

Integrated Control of Vehicle Speeds and Traffic Signals for Reducing Congestion and Energy Use

—Oak Ridge National Laboratory (EEMS095)

June 13, 2023

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ORNL is managed by UT-Battelle LLC for the US Department of Energy

Overview



Timeline

- Project start: Dec 2020
- Project end: Dec 2023
- Percent complete: ~75%

Budget

- Total project funding: \$3,538K
 - DOE share: \$3.150K / 3 years
 - Cost share: \$388,500
- Funding for FY 2023: \$1,050K

Partners/Collaboration

- City of Chattanooga, Tennessee
- Toyota Motor North America R&D
- National Renewable Energy Lab

Barriers

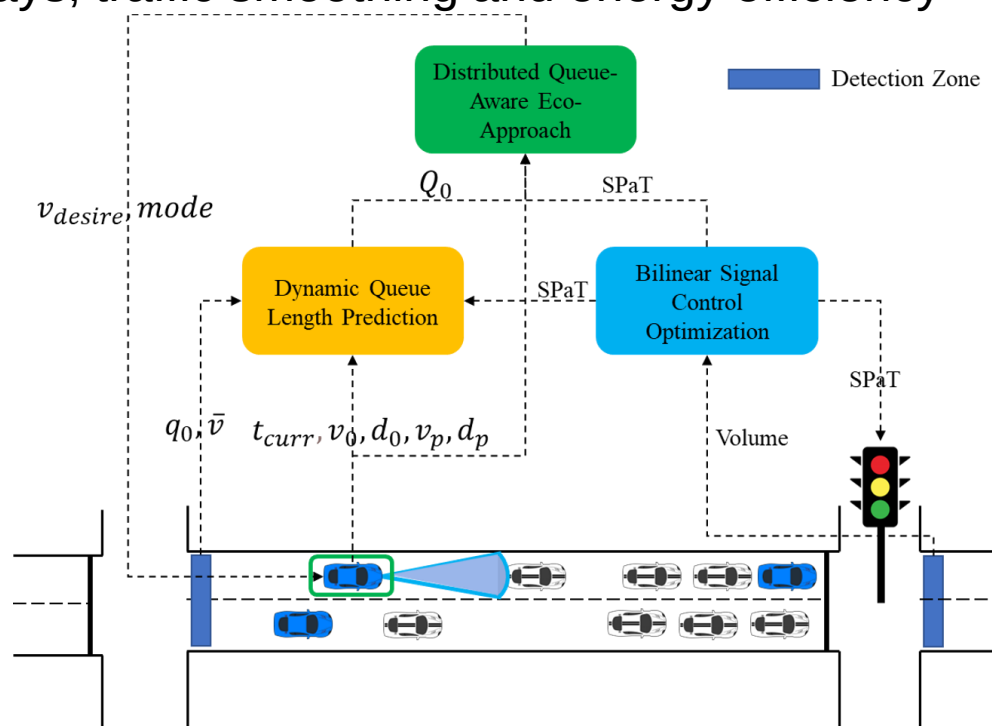
- The benefits achievable with connected and automated vehicle (CAV) technologies in **real-world operation**, including varying traffic conditions, are not clear
 - **Validation** of modeling with real-world data is needed
 - Optimized controls are challenging to develop and **implement for real-time operation**
- *Controls and communications* are key factors to successful coordination of vehicle speeds with signal timing
 - **Range of communications** is critical factor for efficiency applications
 - Controls must function in **real time**, and in many cases vehicle-specific factors influence how effective speed control can be

Relevance

Overall project objective:

- Develop and demonstrate an integrated controls strategy that combines real-time traffic signal timing and vehicle speed controls in CAVs
- Validate energy consumption and traffic flow benefits through
 1. traffic simulation,
 2. dynamometer testing,
 3. on-road field evaluations
- Demonstrate efficiency gains for CAVs of at least 15% under appropriate traffic conditions

- Vehicle speed control
 - Anticipate traffic signal changes $\Rightarrow$ coordinated speeds
 - Speed profile optimization: arrival at signal after red-to-green
- Traffic signal timing control, with communications to vehicles
 - Sharing traffic information: traffic network optimization is possible
- Integration expected to yield significant benefits in travel delays, traffic smoothing and energy efficiency



Relevance



- Major research questions addressed:
 1. What level of energy savings and traffic flow improvements can be realized from the integration of speed and traffic signal controls under different scenarios of implementation?
 2. How well do existing research tools predict the performance of actual control strategies and CAV systems in the real-world?
 3. What impact does the communication topology (direct point-to-point vs. cellular/cloud-based communications), and the corresponding communication range and signal latency, have on the performance of energy efficient mobility systems?
- Impacts:
 - Real world demonstration and validation of advanced CAVs system
 - Investigate impacts on energy and mobility for different traffic scenarios, different control strategies, and the mode of communications
 - This research will inform decisions for selection of technologies that can yield the greatest energy savings benefits as cost effectively as possible

Milestones

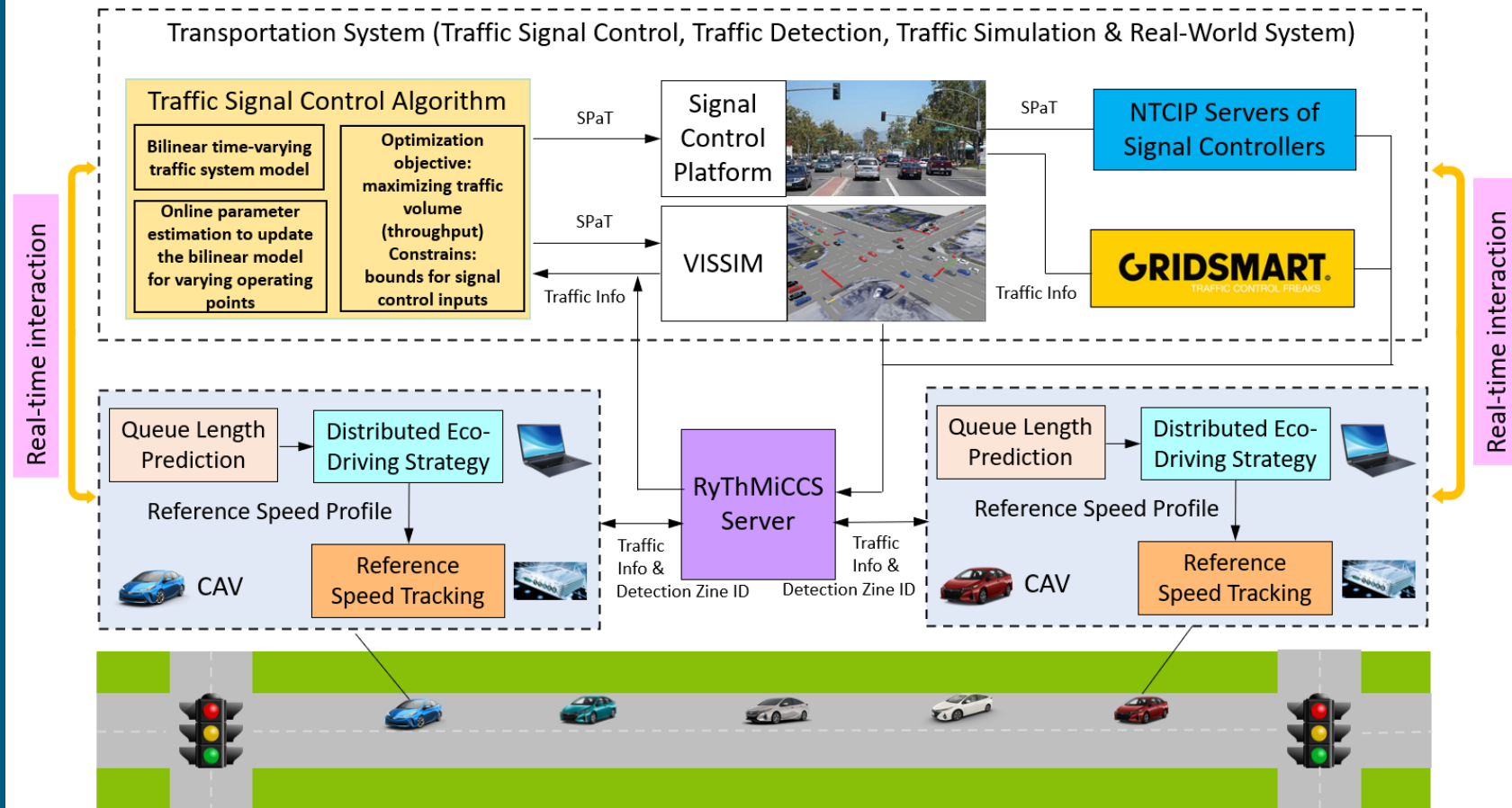
Month/Year	Description of Milestone or Go/No-Go Decision
December 2021 Completed	Queue length and CAV green arrival time prediction to minimize braking at signal stop points in the speed control.
June 2022 Completed	Traffic scenario evaluations via simulation completed.
June 2022 Completed	<u>Go/No-Go</u> : Demonstrate that integrated speed and SPaT controls achieve 15% average energy savings of CAVs in the Shallowford Road corridor via simulation (simulations show 16-20% energy savings for implementable control strategy (for CAV penetration over 40%))
October 2022 Completed	Speed control algorithms integrated in prototype CAV(s)
January 2023 Delayed*	CAVE laboratory evaluation of prototype CAV complete
May 2023 On Track	Traffic Signal Controls implemented in Chattanooga and beta-tested
August 2023 On Track	Integrated control strategy verification on Toyota prototype vehicle

Approach

Overview: 3 primary tasks with performance evaluations conducted at each stage using consistent methodology

Tasks

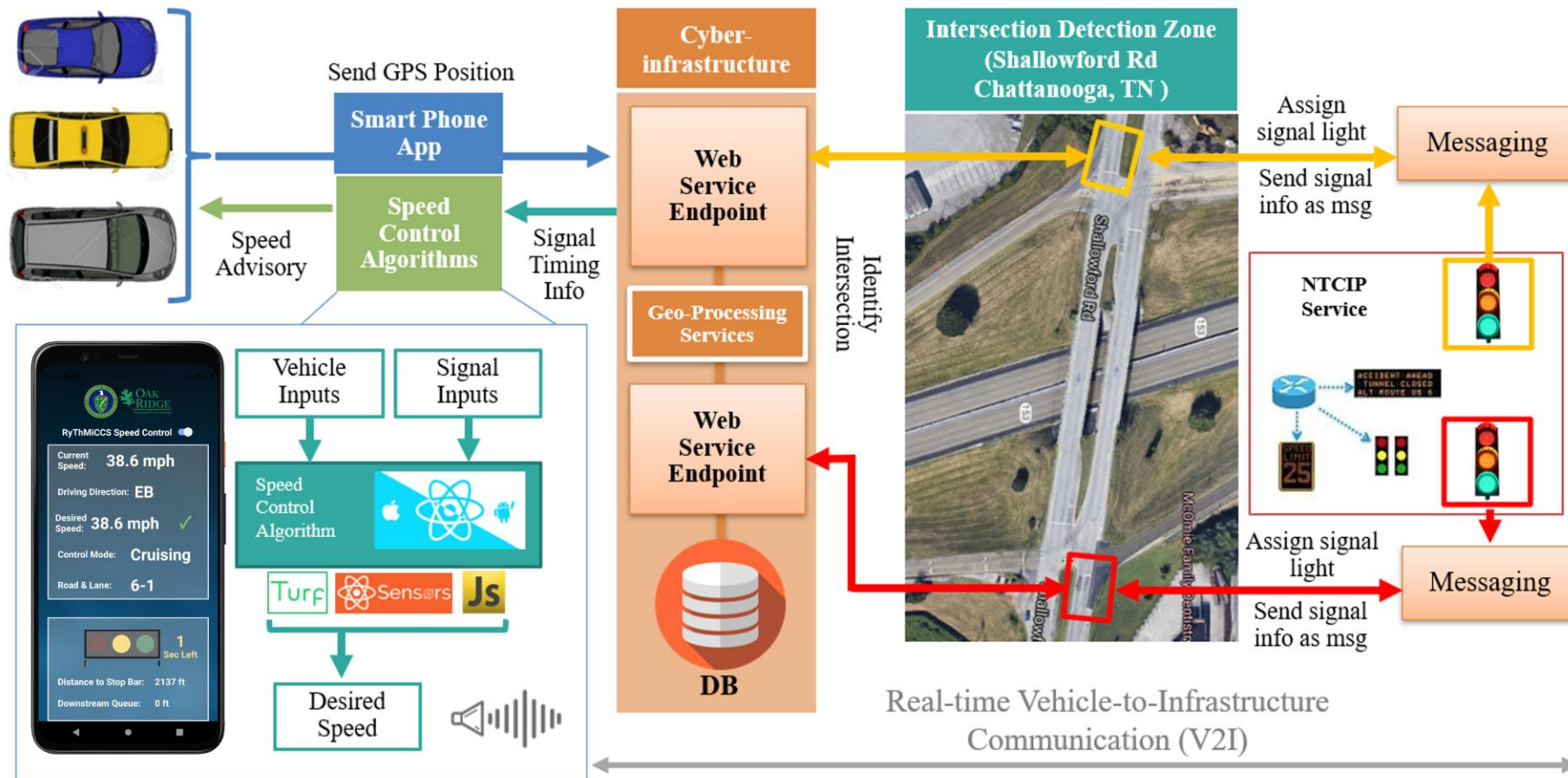
- ❑ Controls development and scenario evaluations via simulation (M1–M18)
- ❑ CAVE Laboratory vehicle dynamometer evaluations (M12–M30)
- ❑ Field evaluation (M20–M36)
- ❑ Performance Evaluations (M10–36)



Approach

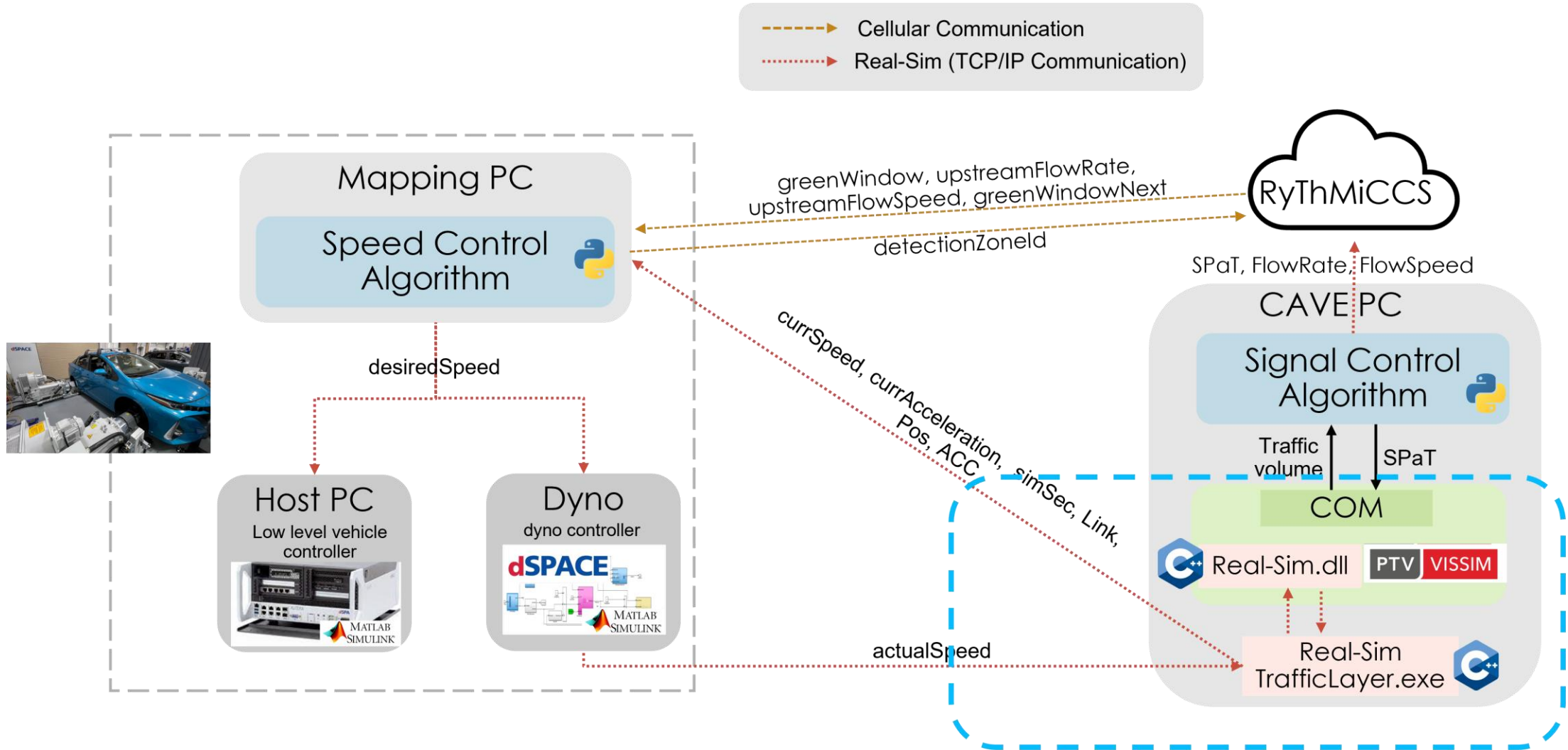
Real-Time Mobility Communications and Control System (RyThMiCCS)

Development and implementation of the communication strategy for this application will proceed in parallel with the control development, in preparation for the on-vehicle evaluations (dynamometer and on-road)



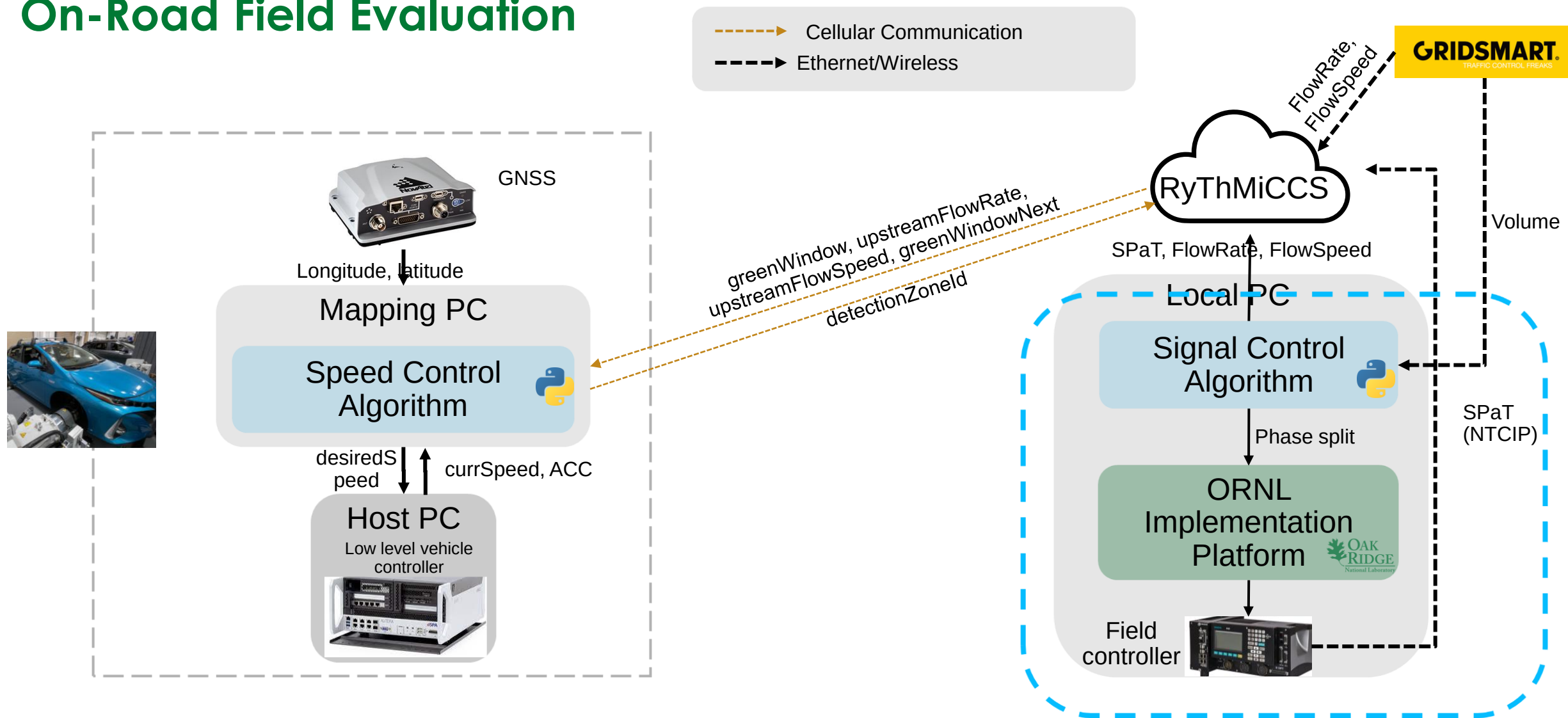
Approach

CAVE Laboratory Dynamometer Evaluations



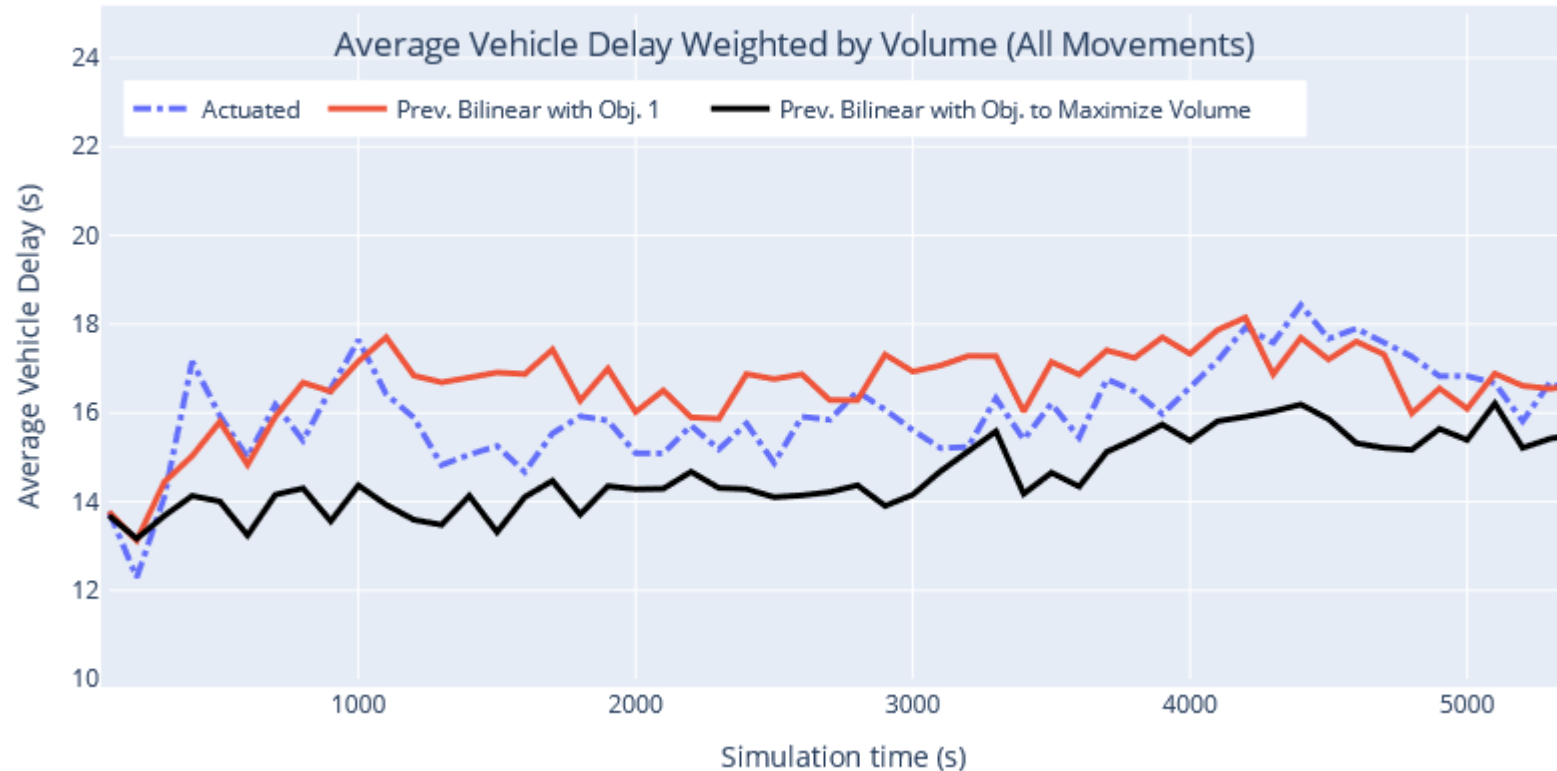
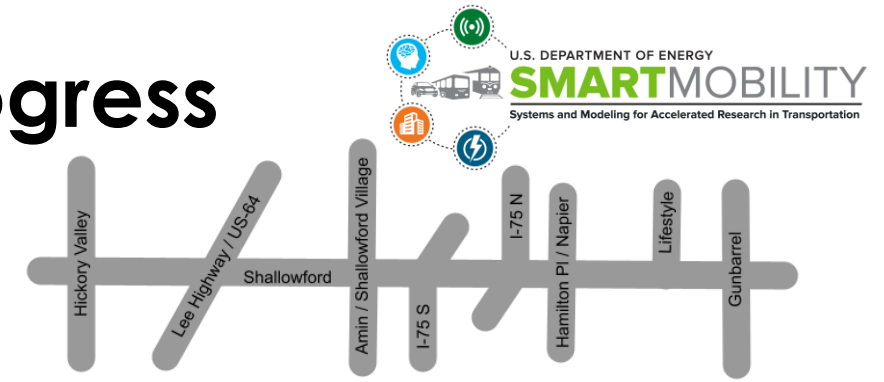
Approach

On-Road Field Evaluation



Technical Accomplishments and Progress

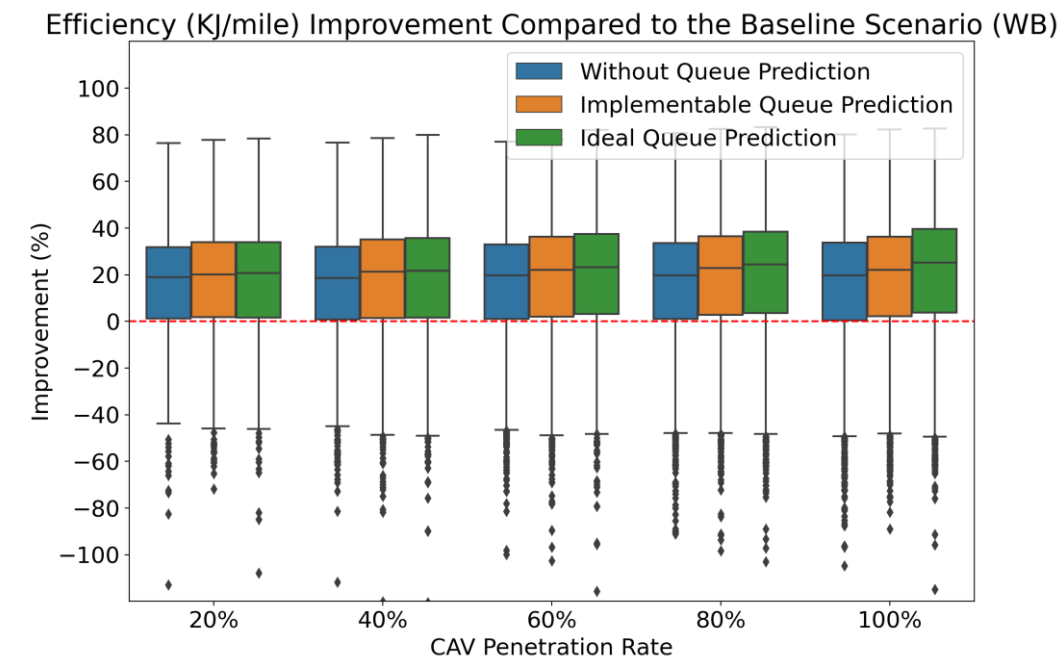
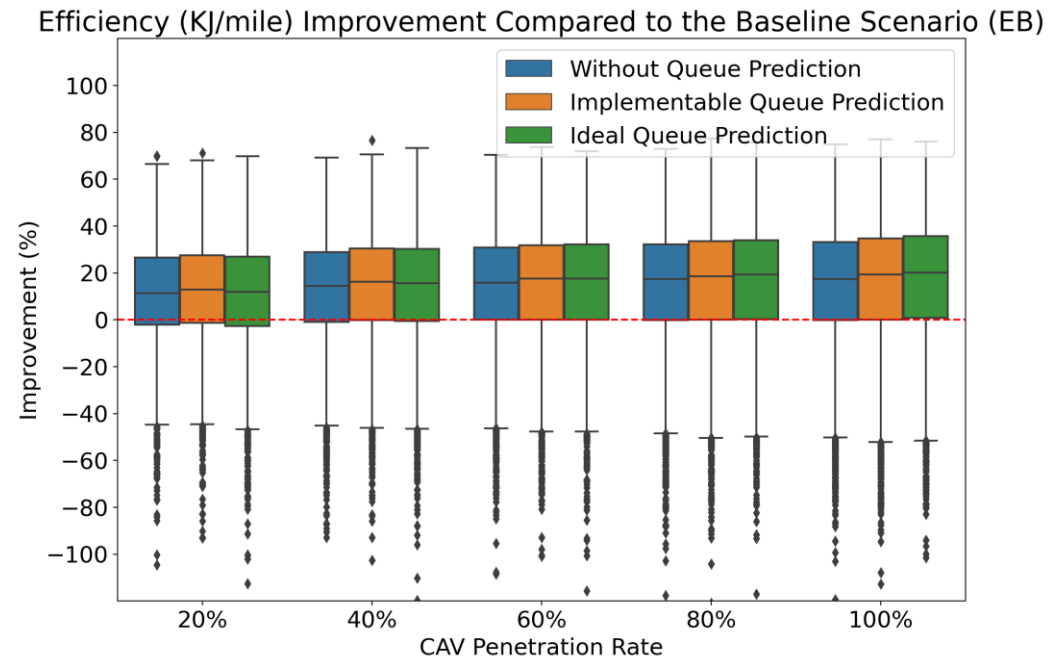
Bilinear Signal Control Algorithm



Signal Control Model	Average Delay	Reduction
Actuated	16.08 s	-
Bilinear (maximize volume)	14.63 s	9.02%

Route-Based Energy Saving Evaluation for CAVs

Integrated Bilinear Signal Control and Queue-Aware Eco-Driving (QAED)

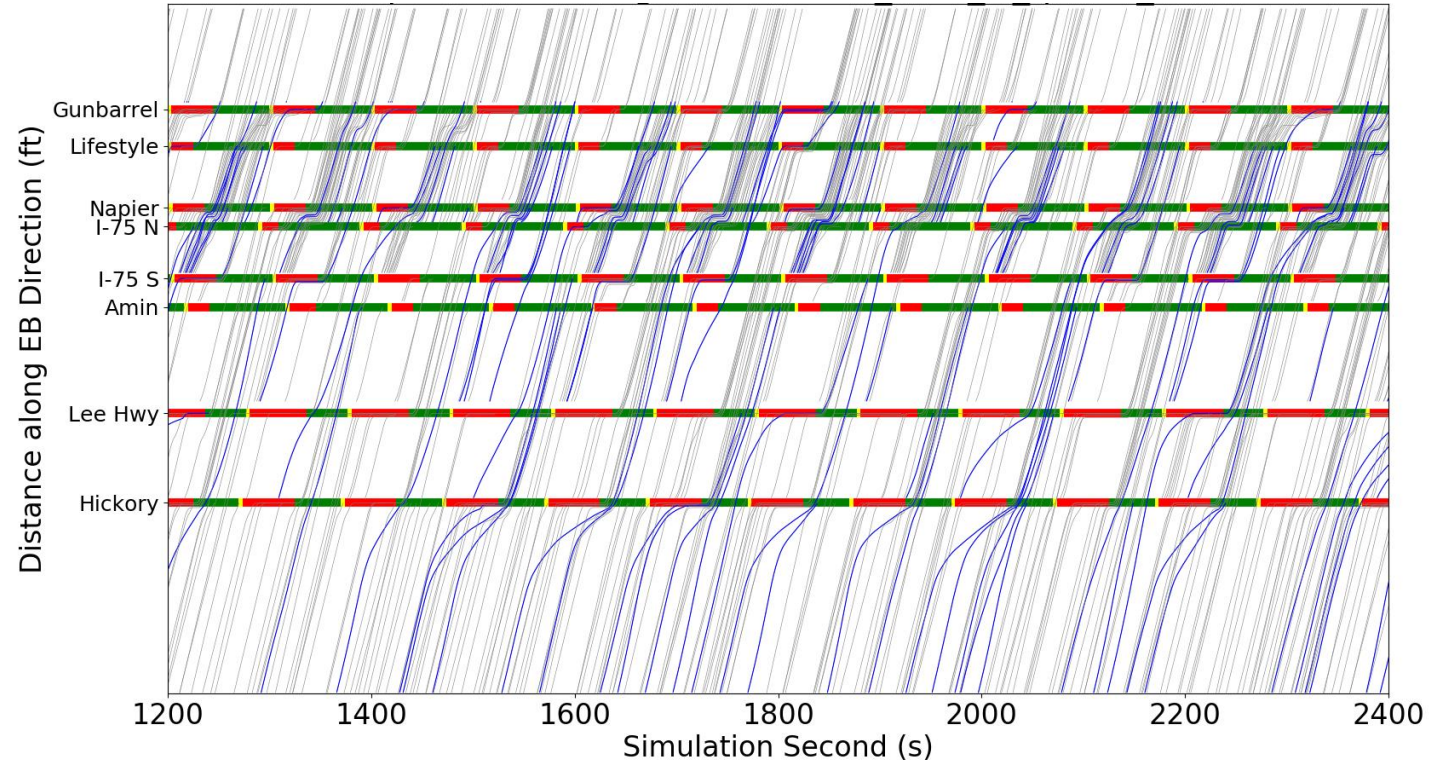


Baseline scenario:
actuated signals and
no speed control

Direction	Energy Efficiency Improvement (%)					
	CAV Penetration Rate	20%	40%	60%	80%	100%
EB	Without Queue	15.12	17.13	18.29	18.91	19.12
	Implementable Queue	16.32	18.53	19.42	19.97	20.33
	Ideal Queue	15.37	18.15	19.68	20.61	21.26
WB	Without Queue	21.15	21.69	22.39	22.56	22.39
	Implementable Queue	22.78	24.09	24.64	25.27	24.72
	Ideal Queue	22.99	24.57	26.02	26.79	27.45

System-Level Energy Saving Evaluation

- In the WB direction, the 100% CAV scenario with the ideal queue length prediction has the highest system energy savings (24.82%).
- At **low** CAV MPR (e.g., 20%), even though the **CAVs** can still achieve up to **22.99%** energy savings compared to the matched Non-CAVs, while the energy saving of the overall transportation **system** is quite limited (up to **7.21%**).



Direction	Energy Efficiency Improvement (%)					
	CAV Penetration Rate	20%	40%	60%	80%	100%
EB	Without Queue	3.16	7.20	11.02	14.52	17.43
	Implementable Queue	3.49	8.08	11.78	15.42	18.69
	Ideal Queue	3.43	8.10	12.23	16.04	19.65
WB	Without Queue	6.82	9.63	13.36	17.04	20.12
	Implementable Queue	6.84	11.02	14.86	19.42	22.42
	Ideal Queue	7.21	11.33	15.94	20.63	24.82

Mobile App Development

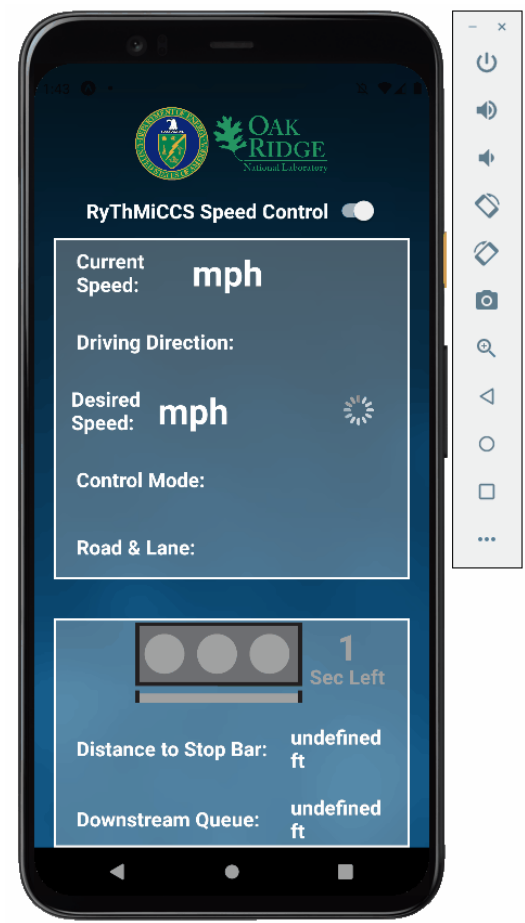


Current Driving Speed ←

Recommended Driving Speed ←

Intersection Name ←

Vehicle Distance to Stop Bar ←
Queue Length ←



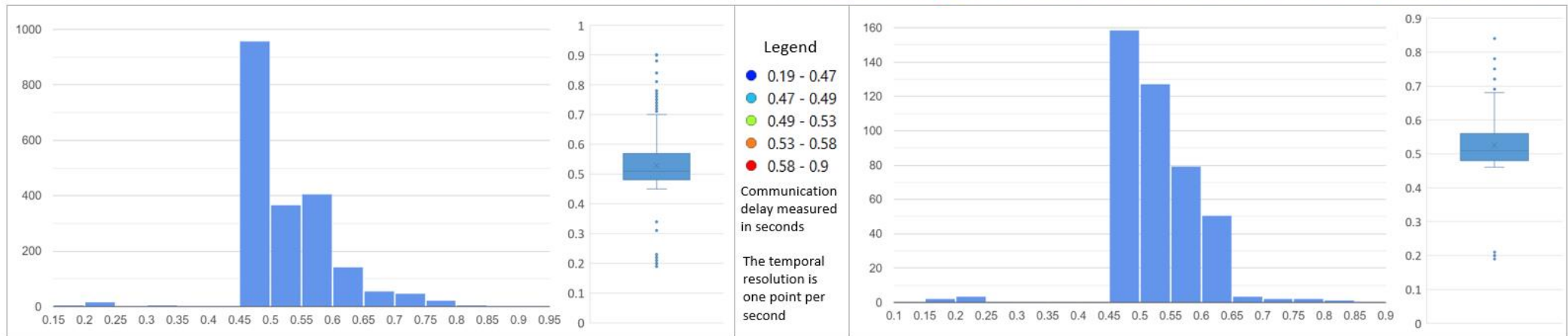
Connected and Automated Vehicle Environment (CAVE) Laboratory

Communication Latency Test (Mobile App)

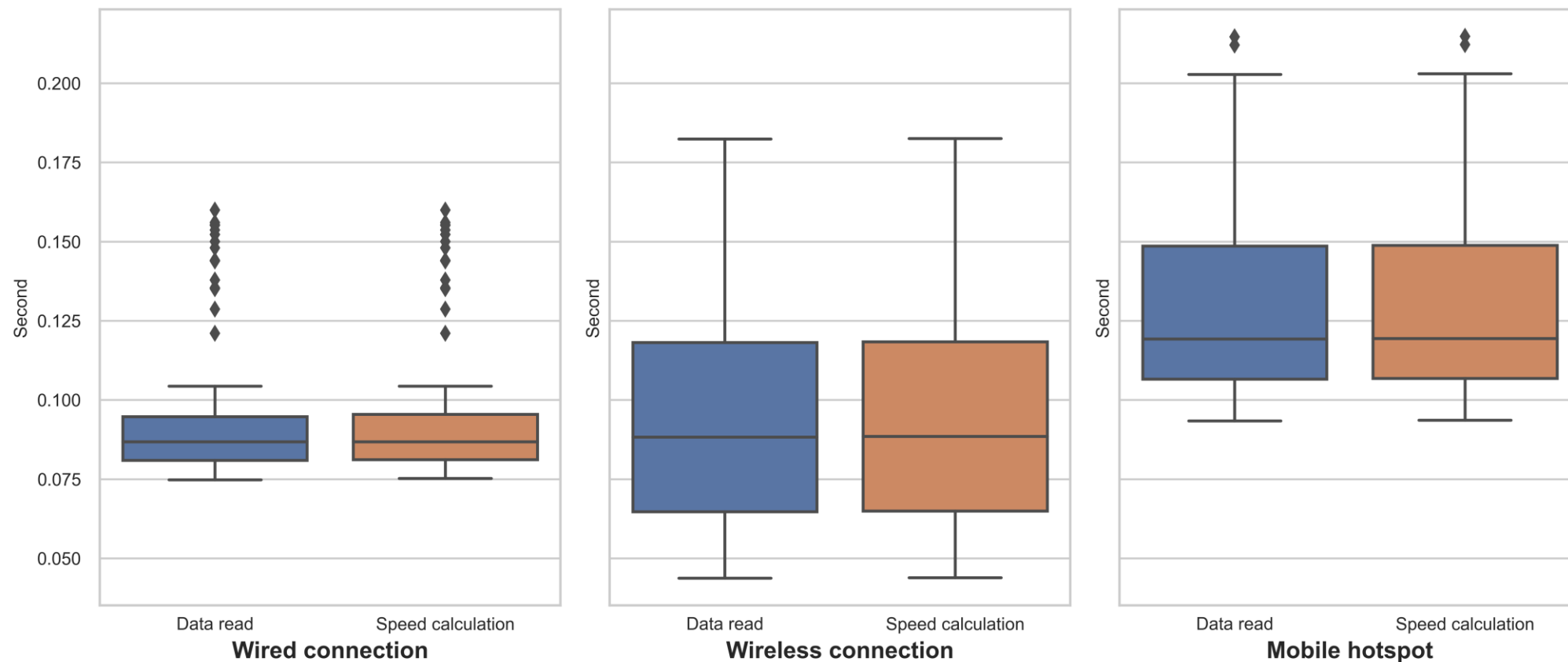
a) 20-mile test drive around the middle brook pike and Kingston pike in west Knoxville, TN.



b) a community within the communication test area near the middle brook pike.



Communication Latency Test (Vehicle)



- **Data read:** Time to get the data from the server
- **Speed calculation:** Total time to get the desired speed

Responses to Previous Year Reviewers' Comments

- *“The team is making good progress on the technical accomplishments and milestones. One area that the team cited as having some uncertainty is the readiness of the CAVE laboratory environment.”*
 - The CAVE lab test for this project involves very heavy integration of several critical pieces, i.e., Mapping PC and Host PC on Toyota vehicle, speed control algorithms, RyThMiCCS communication, CAVE lab PC for dyno control, VISSIM simulation, bilinear signal control algorithm, and Real-Sim interface. With the support of our multi-disciplinary team members, we are still on the right track to fulfil our needs for the lab testing.
- *“While Toyota is listed as a partner, it seems they are primarily participating by supplying the test vehicles. There were no references to active collaboration, nor of any interest in furthering the development effort. The same can be said for Cubic, in that their equipment and maybe IT support is being used, but it's unclear how involved the company is in the research or its findings. Chattanooga seems like a more involved partner, as the tests took place on active roads.”*
 - Toyota is indeed an active partner in the project throughout the algorithm development, algorithm evaluation, vehicle control integration, CAVE lab testing, and on-road testing. We have biweekly meeting with Toyota to discuss the progress regarding control algorithm development and evaluation. Also, Toyota will visit ORNL twice and work with us for a month in total for lab test and field test.

Collaboration and Coordination with Other Institutions

- ORNL (lead): responsible for controls development, modeling and experimental evaluation activities
 - Controls development for integrated speed and signal timing control
 - Energy efficiency modeling/analysis
 - Vehicle dynamometer testing and powertrain controls
 - RyThMiCCS communications system development and data management
- Toyota – R&D support for integration of the control strategies and communications into the prototype research vehicle; technical and commercial advisor to the project
- Chattanooga – support ORNL for implementation of traffic signal controls in the on-road evaluation; provide relevant data needed for the control development and deployment
- Coordinating with/leveraging results from other EEMS activities (EEMS101, 067, 084)

Remaining Challenges and Barriers

- A variety of challenges exist for real-world implementation of any complex system. Hardware and software from different manufacturers introduces possible compatibility issues, which leads to high potential for complications.
- Real-world eco-driving deployment during congested traffic flow will result in many interactions between the surrounding human drivers. These type of human dynamic interactions have not been explicitly examined, which might require some modifications in the control algorithm.
- Continued deployments at new locations in the future is complex:
 - CAV applications require standardization and compatible data and communications systems / protocols, but each location/municipality can have different equipment and constraints
 - Vehicle manufacturers' ability to broadly deploy this technology will depend on municipalities having up-to-date signal controllers and appropriate data and communications systems that employ compatible protocols

Proposed Future Research

Plans for FY23Q3-4 and FY24

- Testing in ORNL's CAVE Laboratory
 - The vehicle-in-the-loop evaluations in the CAVE laboratory are under development, and we are leveraging work in another project (EEMS067) for some of the testing preparations. Integration of VISSIM simulation data with the vehicle are being conducted in parallel with Toyota as well as using other test vehicles in the lab prior to arrival of the prototype CAV. All testing in the CAVE lab will be completed by the end of April 2023.
- Preparations for and completion of the on-road testing –Communications work is on-going and the field evaluation will take place in 2023. The project team is leveraging work done in EEMS061 for signal control implementation.

Summary

- Integrated controls for traffic signal timing and vehicle speeds can enable large gains in energy efficiency in addition to other improvements for mobility
- In this project we are developing and demonstrating integrated signal timing and vehicle speed controls by employing a progression of evaluation methods including traffic microsimulations (mostly complete), lab-based dynamometer testing (completion by April 2023), and on-road evaluation of a prototype Toyota Prius Prime CAV in the city of Chattanooga, Tennessee
 - The optimized traffic signal timing controls will be deployed on the Shallowford Road corridor and evaluated under normal traffic conditions
 - Energy savings of at least 15% will be demonstrated from the integrated controls on the Toyota research vehicle, and the effects on other vehicles will be evaluated through testing and simulations
 - Methodical performance evaluations will be conducted to quantify the fuel savings and mobility benefits of the integrated control strategies at each stage of the project, which will provide direct validation of the modeling tools used for evaluation of CAV performance
 - Evaluations considering a variety of operating conditions, CAVs penetration rates, and other parameters will be evaluated

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Thank you!

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Technical Back-Up Slides



Implementable Queue Length Prediction Using GridSmart

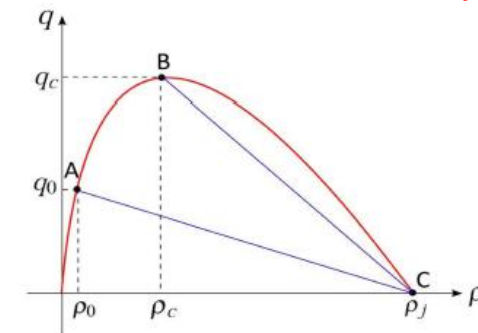
- Basically, we are trying to estimate v_{AC} using shockwave theory.
- The predicted queue length would be the intersecting point of eco-vehicle speed and v_{AC} .

$$\frac{d_0}{d - v_0(t_r - t) - d_0} = \frac{v_{AC}}{v_0}$$

$$d_0 = \frac{v_{AC}}{v_0 + v_{AC}} (d - v_0(t_r - t))$$

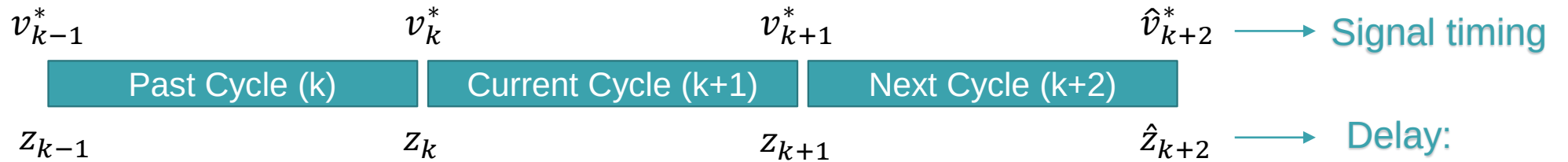
$$\begin{aligned} D_k^* &= d - d_0 = d - \frac{v_{AC}}{v_0 + v_{AC}} (d - v_0(t_r - t)) \\ &= \frac{v_0 * d + v_{AC} * v_0(t_r - t)}{v_0 + v_{AC}} \\ &= \frac{v_0}{v_0 + v_{AC}} (d + v_0(t_r - t)) \end{aligned}$$

$$v_{AC} = \frac{q}{\rho - \rho_j} = \frac{q}{\frac{q}{v} - \rho_j} = \frac{1}{\frac{1}{v} - \frac{\rho_j}{q * r}}$$



Bilinear Signal Control Model

- Objective
 - Minimize travel delay of current cycle k+1 by optimizing signal timing v_{k+1}



Current cycle:

$$\begin{aligned}
 (z_{k+1} - z_k) &= A(z_k - z_{k-1}) + B(v_{k+1} - v_k) + C(v_{k+1} - v_k) \odot (z_k - z_{k-1}) & (1) \\
 y_{k+1} &= z_{k+1} - z_k & (2) \\
 y_{k+1} &= Ay_k + B(v_{k+1} - v_k) + C(v_{k+1} - v_k) \odot y_k & (3) \\
 v_{k+1}^* &= \arg \min_{v_{k+1}} \max(y_{k+1}) & (4) \rightarrow \text{Objective}
 \end{aligned}$$

} Traffic network system

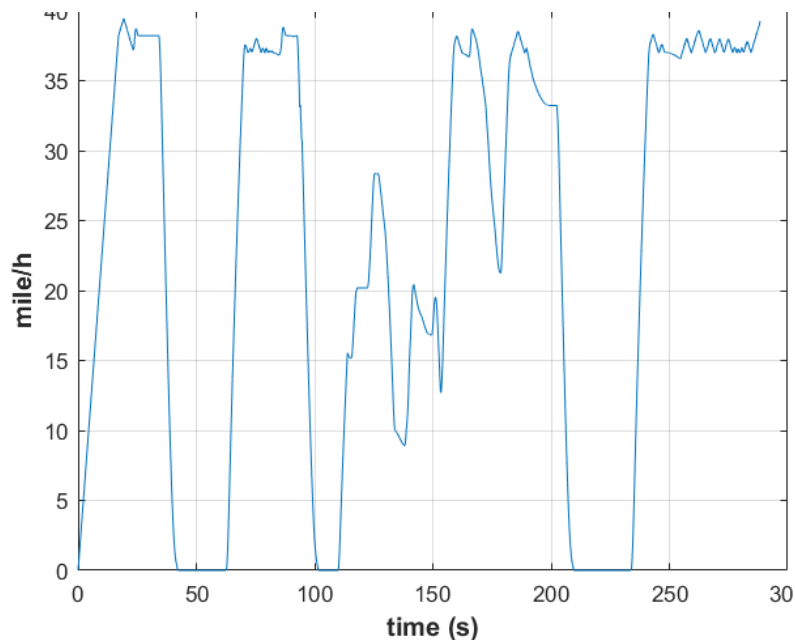
Predicted next cycles:

$$\begin{aligned}
 \hat{y}_{k+2} &= Ay_{k+1} + B(v_{k+2} - v_{k+1}^*) + C(v_{k+2} - v_{k+1}^*) \odot y_{k+1} & (5) \\
 \hat{v}_{k+2}^* &= \arg \min_{v_{k+2}} \max(\hat{y}_{k+2}) & (6)
 \end{aligned}$$

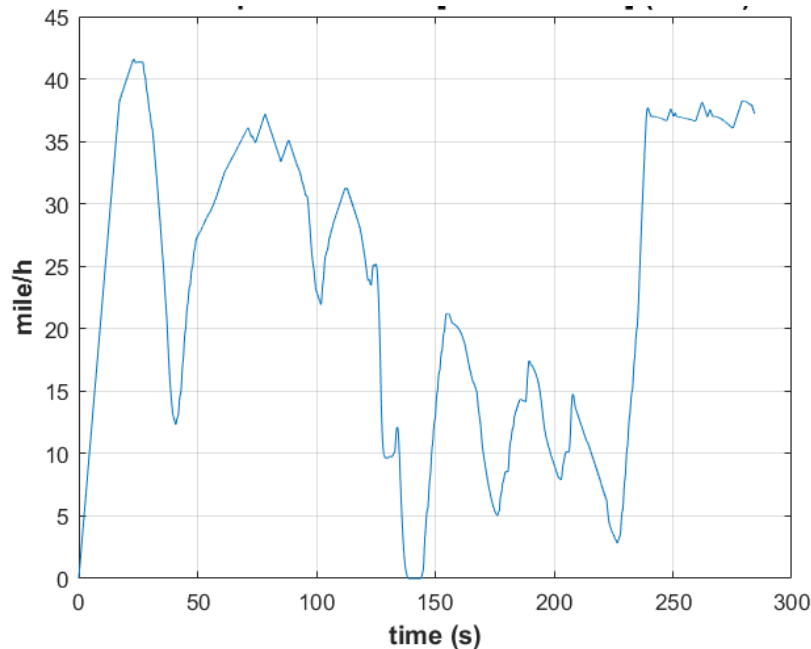
} Prediction for speed control

Autonomie Evaluation for Sample Drive Cycles

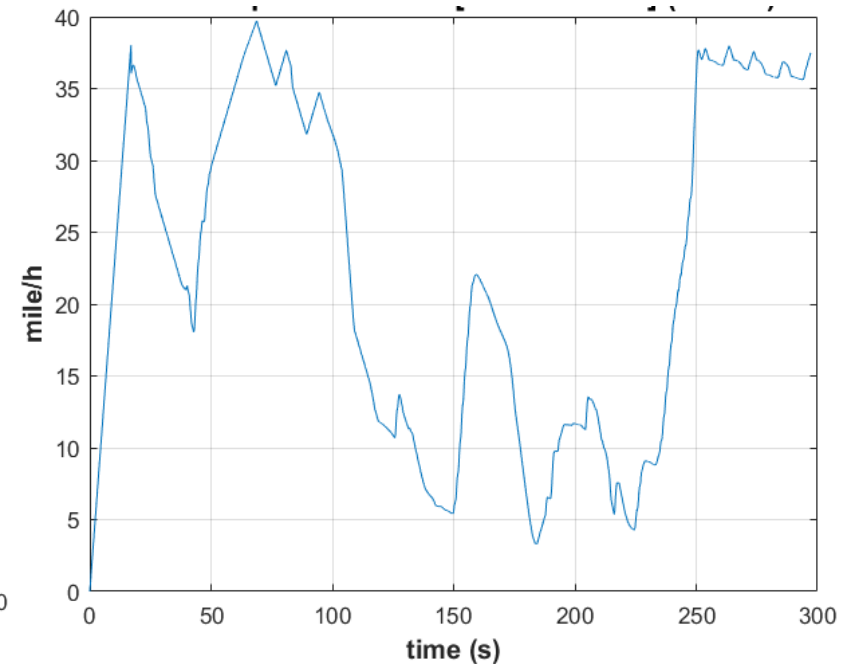
- The drive cycles used in Autonomie need to start from zero velocity. Add same portion of drive cycle in three drive cycles.
- Vehicle model: PHEV20 Power Split Midsize Gasoline with Oneway Clutch



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bilinear_40%_wo_queue_1_6497



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