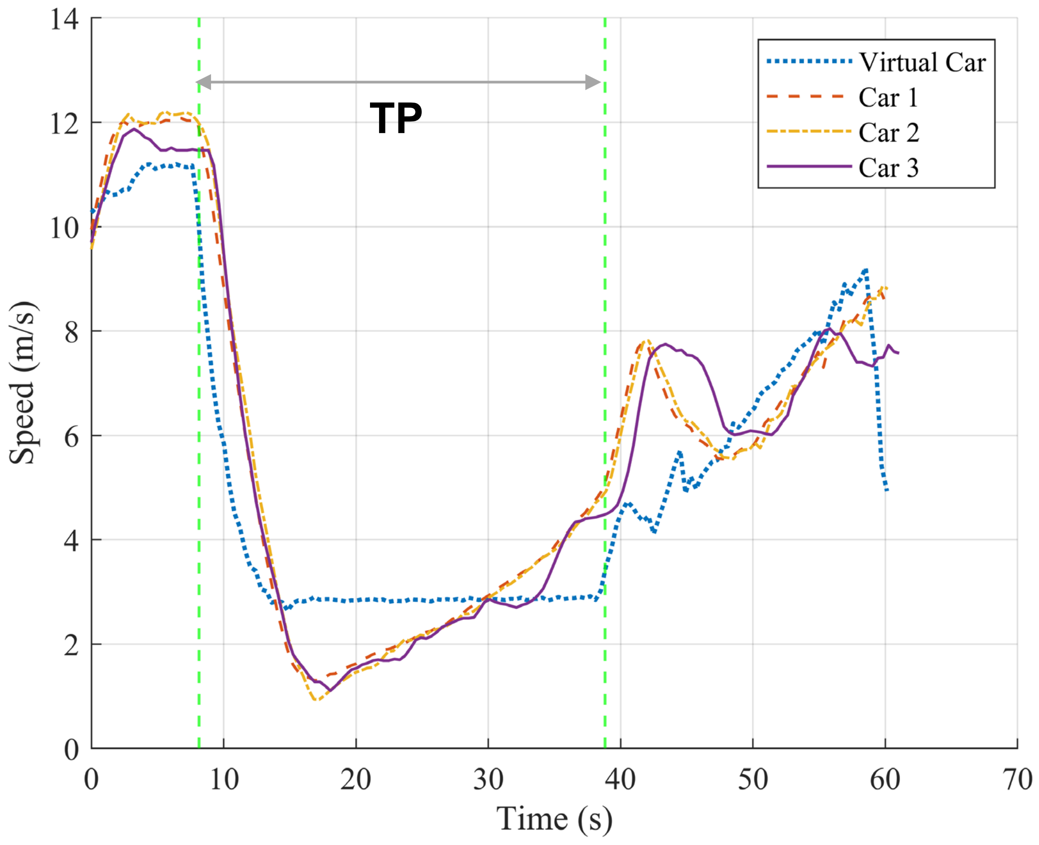
Speed profile for the same lap; Car 2 was following Car 1 in CACC mode.





14

Test Results: Car-Following Patterns



- Virtual car curve shows an ideal implementation of TP
- Physical cars require longer time to converge to a stable state
- Excessive deceleration reduces energy saving
- Aggressive car-following after TP further decreases energy benefits
- TP operates in low speed range, but Car 1 and 2 consume little fuel in that range
- TP does not make significant difference for Car 1 and 2
- TP can be further improved for better performance

Summary

- Developed an **advanced control algorithm** for a single intersection
- Built a **hardware-in-the-loop system** to evaluate the effectiveness of the intersection control
- Identified both **mobility and energy consumption improvement** due to the proposed CAV-based intersection control
- Explored the **mechanism** leading to the system benefits
- Identified further **improvement needs** of the proposed trajectory planning

16