Project ID# eems033
Pillar(s): CAV

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

CAV 7A.3.1.1 Truck CACC Operational Energy Consumption Test at Intersection with Active Traffic Signal Control

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Project Team: Dr. Hao Liu, John Spring, and David Nelson, U. C. Berkeley
2019 Vehicle Technologies Office Annual Merit Review
June 12, 2019

OVERVIEW

- Timeline
  - Project start date: Jan 1 2017
  - Project end date: Sept 30 2019
  - Percent complete: 90%
- Budget
  - Total project funding: $1075K
    - 100% DOE/VTO
  - Funding for FY 2017: $493K
    - LBL: $407K
    - NREL: $86K
  - Funding for FY 2018: $355K
    - LBL: $269K
    - NREL: 86K
  - Funding for FY 2019: $225K
    - LBL: $75K
    - NREL: 150K
- Barriers
  - How to operate signalized intersection with CAVs for energy saving improvement
- Collaborators
  - NREL
  - INL

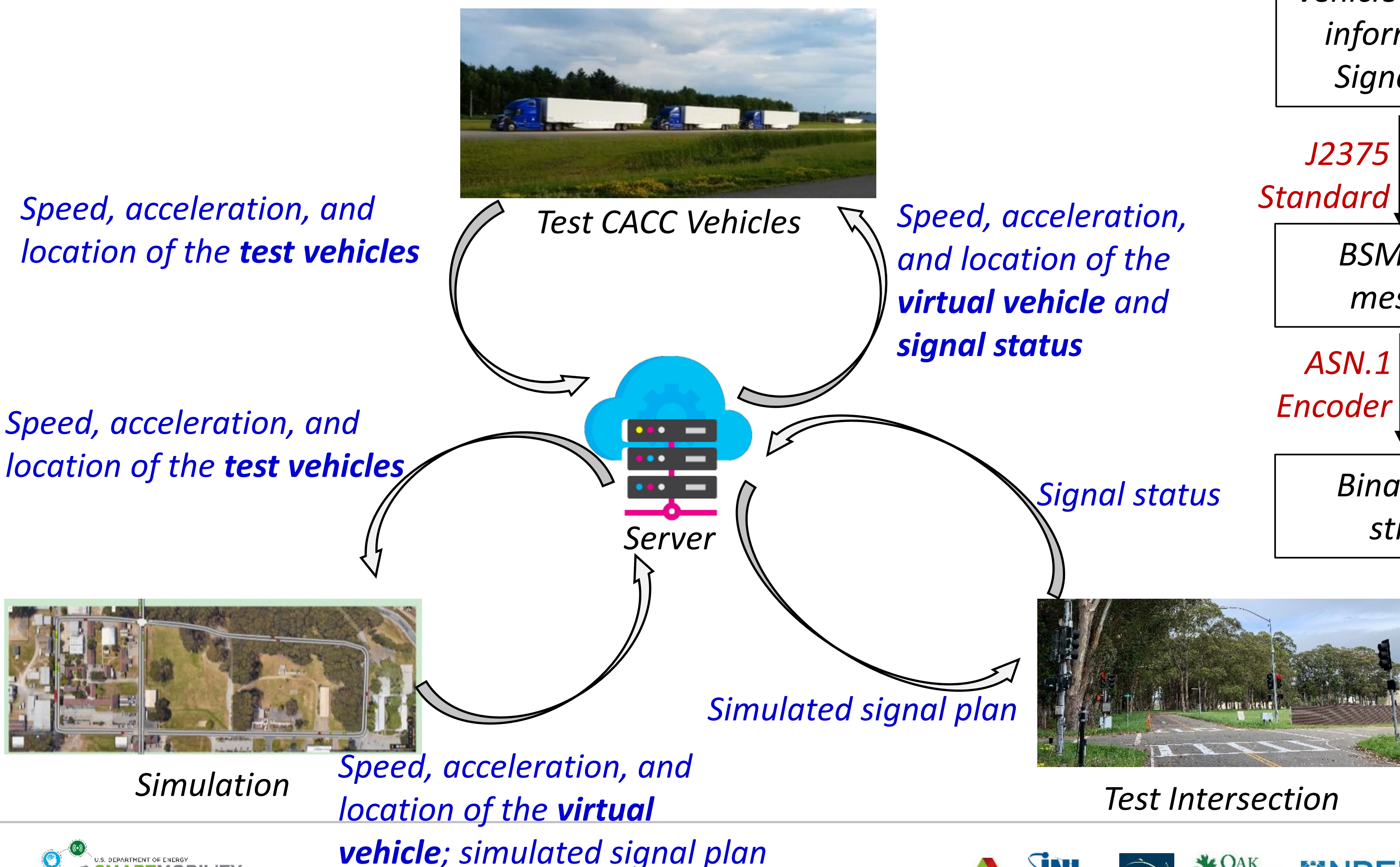
OVERVIEW

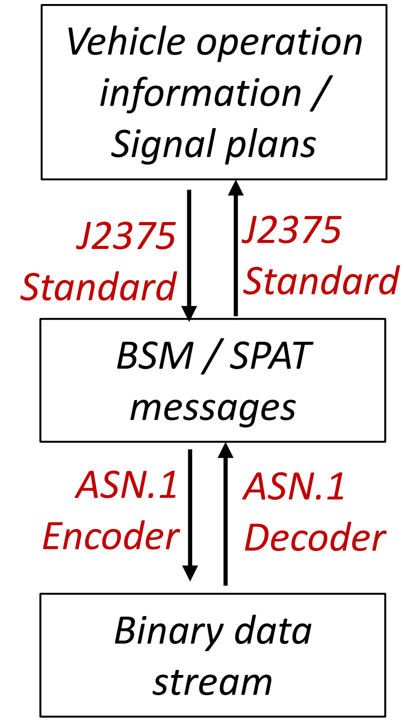
- Objectives:
  - Investigate truck CACC (Cooperative Adaptive Cruise Control) and real-time simulation for operation to study impact on energy use at a signalized intersection with Active Traffic Signal Control (ATSC)

- Concept of Operation: Integrated & synchronized with V2I and V2V
  - CACC trucks
  - Real-time simulation
  - Active Traffic Signal Control

OVERVIEW – Concept of Operations

- **A server program is used to handle the communication.**





RELEVANCE

- **Active Traffic Signal Control and coordinate with CACC trucks at a signalized intersection could reduce energy consumption**
- **Test data will be useful for modeling of CAV movement at arterial intersections for microscopic simulation which could be used for**
  - **Energy consumption evaluation in operation level**
  - **Simulated data in operation level could be used to calibrate Parameterized Fundamental Diagram which can be used for CAV modeling and simulation in meso-macro level**

MILESTONES

Deliverables/Milestones	Status
Full speed range trucks CACC string in operation	Partially accomplished
Microscopic traffic simulation of intersection	Accomplished
Integrated traffic signal control with real-time simulation	Accomplished
Optimal control for minimal energy consumption in operation	Partially accomplished
Wireless communication networks for the integration of overall system	Partially accomplished
Integrated syst.: CACC trucks, signal control, RT simulation	In progress

MILESTONES

Milestone Name/Description	Criteria	End Date
Q2: 3-Truck CACC operational test data at intersection with Active Traffic Signal Control (LBNL)	Q2: Test data available including: real-time simulation data, truck data, and traffic signal data	6/30/2019
Q4: Test data analysis results on energy saving for CACC truck operation at signalized intersection (LBNL)	Q4: Data analysis results for CACC truck intersection operation with Active Traffic Signal Control	11/30/2019
Q4: CACC truck air-flow test data analysis results; the data was obtained at Transport Canada Test Track (NREL)	Q4: Report on data analysis results of air-flow effect on aerodynamic drag and engine temperature	11/30/2019
Q4: Modeling of fuel consumption for 2014 Volvo VNL475 truck model based on field test using year 2001 Freightliner N-14 trucks	Q4: Fuel consumption mapping between 2014 Volvo VNL truck and 2001 Freightliner N-14 truck	9/30/2019

APPROACH

- Extend CACC capabilities of 3-Volvo trucks to low speed
- Developing real-time simulation with 3-CACC trucks imbedded
- Using real-time simulation for Active Traffic Signal Control (ATSC)
- ATSC Algorithm is to directly maximize the intersection overall throughput and minimize the Total Delays
  - ➔ indirectly reduce energy consumption
    - ➔ to generate speed trajectory for CACC trucks
- All parts are connected with V2V and V2I and synchronized
- Whole process repeating for multiple times
- J-Bus fuel rate to be used for energy consumption evaluation
- Comparing with baseline case with Actuated Traffic Signal Control without integration with CACC trucks

TECHNICAL ACCOMPLISHMENTS

- **Prepare Volvo CACC trucks for low speed CACC: 80% done**
- **Developing Dedicated Short Range Communications (DSRC) units packets for roadside units V2I: 90% done**
- **Developing Signal Cooperation for CACC Vehicle Strings Operation: done**
- **Developing Hardware-in-the-Loop Algorithms: done**
- **Developing Hardware-in-the-Loop Simulation: done**
- **Working on traffic signal control system: 80% done**
- **System integration: 60% done**

Signal Cooperation for CACC Vehicle Strings

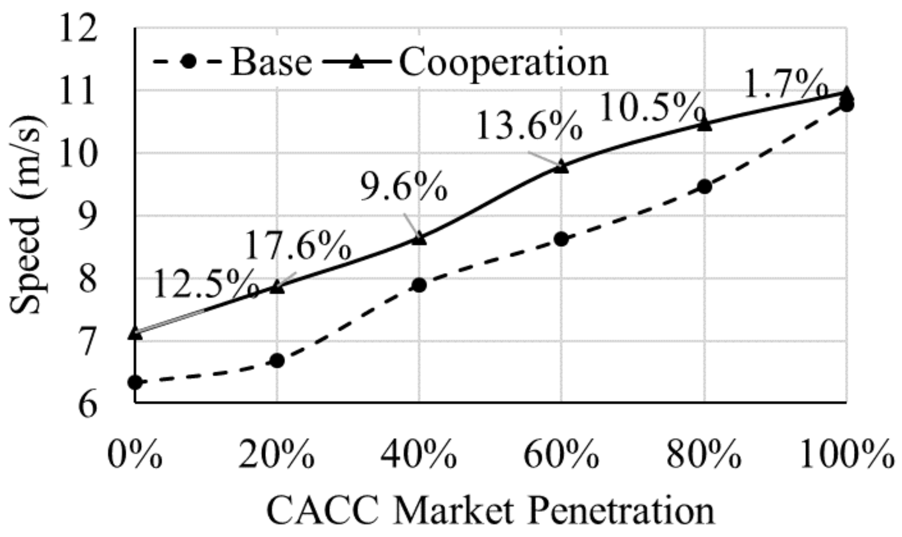
- Develop an algorithm to maximize the overall throughput of an intersection with the mixed flow
  - Maximizing throughput is essentially minimizing the queue length:
    - Queue = Number of vehicles in system + Input Traffic – Throughput
  - Objective function: $Max \sum_{i=1}^{N} \delta_i$
    - N is the number of vehicles in the intersection area (e.g., intersection plus 300 m road segment of each approach)
    - i is the vehicle ID
  - Constraints:
    - Signal phase
    - Vehicle movement
  - Giving priority to the movement with more CACC strings

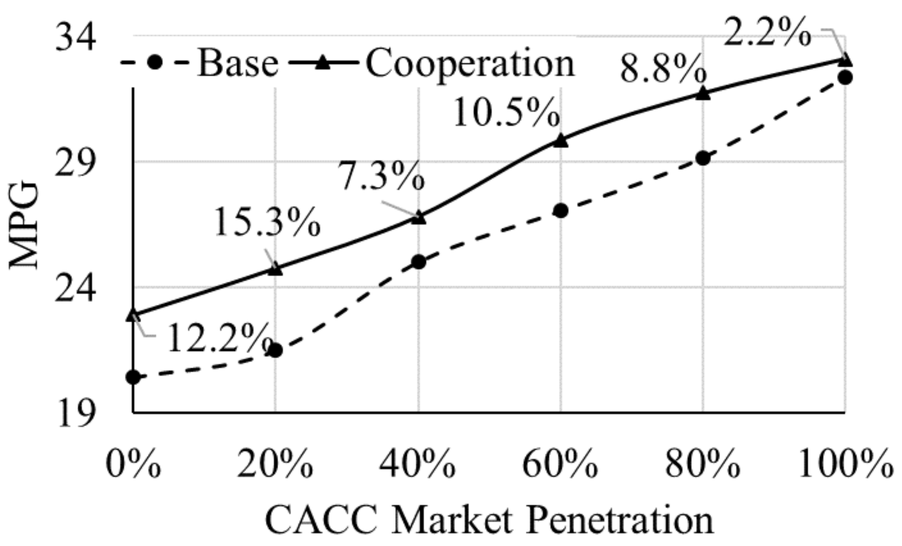
Signal Cooperation for CACC Vehicle Strings

- To use the algorithm, we need to know the speed and location of each vehicle, and queue length in the intersection area
  - For the CACC vehicle, the information can be obtained via V2I communication
  - For the manual vehicle, the information needs to be inferred from the CACC data and the loop detector data
    - Four cases to be considered for the location and speed of manually driven vehicles
- Estimating the location and speed of the manual vehicles:
  - Case 1: When both preceding and the subject CACC vehicles are moving
  - Case 2: When both preceding and the subject CACC vehicles stop
  - Case 3: When the subject CACC vehicle is moving and its preceding CACC vehicle stops in the queue
  - Case 4: When the subject CACC vehicle stops in the queue and its preceding CACC vehicle is moving

Signal Cooperation for CACC Vehicle Strings

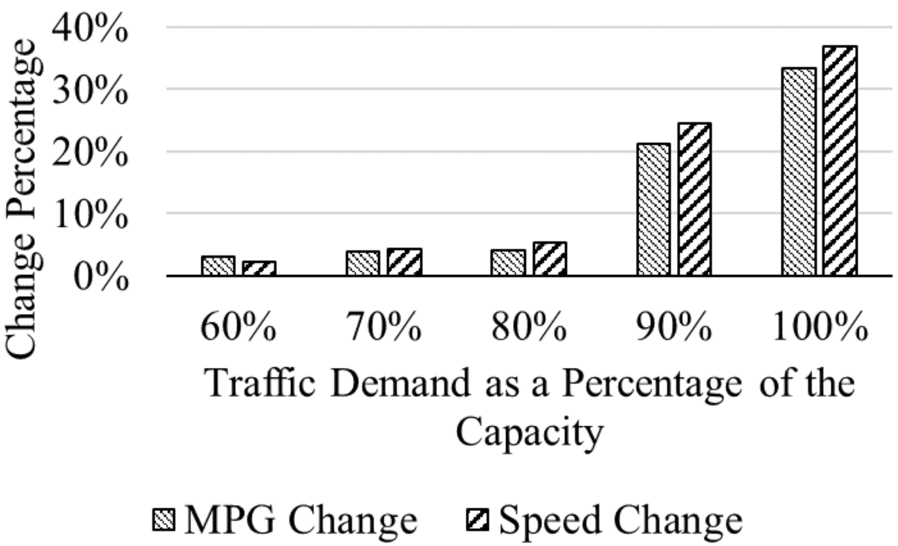
- Simulation examination of the algorithm.
  - Traffic input equals to the saturation flow measured in 0% CACC case.
  - Two sections for baseline cases: below 40% CACC and above 40% CACC.
  - Below 40% CACC, vehicles need to wait more than 1 cycle to pass.
  - Algorithm has major benefit for cases CACC below 40%
  - Above 40% CACC, baseline substantially improved by CACC operation



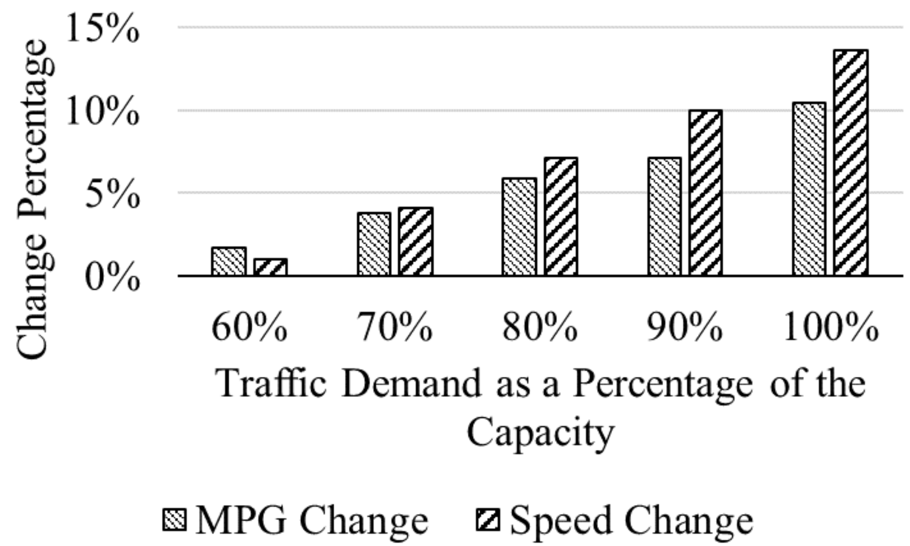


Signal Cooperation for CACC Vehicle Strings

- **Simulation examination of the algorithm.**
  - **Algorithm performs the best as traffic input close to the capacity**
  - **Higher benefit for 40% CACC market penetration than 100%**
  - **100% CACC has good performance without cooperative signal algorithm**



40% CACC Case

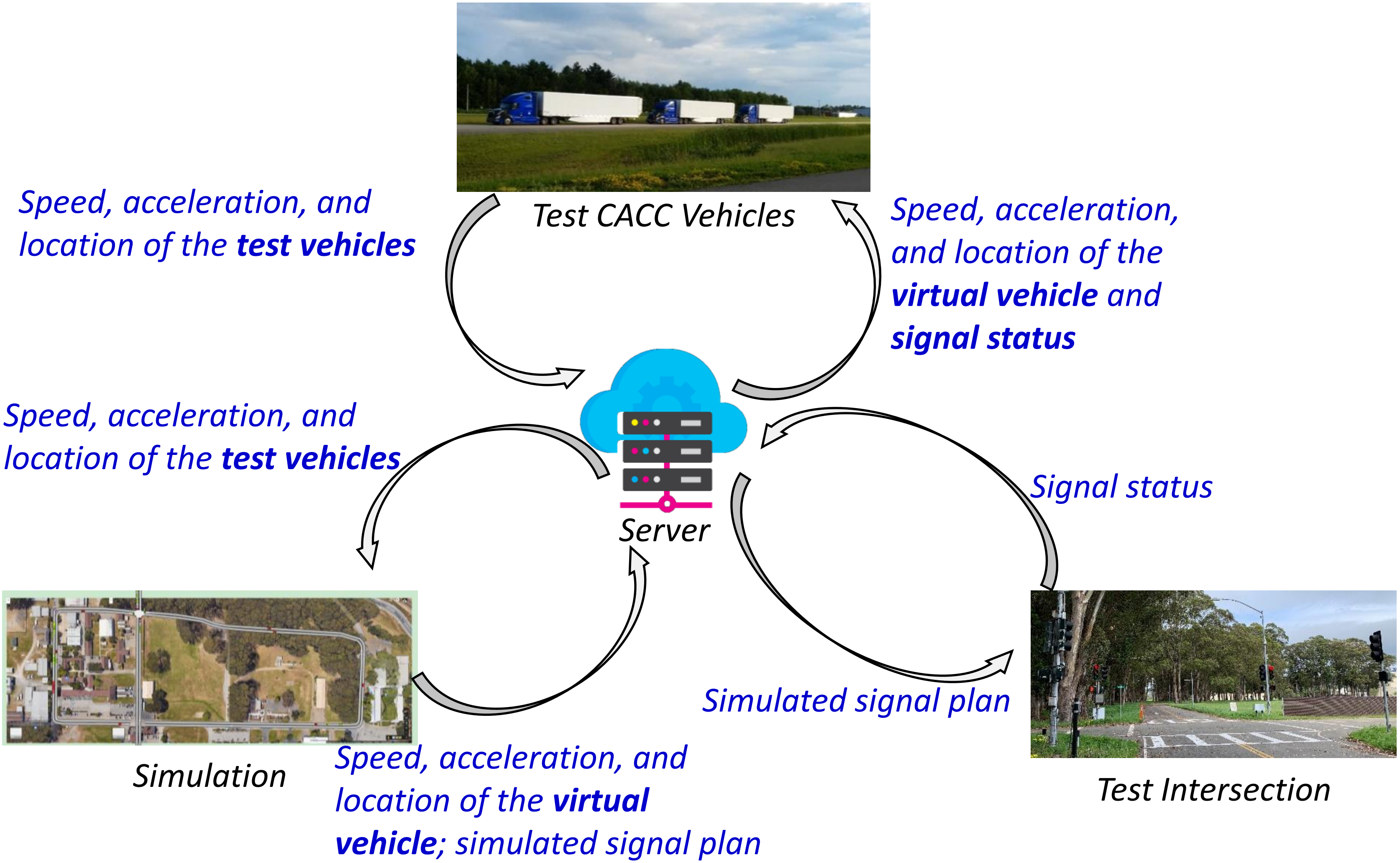


100% CACC Case

Developing Hardware-in-the-Loop Algorithms

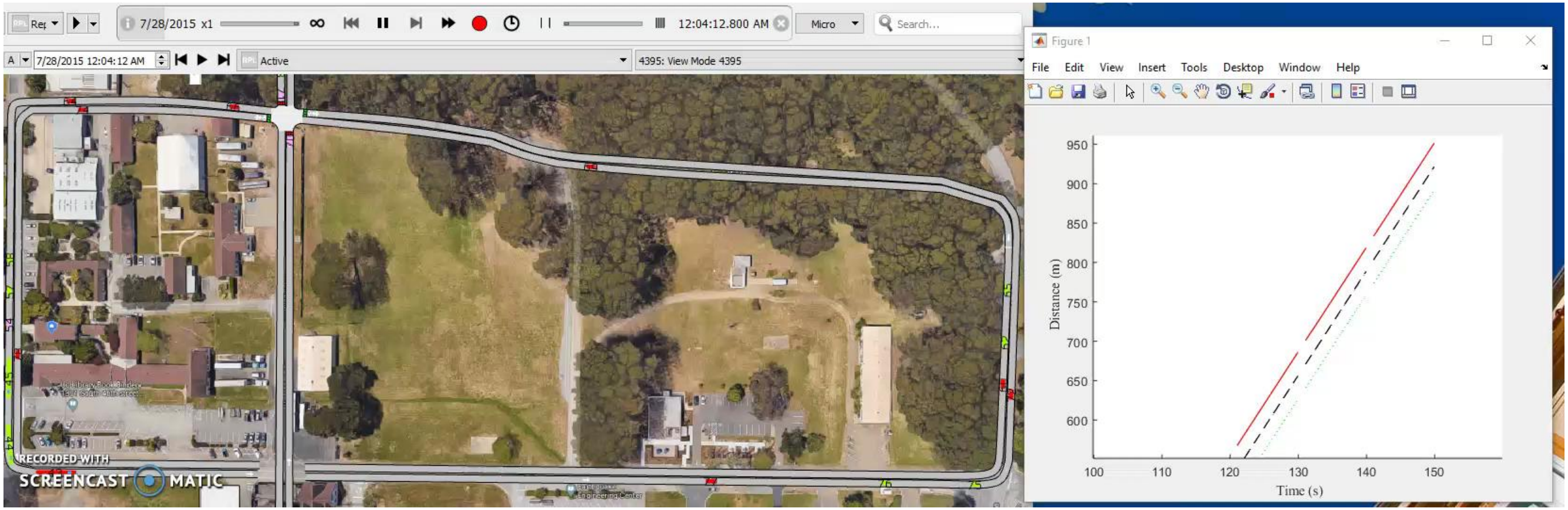
- **Algorithm framework:**
  - **Step 1: create simulated traffic scenario**
  - **Step 2: initialize simulated CACC truck string**
  - **Step 3: connect to server, synchronize simulation speed**
  - **Step 4: exchange truck info, update simulated trucks**
  - **Step 5: delete simulated trucks after they leave the network**
  - **Step 6: repeat Step 1-5 for multiple test runs**

Developing Hardware-in-the-Loop Algorithms



Developing Hardware-in-the-Loop Algorithms

- **Simulation**



Red: CACC string leader

Green: CACC string follower

3 truck real-time running distance trajectory

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- **Explicitly addressing how the industry could benefit from the results and how the results will be conveyed to the industry and put into practice.**
  - **US DOT (Department of Transportation) initiated a new BAA (Broad Agency Announcement) program on Truck Platooning Field Operational Tests in two phases with Phase I started in March 2019. It intends to investigate: system readiness, operation logistics by truck operator, safety issues, driver training, driver behavior (regulation and human factor), institutional issues such as legal and crossing state boarder, truck maintenance, etc.**

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

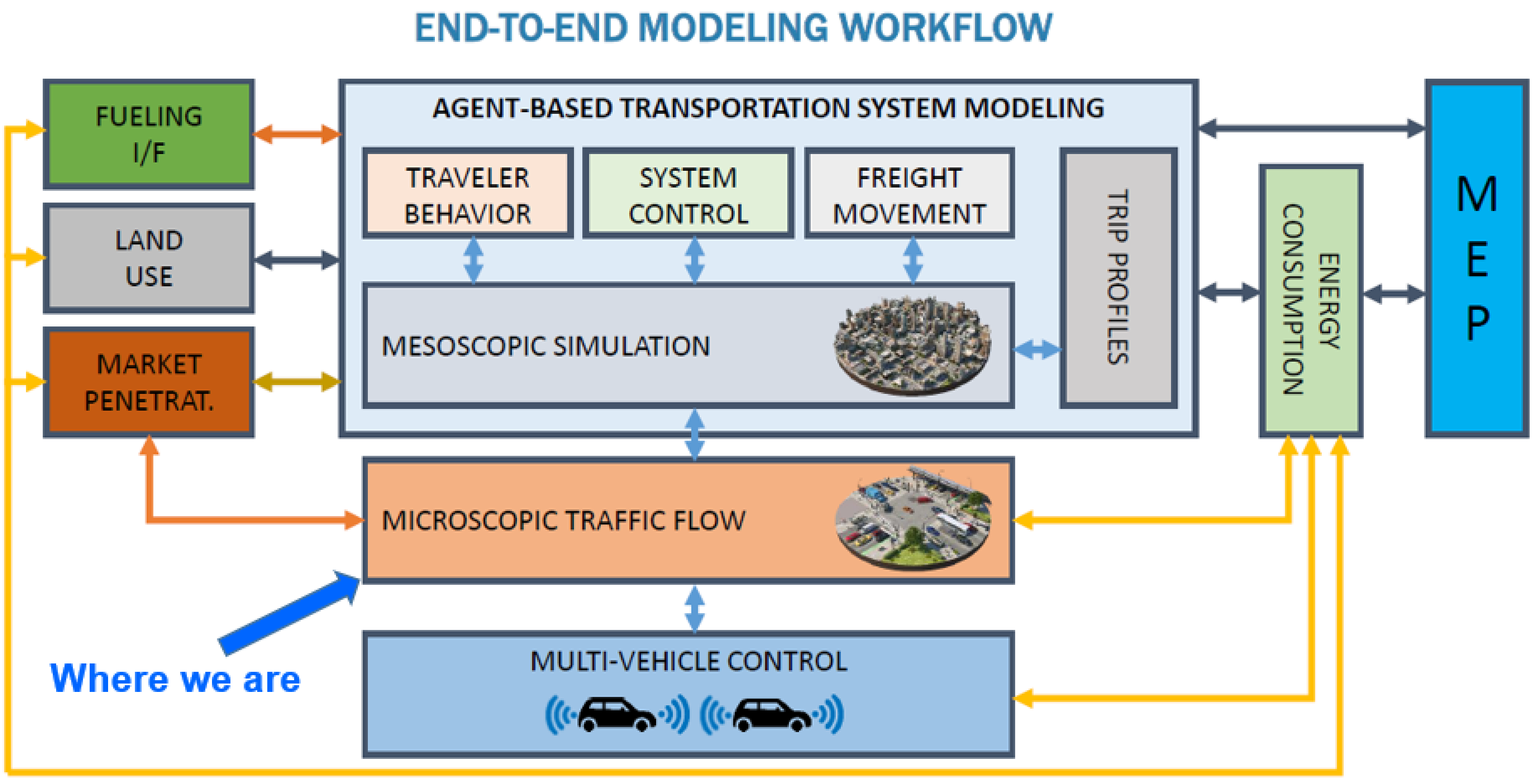
- **The field test sensor data could be used for micro-scale modeling.**
  - **The sensor and J-Bus data of the track and freeway tests have been used for developing microscopic simulation model to capture the dynamic interactions among CACC vehicles and between CACC vehicles and other manually driven vehicles.**

- **Acknowledgement:**
  - **The platooning-equipped trucks were from a previous project funded by FHWA Exploratory Advanced Research (EAR) Program and Caltrans (Cooperative Agreement No. DTFH61-13-H-00012). The project team includes PATH, Volvo Technology of America, LA Metro, the Gateway Cities COG, and Cambridge Systematics, Inc.**

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- **LBNL: Project lead**
- **National Renewable Energy Laboratory (NREL): on data analysis**
- **UC Berkeley PATH program: researcher and hardware and software engineers participated**
- **Using the calibrated microscopic simulation to generate data for modeling Fundamental Diagram parameterized with respect to the market penetration levels of CAVs (EEMS075: Lu an Joshua);**
- **Link with Autonomie for energy consumption evaluation: EEMS016 – RoadRunner**
- **Providing test data to ANL and INL for model validation**

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS – Where it Fits in the WORKFLOW



REMAINING CHALLENGES AND BARRIERS

- **Challenges:**
  - **3 Volvo VNL Trucks with CACC capability for low speed control for Stop&Go traffic at signalized intersection**
  - **To quantify fuel saving benefit for CACC truck operation at signalized intersection with Active Traffic Signal Control**
  - **To quantify fuel saving benefit in the real-time simulation for all the traffic involved, which will need a reasonably accurate model**

PROPOSED FUTURE RESEARCH

- **Energy Consumption Evaluation for the operation of CAVs along arterial corridor with multiple intersections with Active Traffic Signal Control with**
  - **CACC Trucks**
  - **CACC passenger cars with different powertrains**
  - **With real-time simulation in the loop to create a nearly realistic traffic environment for CAV tests**
- **Combined Fuel consumption and emission tests for 3-truck CACC operation along a freeway corridor (or for long distance freight movement operation) with real-world traffic and professional truck drivers**
- **Developing capabilities for partially automated vehicle merging into freeway with mixed traffic of manually driven vehicles and CAVs**
- **Future research will be subjected to the availability of funding**

SUMMARY SLIDE

- Developed feasible Concept of Operations
- Developed real-time simulation which can imbed the 3 CACC truck movement and with flexible levels of CAVs
- Developed Active Traffic Signal Control (ATSC) Algorithm to incorporate CAVs simulation
- Developed DSRC (Dedicated Short Range Communication) packets for integration of the system using RSU (Roadside Units) to cover test track with truck movement and preliminarily tested
- Enabled low speed control for three CACC-capable Volvo VNL trucks
- Next Step:
  - To integrate the reference speed generated by the ATSC in truck CACC (June 2019)
  - CACC Truck localization with onboard sensor and GPS (Jul 2019)
  - Synchronize and integrate the overall system (Aug 2019)
  - Conduct initial test, iteratively tune the system, & conduct extensive tests (Sept – Nov 2019)

PUBLICATION AND PRESENTATION

- X. Y. Lu, S. Shladover, and S. Bergquist, Truck CACC implementation and test to verify control performance, Transportation Research Record, 2019, sagepub.com/journals-permissions, DOI: 10.1177/0361198119842122, journals.sagepub.com/home/trr
- H. Ramezani, X. Y. Lu, and Steven Shladover, Calibration of Motor Vehicle Emission Simulator (MOVES) using Real Heavy-Duty Truck Data, TRB Annual Meeting, Jan. 2019, Washington, D. C.
- H. Ramezani, X. Y. Lu, and Steven Shladover, Calibration of Motor Vehicle Emission Simulator (MOVES) to Incorporate Effect of Truck Platooning, TRB Annual Meeting, Jan. 2019, Washington, D. C.
- X. Y. Lu, and S. E. Shladover, B. McAuliffe, S. Bergquist and A. Kailas, New 3-Truck CACC Field Test for Fuel Consumption and Control Performance, Automated Vehicle Symposium, San francisco, July 2018

QUESTIONS?

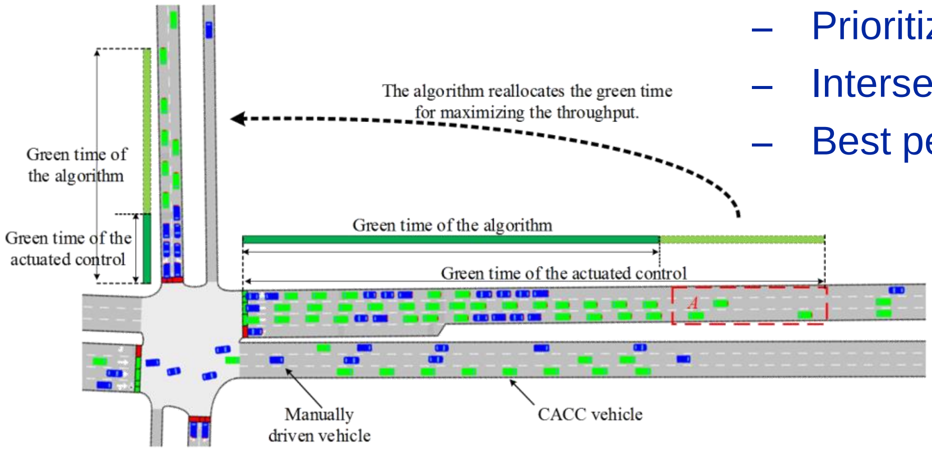
TECHNICAL BACK-UP SLIDES

Cooperative Signal Control Algorithm

- Maximize **total intersection throughput**
  - Using Connected Automated Vehicle **(CAV) information** and data from **traditional traffic sensors** (e.g., loop detectors)
  - Leveraging Cooperative Adaptive Cruise Control **(CACC) vehicle string** capability
  - Compatible with existing **8-phase signal controller**
- Max throughput = Min queue length:
  - $Queue = N_{exist} + Q_{in} - Q_{out}$
  - N_{exist} and Q_{in} depend on input traffic flow
  - Q_{out} affected by signal control
  - Max Q_{out} = Min $Queue$

CALIFORNIA PATH

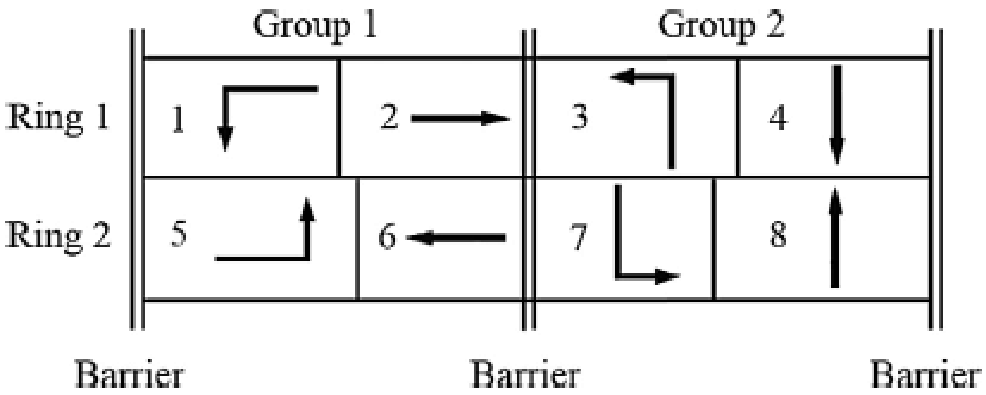
Cooperative Signal Control Algorithm



- Our algorithm outperforms actuated signal controllers:
  - Better perception of traffic flow
  - Give priority to approaches with more CACC vehicle strings
  - Prioritized approaches output high flow rate
  - Intersection operate under **great efficiency**
  - Best performance in congested conditions

Signal Cooperation for CACC Vehicle Strings

- **Constraints:**
  - $\sum_{j=1}^{4}(g_j + t_{YR}) = C$
  - $\sum_{j=5}^{8}(g_j + t_{YR}) = C$
  - $\sum_{j=1}^{2}(g_j + t_{YR}) = \sum_{j=5}^{6}(g_j + t_{YR})$
  - $\sum_{j=3}^{4}(g_j + t_{YR}) = \sum_{j=7}^{8}(g_j + t_{YR})$



Remark:

- **1st and 2nd constraints: cycle length constraints.**
- **3rd and 4th constraints state that the green time of the two rings in a group should be the same.**

Signal Cooperation for CACC Vehicle Strings

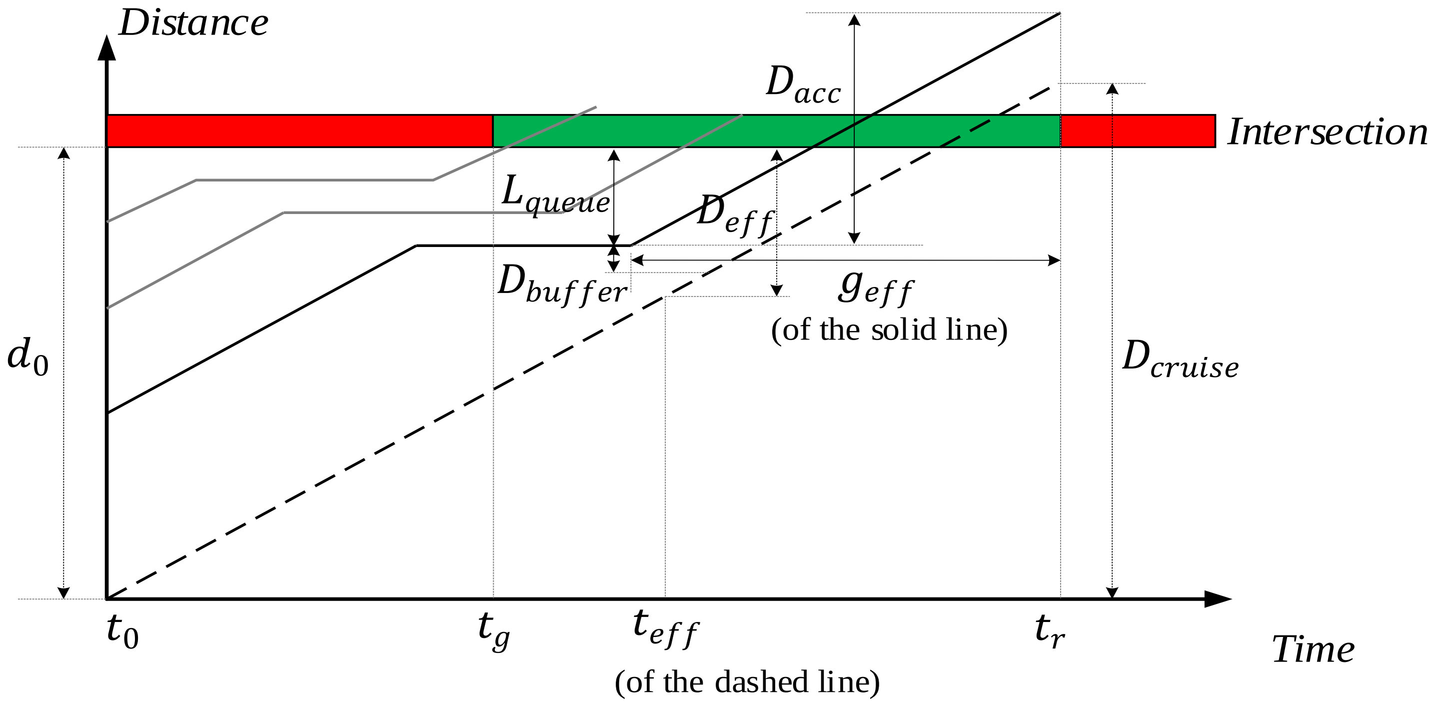
- **Vehicle movement constraints:**

  - $\boldsymbol{\delta_i = \begin{cases} 1 & D_{cruise} > d_0 \\ 0 & otherwise \end{cases}}$
  - $\boldsymbol{\delta_i = \begin{cases} 1 & D_{acc} > L_{queue} \\ 0 & otherwise \end{cases}}$
  - $\boldsymbol{D_{acc} = \begin{cases} 0.5 \cdot a_i \cdot g_{eff}^2 & t_{acc} < g_{eff} \\ 0.5 \cdot a_i \cdot t_{acc}^2 + v_{free} \cdot (g_{eff} - t_{acc}) & otherwise \end{cases}}$

See remarks in the next slide

Signal Cooperation for CACC Vehicle Strings

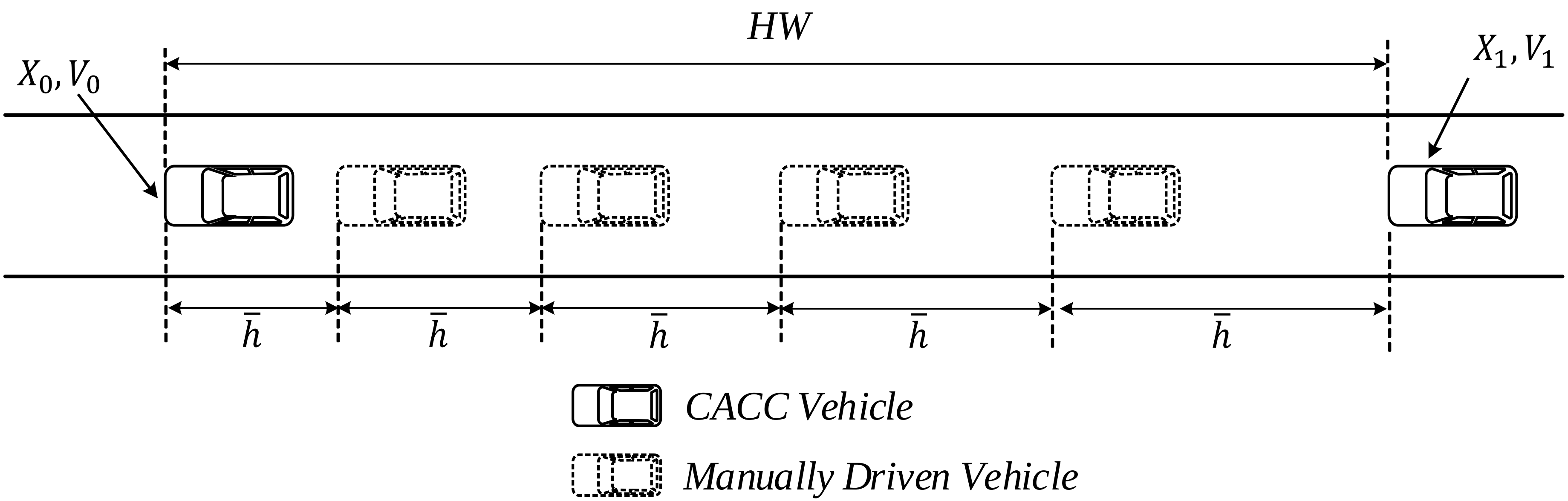
- **Vehicle movement constraints:**
  - **1st constraint applies to vehicles that do not stop in the next cycle**
  - **2nd constraint applies to vehicles that need to stop**
  - **Vehicle travel distance in the next cycle needs to be estimated.**



Signal Cooperation for CACC Vehicle Strings

- **Estimating the location and speed of the manual vehicles:**

Case 1: When both preceding and the subject CACC vehicles are moving

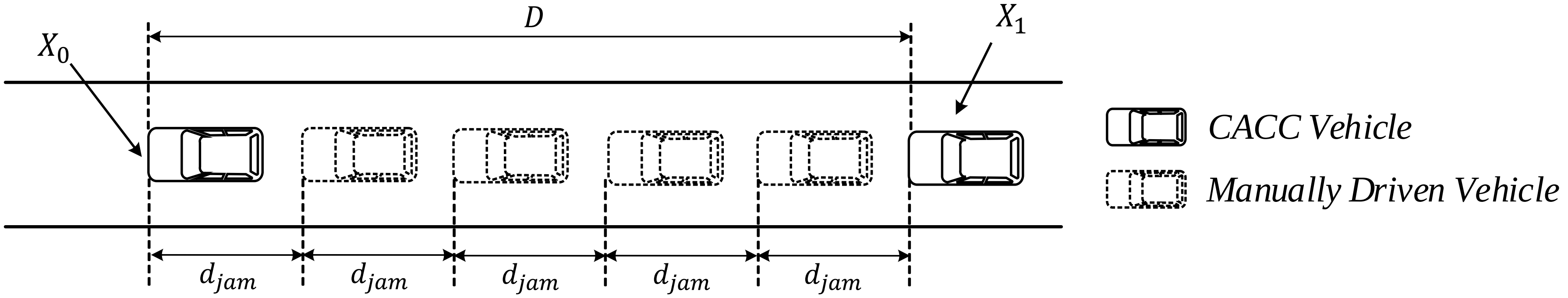


Assume a constant headway and linear speed change

Signal Cooperation for CACC Vehicle Strings

- **Estimating the location and speed of the manual vehicles:**

Case 2: When both preceding and the subject CACC vehicles stop

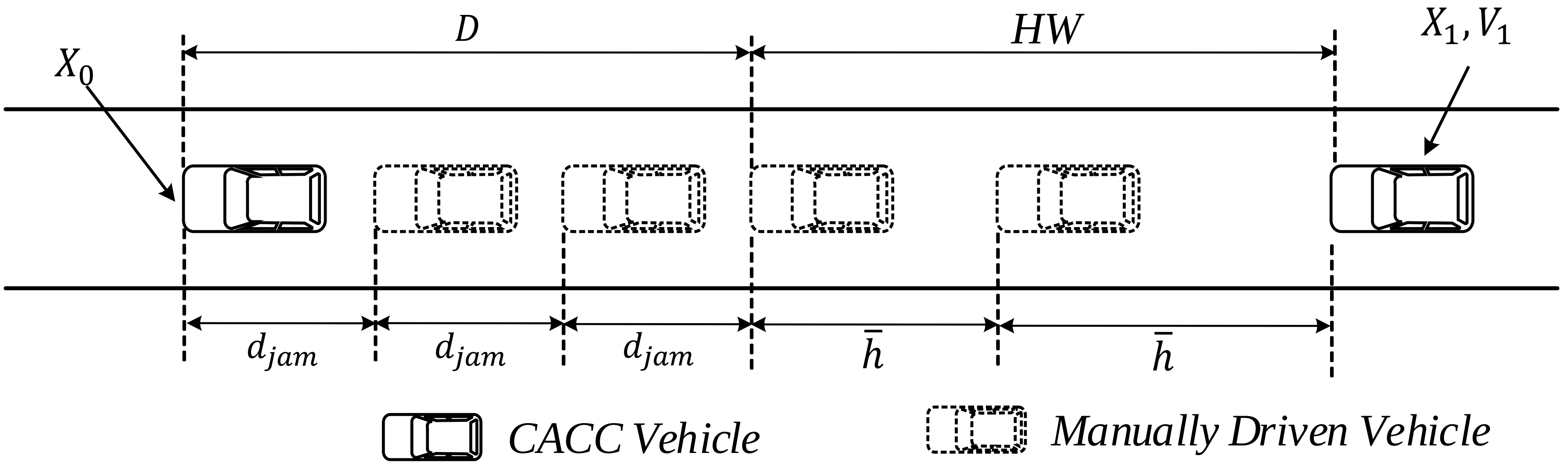


Assume a jam gap

Signal Cooperation for CACC Vehicle Strings

- **Estimating the location and speed of the manual vehicles:**

Case 3: When the subject CACC vehicle is moving and its preceding CACC vehicle stops in the queue

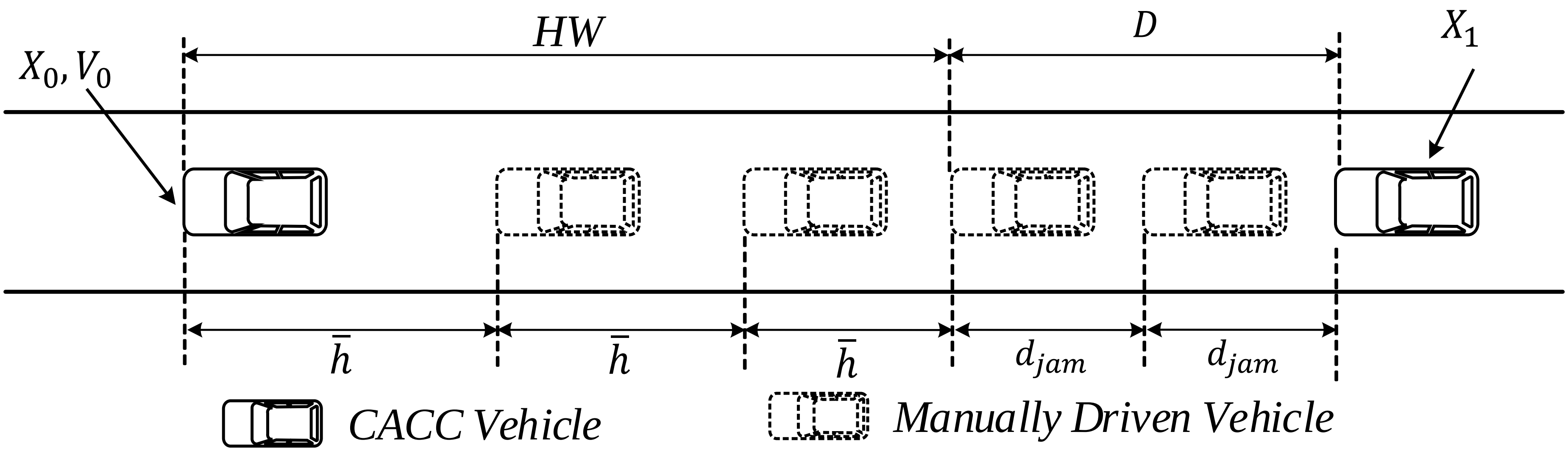


A stochastic method is used to estimate the number of queued vehicles

Signal Cooperation for CACC Vehicle Strings

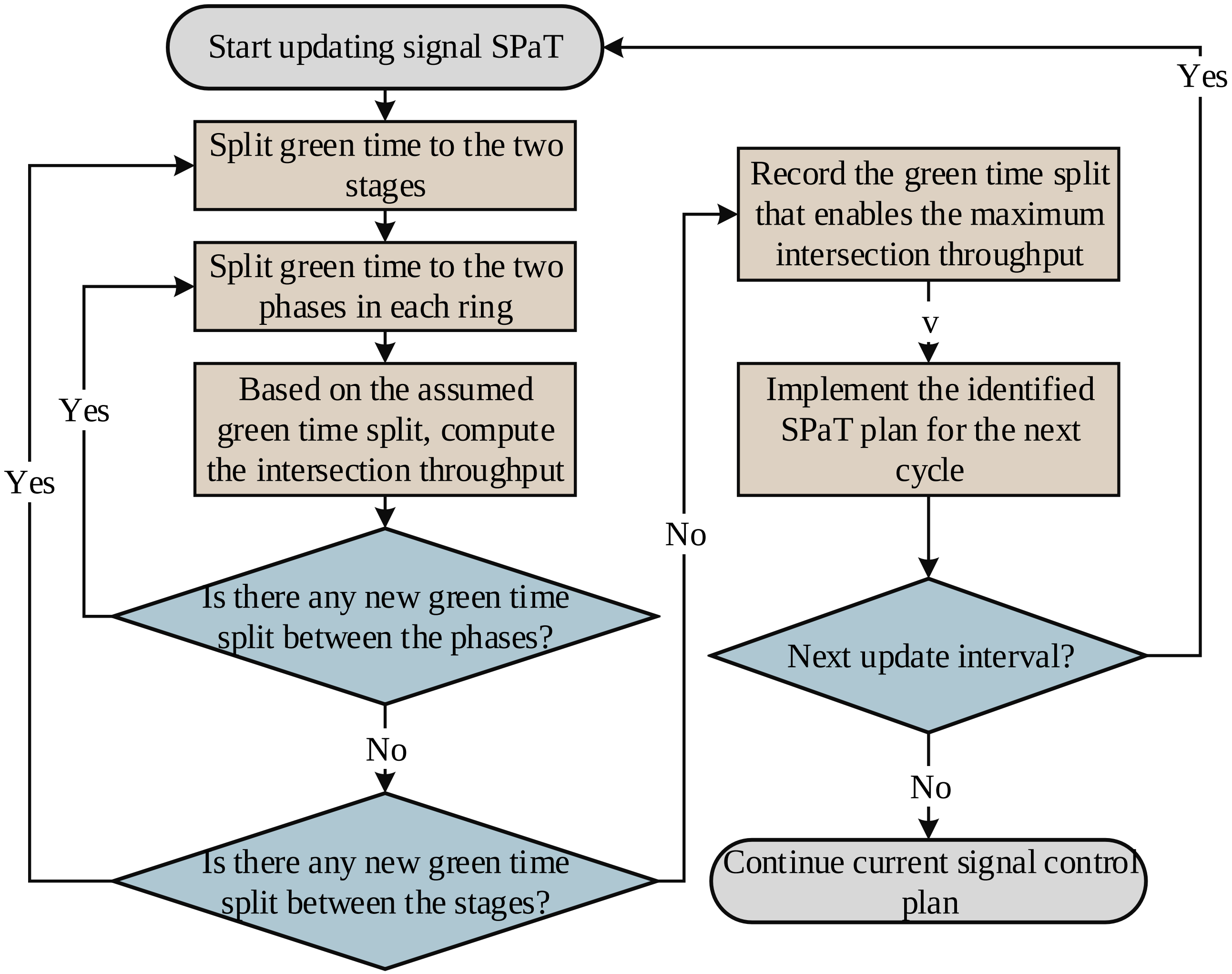
- **Estimating the location and speed of the manual vehicles:**

Case 4: When the subject CACC vehicle stops in the queue and its preceding CACC vehicle is moving



The traffic wave theory is used to estimate the number of moving vehicles

Signal Cooperation for CACC Vehicle Strings

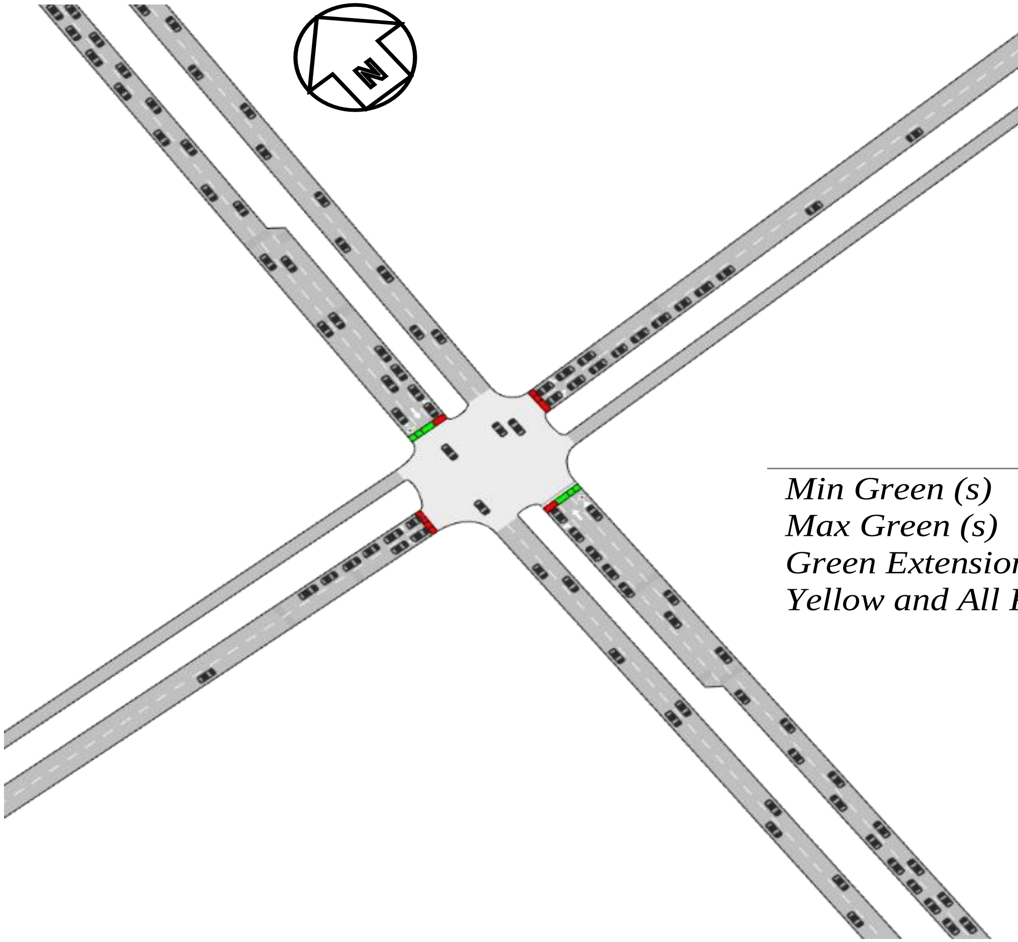


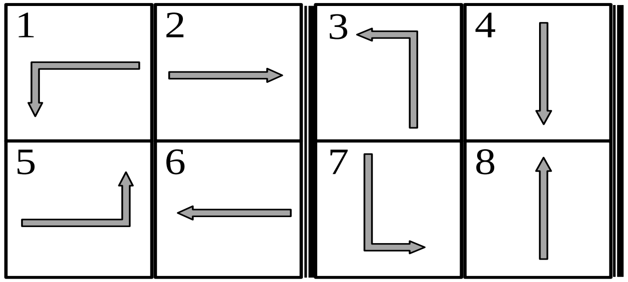
1. ***Assign all green time to the first stage***
2. ***Gradually increases the green time of the second stage with an increment of 3 seconds***
3. ***Stop searching when assigning more green time to the second stage does not increase the throughput***

- ***Remark***:
  - **Update the signal SPaT at the beginning of each cycle**
  - **Algorithm relies on data collected at the moment of update**

Signal Cooperation for CACC Vehicle Strings

- Simulation examination of the algorithm.

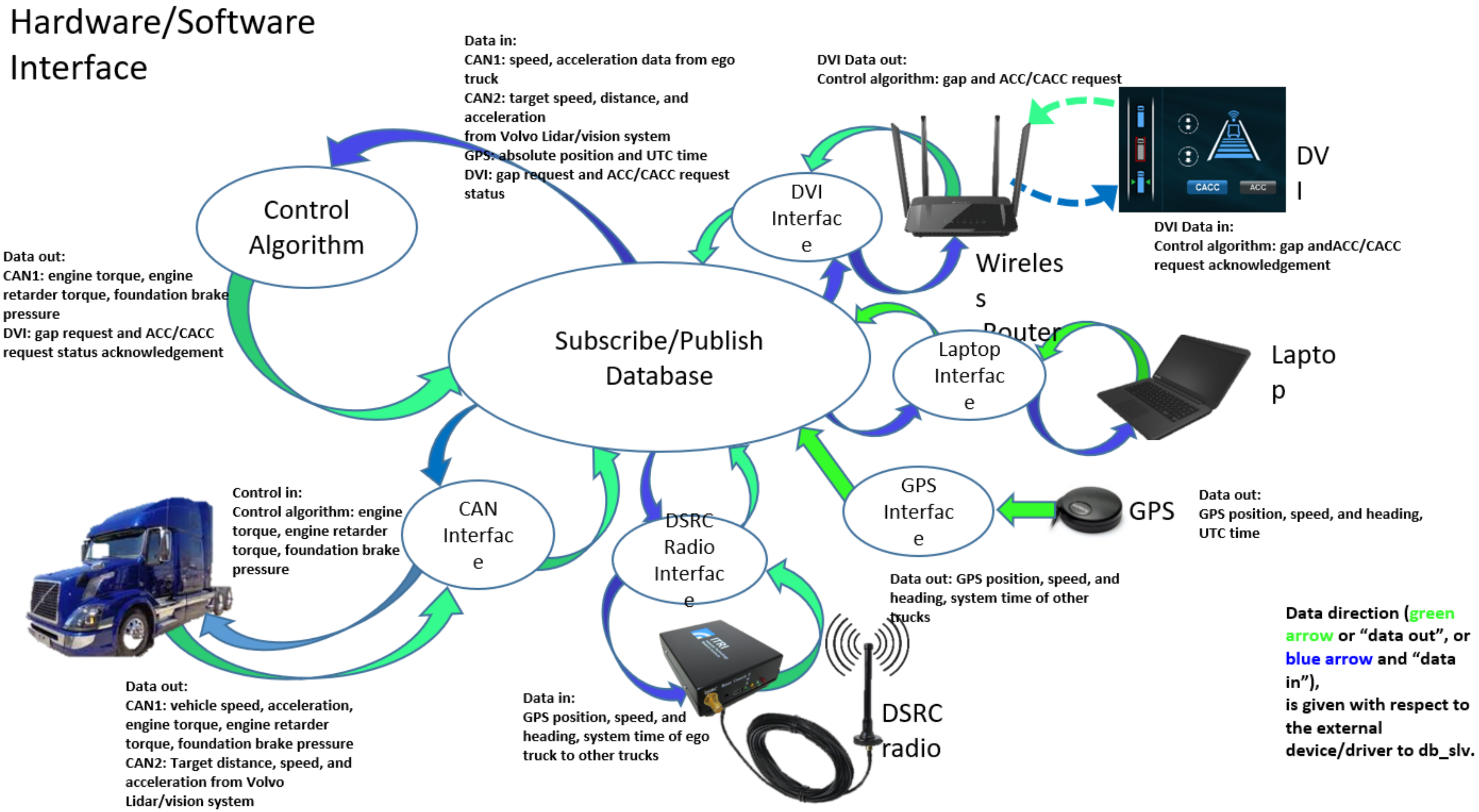




	EB/WB Left	*EB/WB Through*	*NB/SB Left*	*NB/SB Through*
Min Green (s)	0	0	0	0
Max Green (s)	8	14	6	46
Green Extension (s)	1.5	1.5	1.5	1.5
Yellow and All Red (s)	4	4	4	4

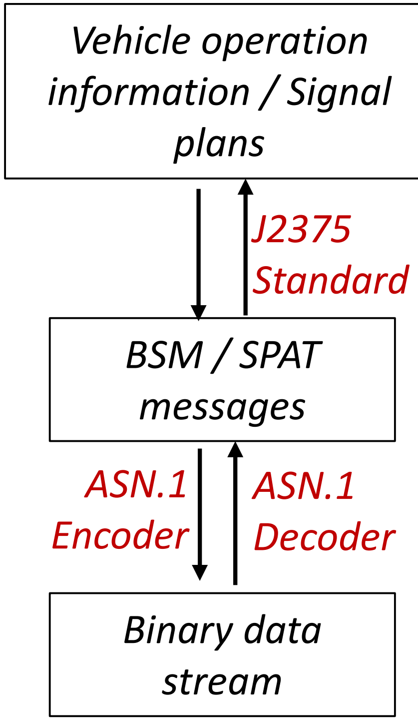
The algorithm is tested at an isolated intersection.
Its performance is compared with an actuated controller.

HARDWARE AND SOFTWARE INTERFACE



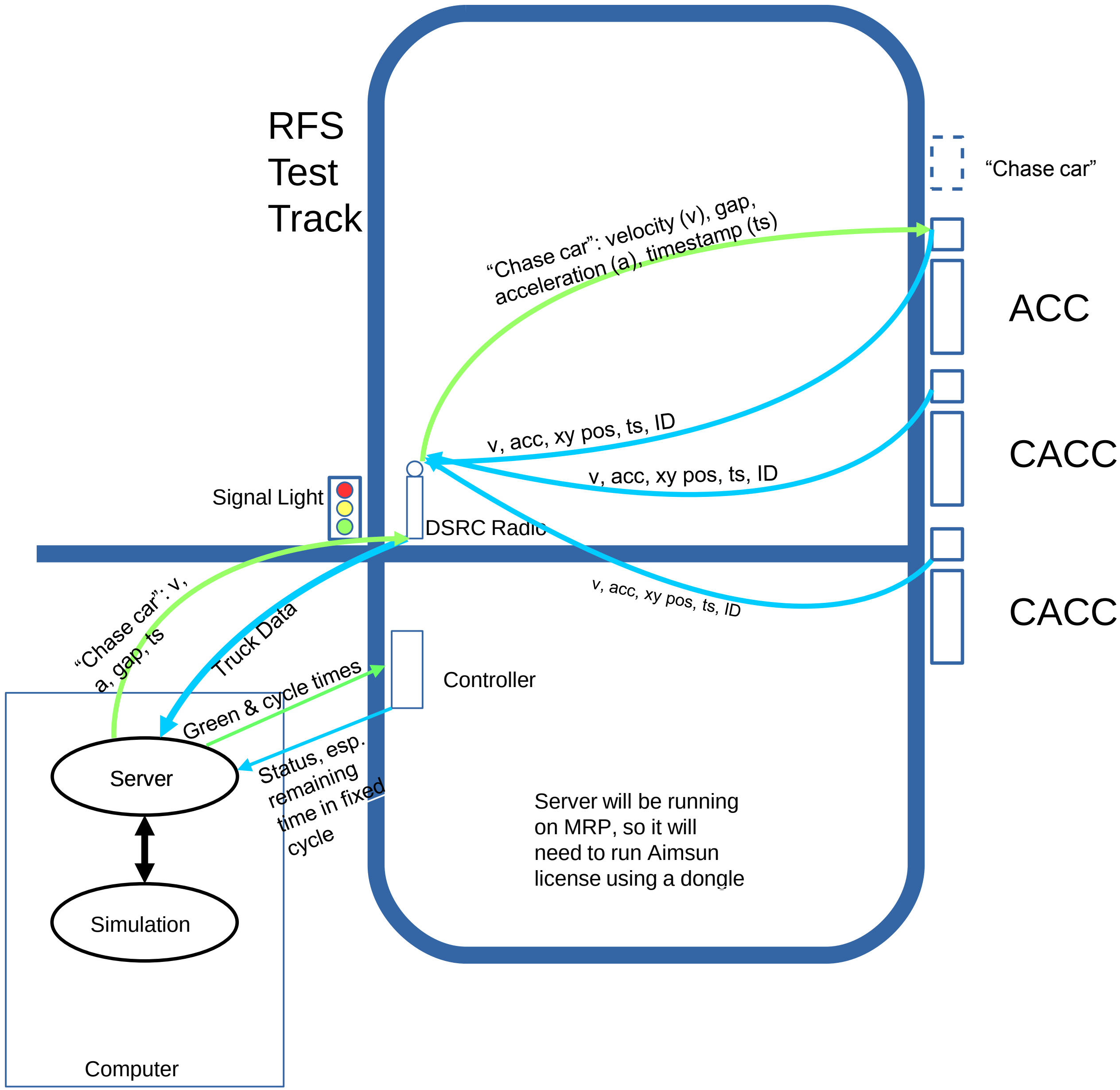
APPROACH

- Step 4: exchange vehicle and signal info, update simulated vehicles and real-world signal controller



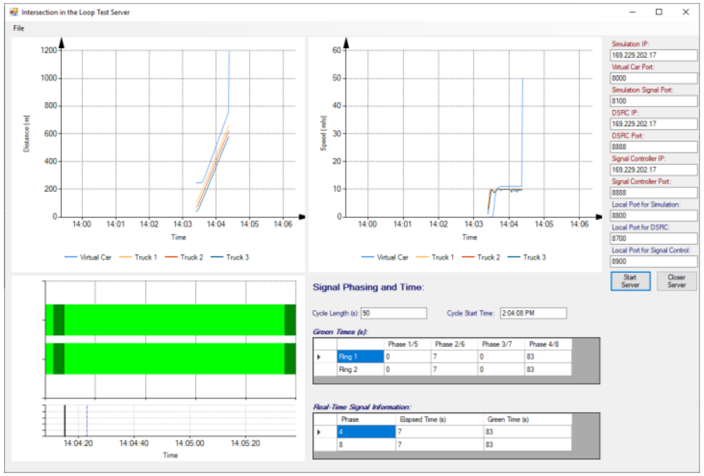
Test Intersection

Truck CACC controlled by simulated traffic data flow schematic

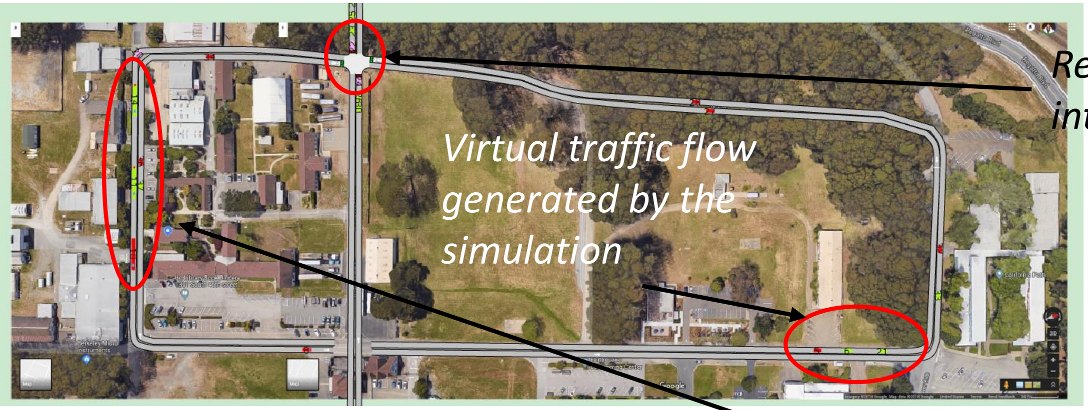


Developing Hardware-in-the-Loop Algorithms

- A testbed for realistic CAV tests.
  - Integrates the **simulation model**, **cooperative signal control algorithm**, real-world **intersection controller**, and test **CACC vehicles**
  - Real-time information exchanged via LAN and DSRC communications



A server program that monitors the real-time data flow and sends, receives, visualizes, and stores test data



Real-world intersection

Test track coded in the simulation model

Test CACC fleet captured in the simulation

Developing Hardware-in-the-Loop Algorithms

- **Algorithm framework:**
  - **Step 1: create simulated traffic scenario**
  - **Step 2: initialize simulated CACC truck string**
    - **Specify the traffic demand**
    - **Run the simulation for a warm-up period**
    - **Create three simulated trucks at the beginning of the link**
    - **Stop the simulation**
    - **Waiting for the updates from the real-world fleet**

Developing Hardware-in-the-Loop Algorithms

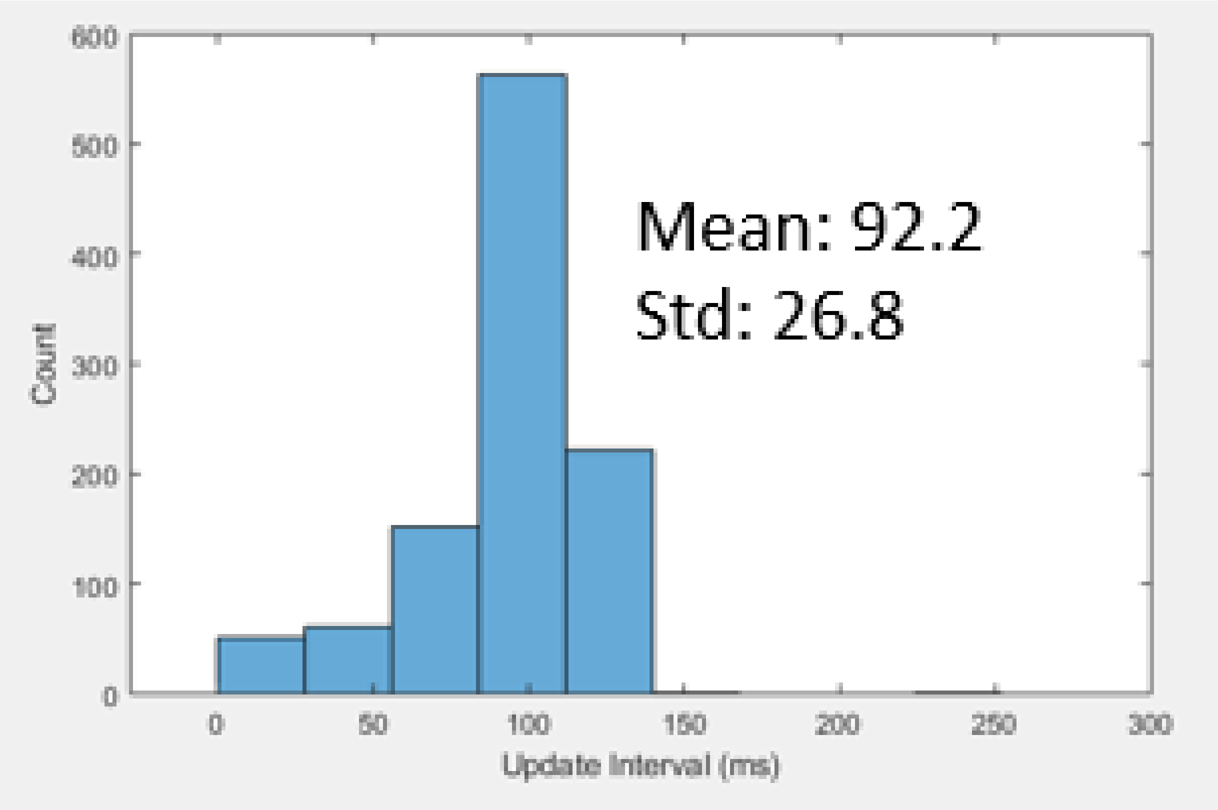
- **Algorithm framework:**
  - **Step 3: connect to server, synchronize simulation speed**
  - **Step 4: exchange truck info, update simulated trucks**
    - **Once connected, put a timer in Aimsun that allows the simulation to run in real time**

Send/receive → Update simulated vehicles → Wait until 0.1s elapsed

3 truck real-time running distance trajectory

Developing Hardware-in-the-Loop Algorithms

- Algorithm framework:
  - Step 3: connect to server, synchronize simulation speed
  - Step 4: exchange truck info, update simulated trucks
    - Send/receive and simulation update to be completed in 0.1 s



Real-time updating statistics for synchronization

REVIEW ONLY SLIDES