40th Traffic Engineering Workshop

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“Pictures of PICTURE” Scenarios

CAV-Enabled Cooperative and Automated Traffic Control

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Outline

- ❑ Traffic Signal Control Methods in CAV Environment
- ❑ Self-organized Cooperative & Automated Traffic Control (SoCAT-C)
- ❑ UC Research
    - Signal-Free Autonomous Intersection Control
    - CV Data to Support Adaptive Signal Control
    - Cyber-Physical System Solution
    - Framework and modeling mechanism
    - Preliminary research results
- ❑ New ASCE Book "*Disruptive Emerging Transportation Technologies*"

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Traffic Signal Control Methods in CAV Environment

1. Advanced driver guidance based on CAVs
2. Actuated and/or adaptive signal control
3. Platoon-based signal control
4. Planning-based signal control
5. Signal-vehicle coupled control (SVCC)
6. Eco-driving and signal control
7. CAV cooperation intersections with no signal control
8. **Self-organized Cooperative & Automated Traffic Control (SoCAT-C)**

Note:

- *Summary was made based on literature review of* ***31*** *relevant papers (Annam and Wei, 2020; CVRIA 2016; Guler et al. 2014; Guo et al. 2019; He et al. 2012; Katsaros et al. 2011; Li et al. 2012; Liang et al. 2018; Lioris et al. 2017; Mirchandani and Head 2001; Pandit et al. 2013; Roess et al. 2011; Schneeman and Gohl, 2016; Schuricht et al. 2011; Sun et al. 2017; Tang et al. 2018; Ubiergo and Jin 2016; Varaiya, P. 2013; Wei, 2018; Wei and Kashyap, 2019; Wei et al., 2015; Wei et al., 2018; Wei et al., 2019a; Wei et al., 2019b; Wei et al., 2020; Wu et al. 2010; Xie et al. 2012; Xu et al. 2017; Yang et al. 2016; Yu et al., 2018; Zhang and Wang 2011);*
- *See more details in Wei, H. (also a key Author), Wang, Y.H., Ma, J.M. (2022). Disruptive Emerging Transportation Technologies. Published by American Society of Civil Engineer (ASCE). ISBN 978-0-7844-1598-6 (print) ISBN 978-0-7844-8390-9 (PDF) ISBN 978-0-7844-8419-7 (ePub).*

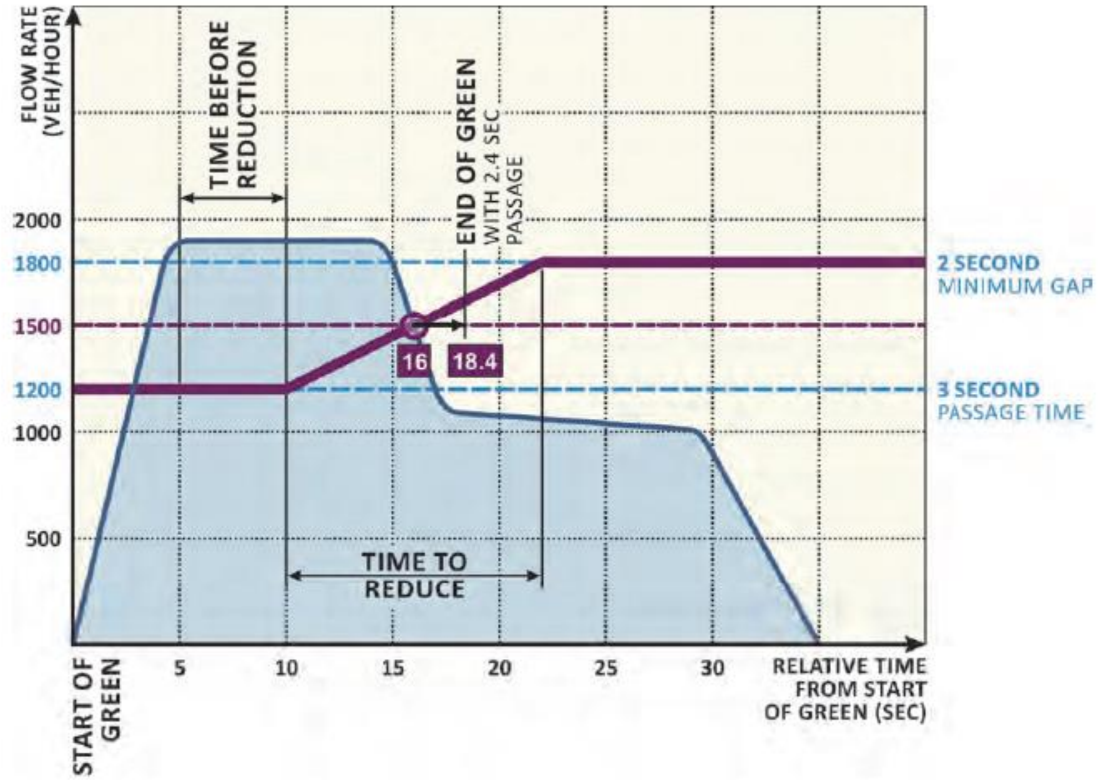
Traffic Signal Control Methods in CAV Environment

1. Advanced driver guidance based on CAVs:

- **Optimal speed guidance** for human drivers to help improve the driving control performance.
- Help drivers to reduce uncertainty in avoidance of safety risk (e.g. running red lights), while saving fuel by driving in ecological mode.
  - Vehicle state variables -- vehicle speed and position, vehicle accelerations and turn angles, parameters involved in vehicle dynamics/Kinestics models
  - Traffic state variables – state identification parameters involved in traffic flow models
  - Environment condition -- the signal timing and phases

2. Actuated and/or adaptive signal control:

- Accurate positions of the arriving CAVs, the actuated or adaptive control can dynamically adjust the timing parameters to respond to real-time traffic arrival changes, for example,
  - extending or shortening the current phase or
  - adding an extra phase to make on-time changes
- More efficiently utilize intersection capacity than traditional fixed-time signal control or inductive loop based actuated signal control in which signal phases and cycle lengths are pre-selected based on historical traffic patterns.



Traffic Signal Control Methods in CAV Environment

3. Platoon-based signal control :

- Identify the platoons by categorizing individual vehicles into pseudo platoons and predict their arrival time in advance. Based on the prediction, the signal timing plans are scheduled to allow the platoons to pass the intersections with no or little interruptions along the corridor.
- The concept was raised several decades ago, but not feasible until the V2X technique has been emerging in recent year to enable platoon identification so that platoon-based optimal signal timing plans can be generated.
- In the platoon-based method, the concept of vehicular ad-hoc networks (VANETs) has been proposed to collect real-time speed and position information of the CAVs. The information is then grouped into approximately equal-sized platoons to minimize difference of the maximum and minimum required processing time.

4. Planning-based signal control:

- Under assumed arrival distributions such as Poisson or uniform pattern within each platoon, the actual arrival time of every vehicle is predicted in a forward time horizon, on the basis of which the dynamic control is implemented.
- Comparison of planning-based and platoon-based methods:
  - The platoon method categorizes the incoming vehicles as platoons and ignores the inner dynamics and disturbances among vehicles in the same platoon.
  - The planning-based method treats all vehicles at the same level.

Traffic Signal Control Methods in CAV Environment

5. Signal-vehicle/multiple-vehicle coupled control (SM-VCC):

- Information between signals and CAVs is exchanged in real time via V2X to optimize the vehicle operations and signal timing simultaneously.
  - Vehicle state variables
  - Signal control variables
  - Implemented in transit priority control problems.

6. Eco-driving and signal control:

- A special adaptive traffic signal control system to balance environment impact with mobility performance (e.g., maximized throughputs or improved level of service) by using real-time and historical connected vehicle data
- It is applicable to signalized intersections along a corridor, or for a region.

7. CAV cooperation intersections with no signal control

- The intelligent intersection management of CAVs operation and control at un-signalized intersections or intelligent roundabouts with the support of V2X and other advanced data process analytics via computing technologies.
- Technically, the application of autonomous vehicles makes it possible to eliminate traditional traffic signals from the intersection, and hence has potential to maximize intersection capacity, significantly enhancing vehicle mobility at intersections.

Traffic Signal Control Methods in CAV Environment

Evolution of CAV-based traffic control approaches

Legends

- The upper arrow: the trend of considering more vehicle driving automation in traffic control systems
- The lower arrow: the trend of considering more traffic flow management in vehicle control systems.
- The curves: three stages of transportation-vehicle integration (from lower left to upper right): the past, the current, and the future.

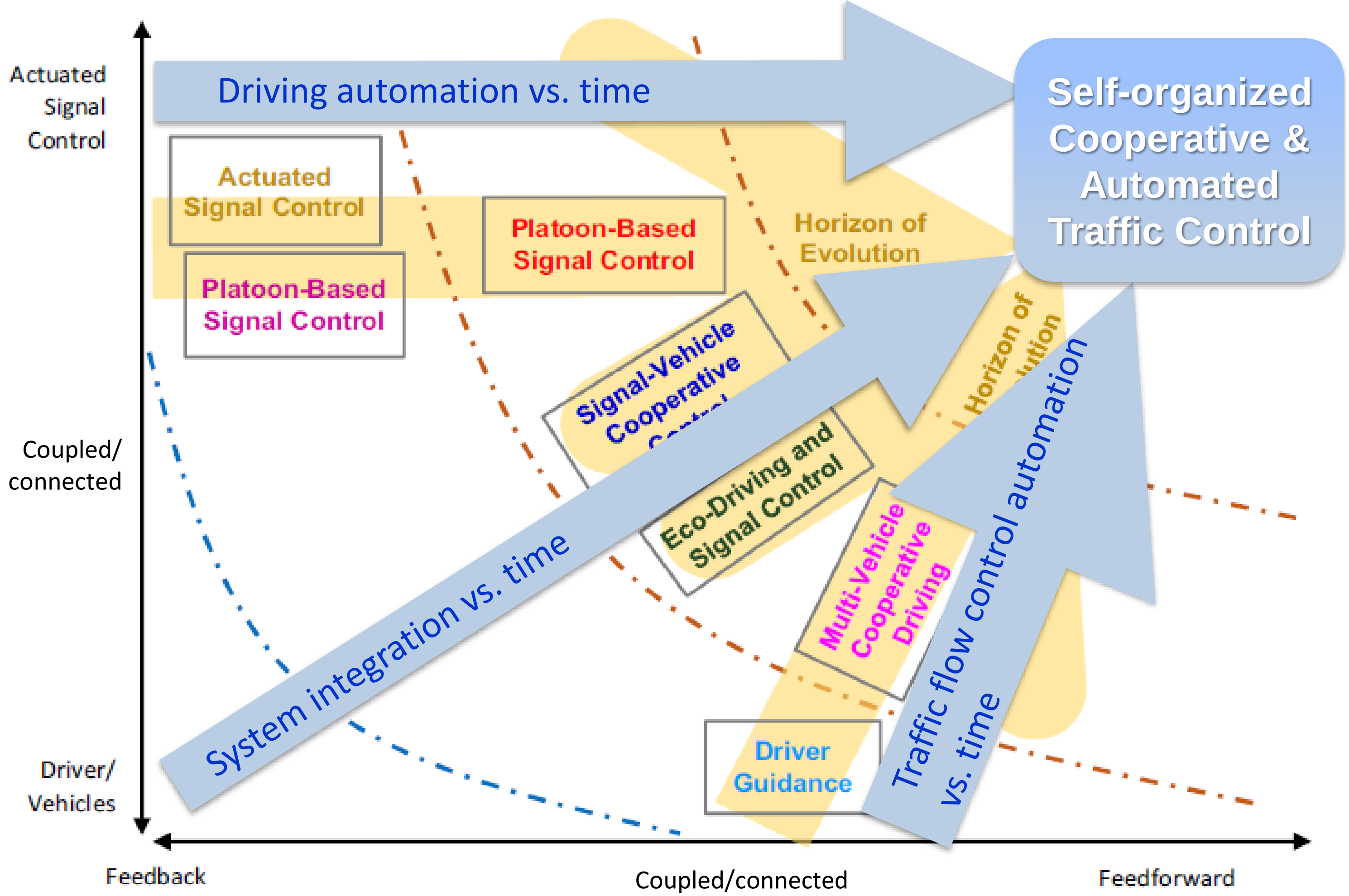


Figure 6-1. Illustration of an evaluation of CAV-based traffic control approaches.

Source: Revised diagram on the basis of Figure 1 presented in Guo et al. (2019).

Source: Wei, H. (also a key Author), Wang, Y.H., Ma, J.M. (2022). Disruptive Emerging Transportation Technologies. Published by American Society of Civil Engineer (ASCE). ISBN 978-0-7844-1598-6 (print) ISBN 978-0-7844-8390-9 (PDF) ISBN 978-0-7844-8419-7 (ePub).

Self-organized Cooperative & Automated Traffic Control (SoCAT-C)

Key system components:

- Cyber-physical system
  - IoT based V2X-enabled integration of sensing and data processes via edge/fog/cloud computing
  - CAV-generated data between OBU, RSU, Signage and Smart Signal Controller, etc.
- SoCAT-C data fusion
  - Integrating vehicle and control infrastructure data at ad-hoc network via communications between OBUs, RSUs, signage and controllers, among other ITS equipment.
- SoCAT-C analytics/modeling
  - CAV mobility behavior status
  - Traffic flow state
  - Control status
  - Feedback and feedforward
- Digital integration platform
  - Active status monitoring and performance of TSMO (efficiency, safety, energy, emission, GHGs, etc.)
  - Data archiving functions for applications in planning, engineering and management, as well as policy.

(Wet et al., 2022)

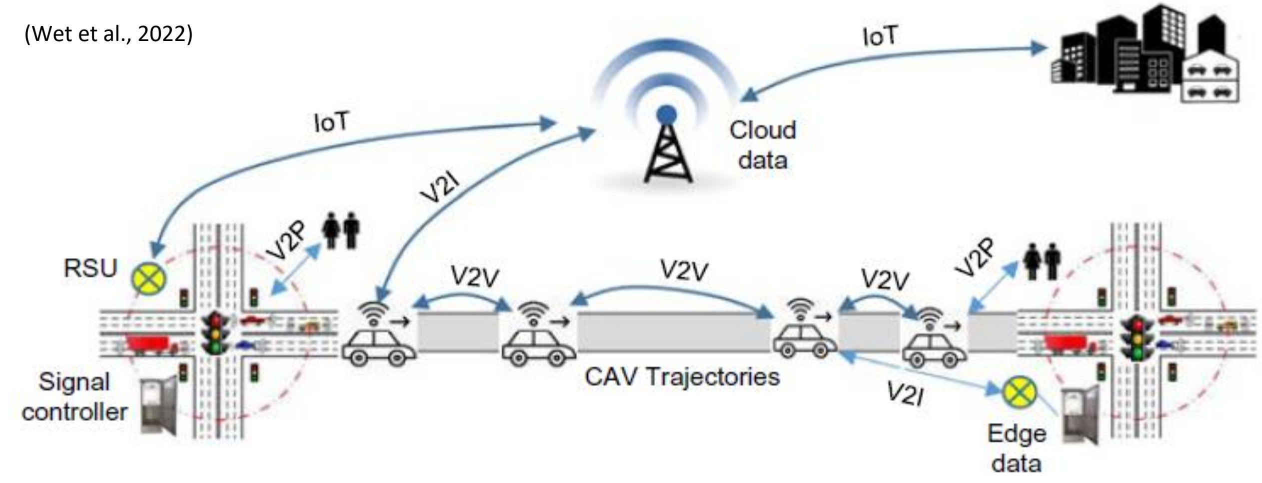
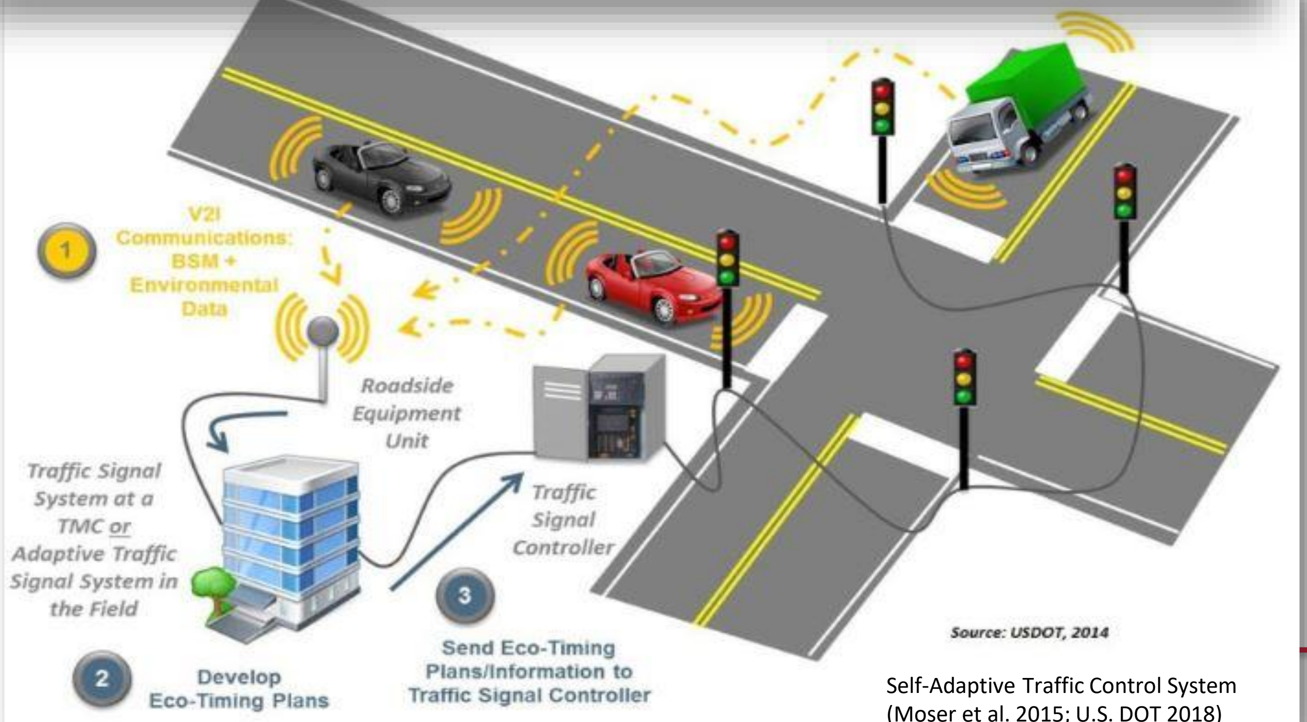


Figure 6-3. Conceptual interactions of self-adaptive traffic control systems.



Self-Adaptive Traffic Control System (Moser et al. 2015; U.S. DOT 2018)

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Self-organized Cooperative & Automated Traffic Control (SoCAT-C)

Control technologies:

- Centralized Intersection Traffic Control
  - the decision-making and control of traffic flow are concentrated in a central authority or control center.
  - A central intersection controller that regulates the entire intersection.
  - Traffic Management Center where traffic conditions are monitored in real-time using various sensors, cameras, and data sources, and the center collects and analyzes traffic data, makes decisions, and sends control signals to the field devices.

- Decentralized Traffic Control
  - Vehicles need to communicate with each other to negotiate a passing sequence when arriving at the intersection, rather than relying on a centralized control system.
  - V2X communication enables cooperative maneuvers, such as cooperative merging, platooning, and cooperative collision avoidance, etc. to improve flow efficiency and safety.

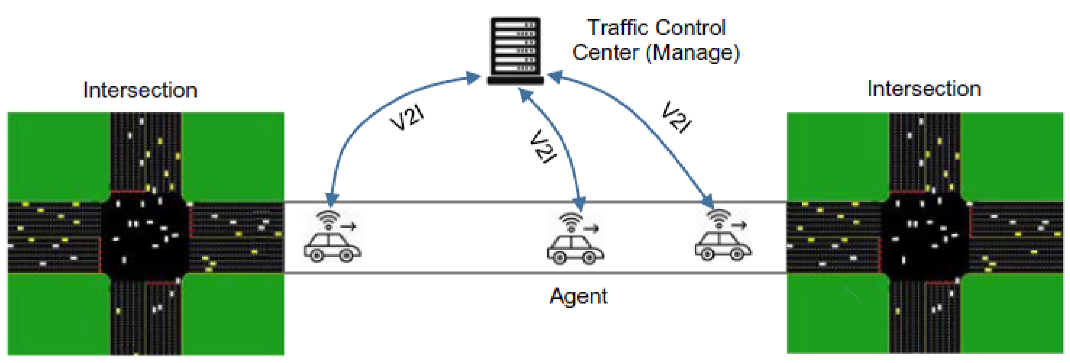

Figure 6-4. Concept of a centralized intersection traffic control system.

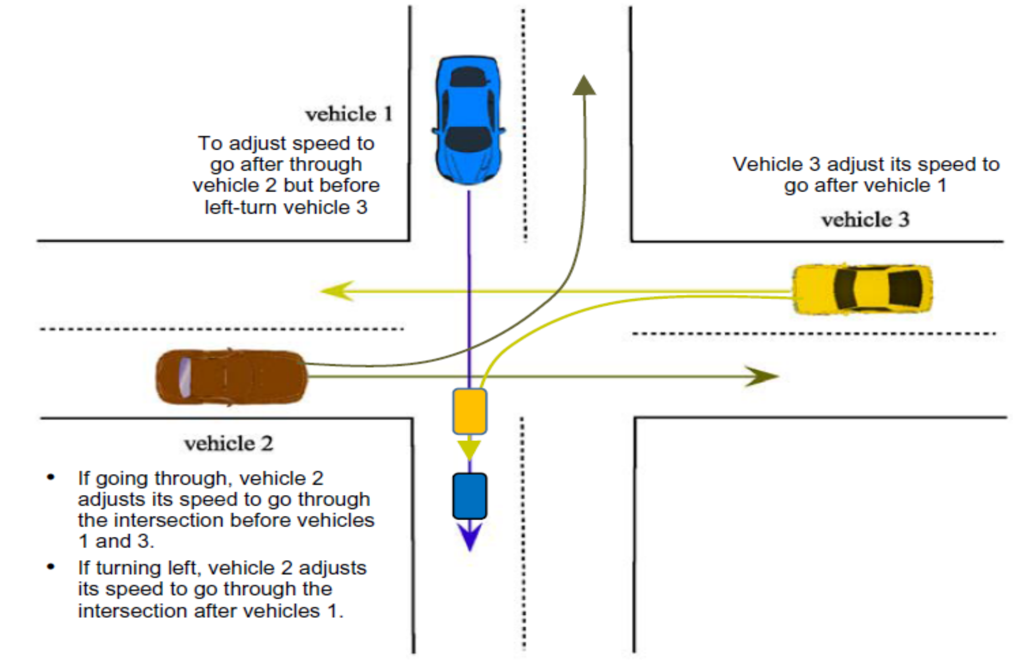

Figure 6-5. Decentralized autonomous intersection control.

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Self-organized Cooperative & Automated Traffic Control (SoCAT-C)

- Intelligent Roundabout (similar to concept of Max-pressure control)
  - Given roadside unit (RSU) at approaches of the roundabout and its upstream intersections wherein adaptive signal control system is deployed. The RSU at the roundabout receives the CAV trajectory data via V2I and then process the data to produce aggregate flow states (e.g., vehicle arrivals, speed variation). The RSU sends such traffic state data as a control feedback to the controller at the immediately upstream intersection. If the vehicle arrival is close to the capacity of the roundabout or prone to form queue at the entering approach of the roundabout, the signal controller at the immediate upstream intersection will timely adjust the timing plan to change the discharging interval or rate so as to mitigate the demand at the entering approach of the roundabout.

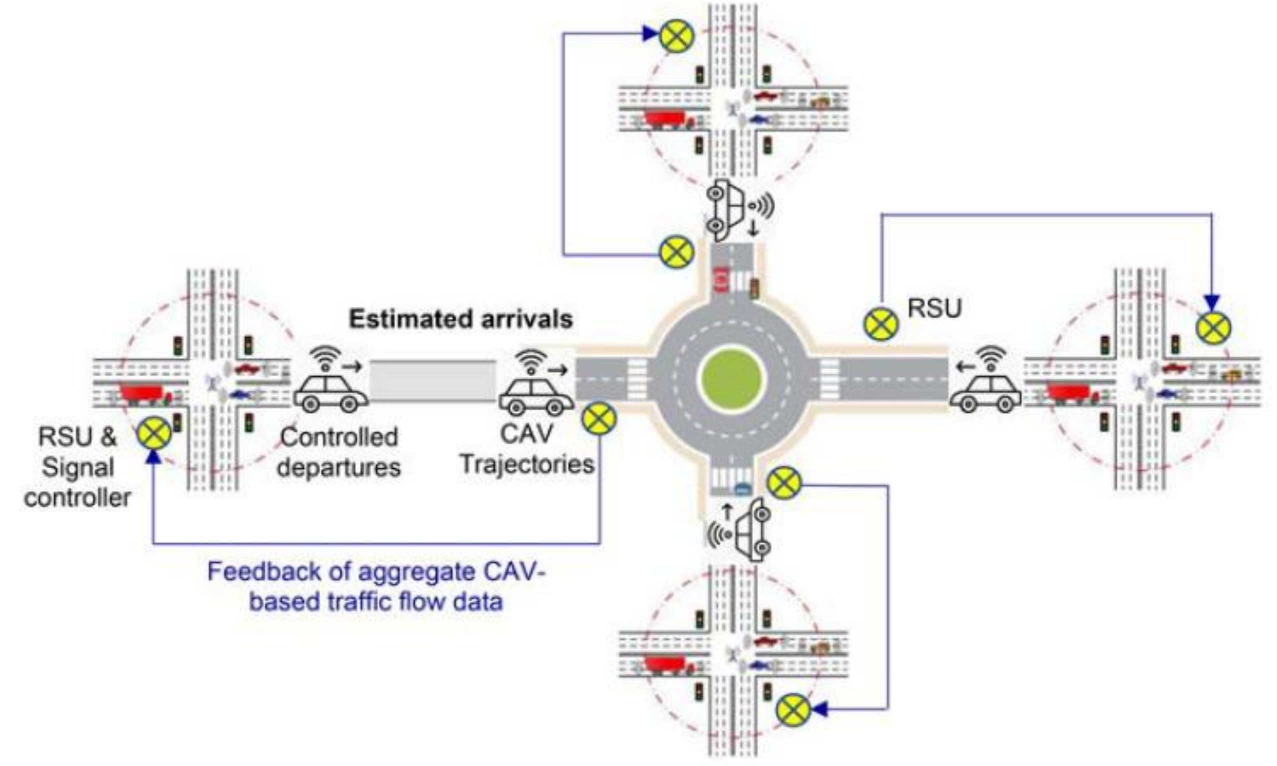

Figure 6-6. Illustration of the concept of operation of the intelligent roundabout.

Source: Courtesy of Heng Wei.

- Varaiya, P. (2013). The max-pressure controller for arbitrary networks of signalized intersections. In Advances in Dynamic Network Modeling in Complex Transportation Systems. Springer, 27–66.
- Wei, H., Zheng, G., Gayah, V. and Li, Z. (2019a). “A Survey on Traffic Signal Control Methods.” <https://arxiv.org/pdf/1904.08117.pdf> (Dec. 12, 2019).
- Annam Raja Bharat (2021). Synthetic Innovation to Complex Intersection Control: Intelligent Roundabout in Connected-Vehicle Environment. MS Thesis, University of Cincinnati

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Signal-Free Autonomous Intersection Control

- Theory Behind: maximize the use of intersection time space
- How to maximize: transfer conflicts between traffic movements to conflicts between individual vehicle.
- Funded by National Center for Freight Infrastructure Education and Research (CFIRE)
- Two papers published are cited by 135 times in Google Scholar

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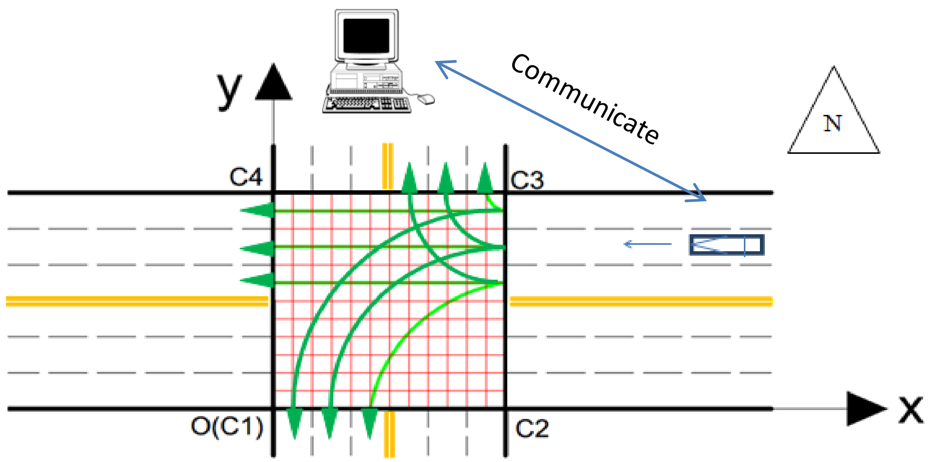
Signal-Free Autonomous Intersection Control

- **Centralized control algorithm: Agent-based Next-Generation Intersection Control of AVs**

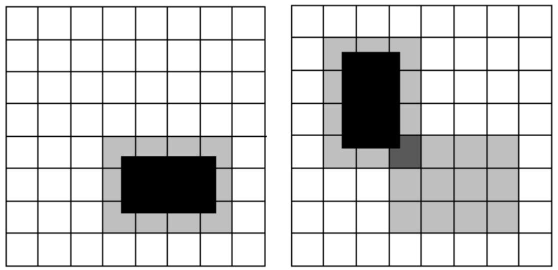
  – Step 1: Vehicle requesting reservation



  – Step 2: CIC processing a reservation request
    - Internal simulation to check conflicts
    - Minimum speed to allow fixed-speed reservation

– Step 3: CIC declining and approving the reservation request

$$a_{Dec} = {v_0}^2 \Big/ 2(s_0 - d_0 - v_0\delta)$$



(a) Successful (b) Rejected

CIC's Internal Simulation
n trials of different *a*

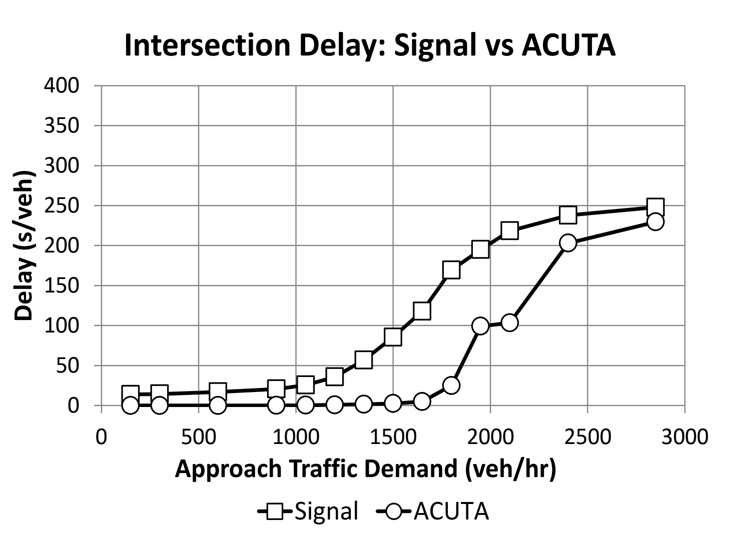
$$a_i = 0 \qquad (i = 1)$$

$$a_i = a_{\max} - (i-1)\frac{1}{n}a_{\max} \qquad (i > 1)$$

Signal-Free Autonomous Intersection Control

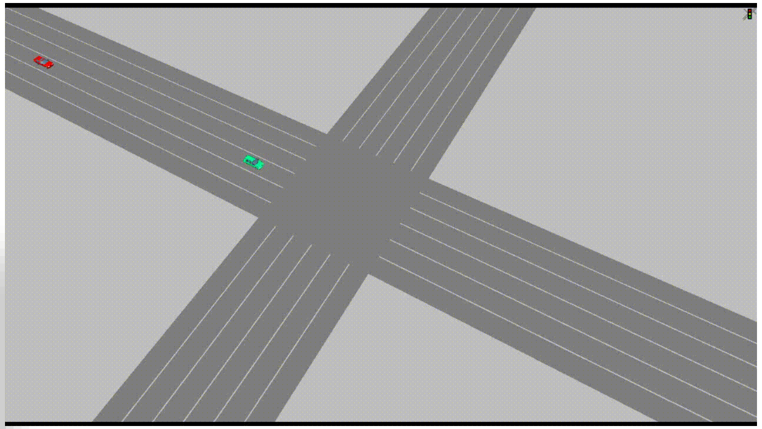
- Centralized control algorithm: Agent-based Next-Generation Intersection Control of AVs

  - **Multi-tile ACUTA** Granularity = 12

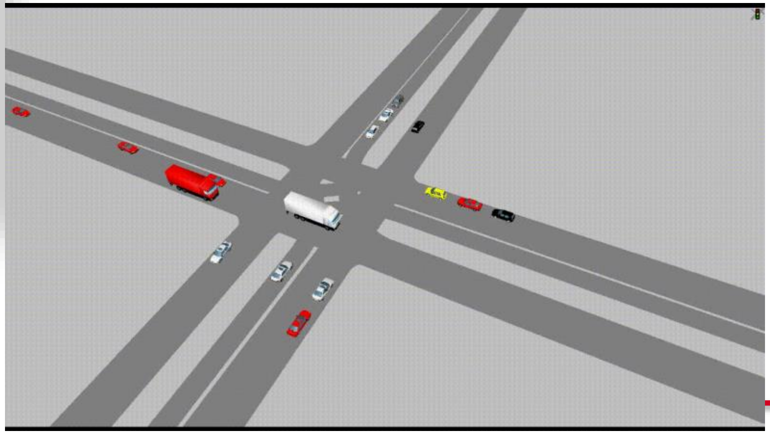


Emission/ hr (g)	Signal	ACUTA	Reduction
CO	49906	47453	4.9%
PM2.5	129.3	122.5	5.2%

Single-tile ACUTA



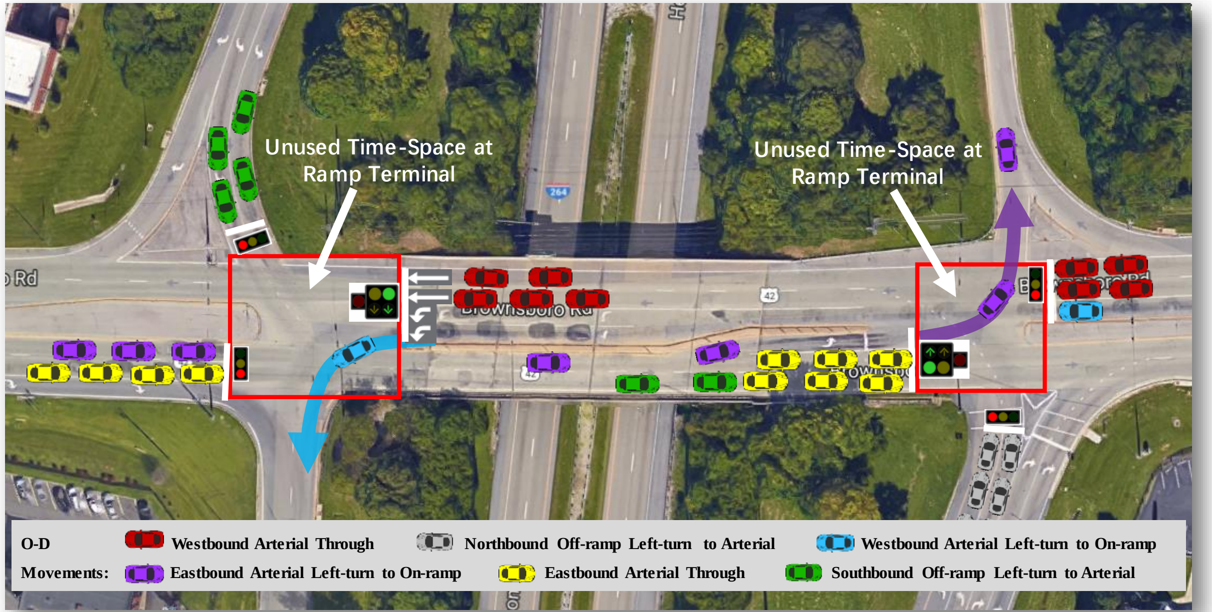
All way stop control

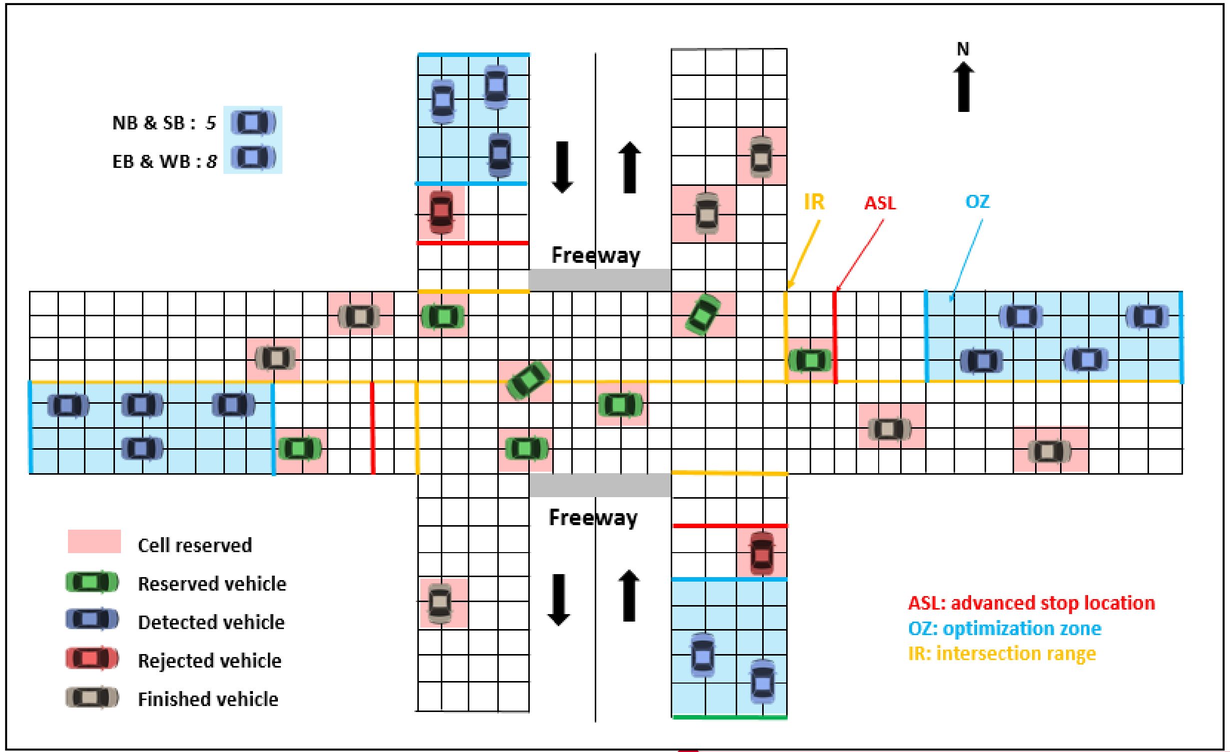


Signal-Free Autonomous Intersection Control

- Connected and Autonomous Vehicle Empowered Next-Generation Interchange Control with Improved Operational Efficiency and Energy Consumption (NIC)

- Funded by National Science Foundation (PI)
- The primary goal of this project is to develop an interchange control system that effectively manages Connected and Autonomous Vehicles (CAVs) at interchanges and enhances the interchange efficiency and sustainability.

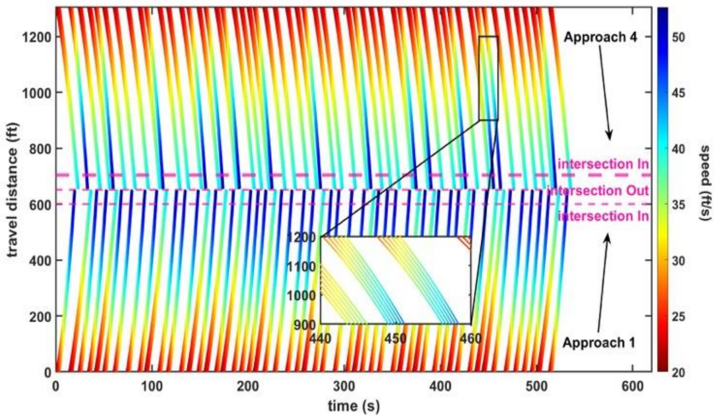




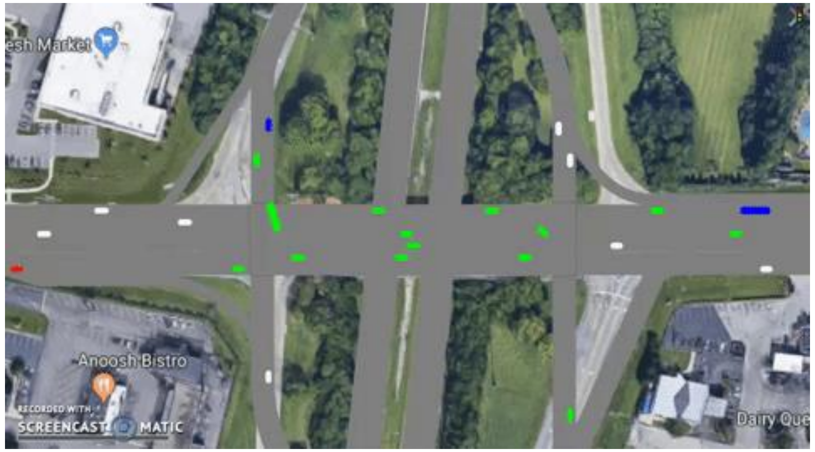
Signal-Free Autonomous Intersection Control

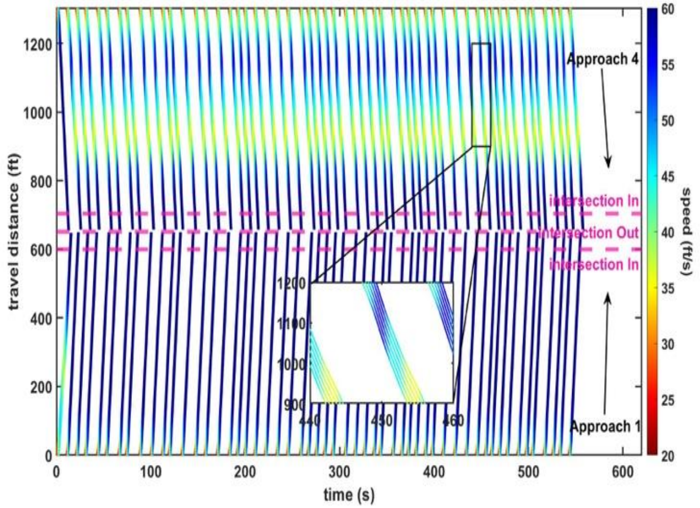
- Connected and Autonomous Vehicle Empowered Next-Generation Interchange Control with Improved Operational Efficiency and Energy Consumption (NIC)

Traffic Signal



NIC (100% CAV)





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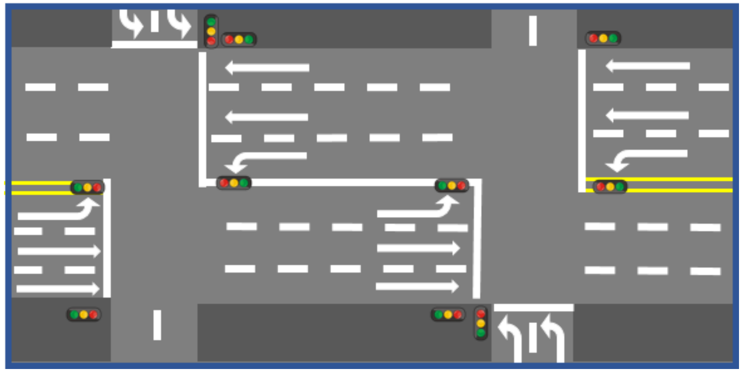
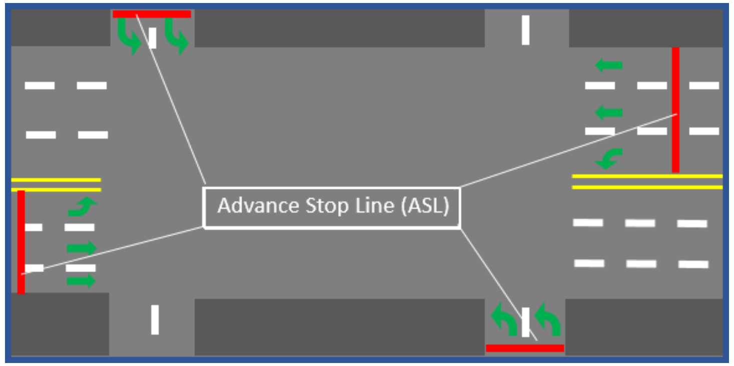
Signal-Free Autonomous Intersection Control

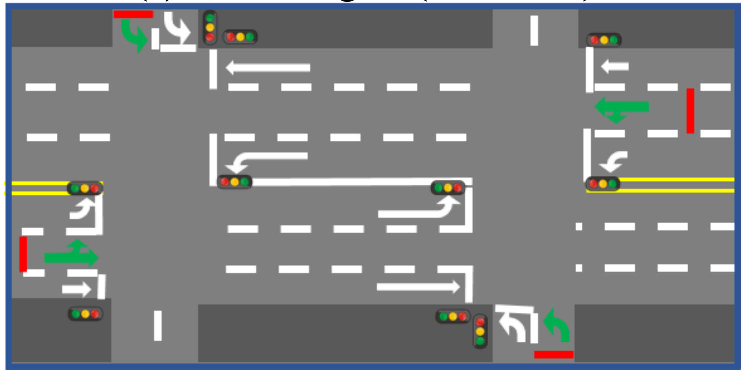
- **Connected and Autonomous Vehicle Empowered Next-Generation Interchange Control with Improved Operational Efficiency and Energy Consumption (NIC)**
- NIC accommodates mixed traffic (CAV and human-operated), four market penetration rates are considered including 25%, 50%, 75%, and 100%



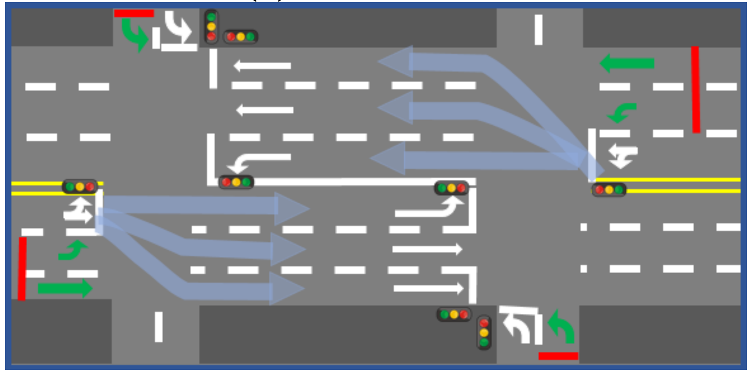
(a) Traffic Signal (MPR: 0%)



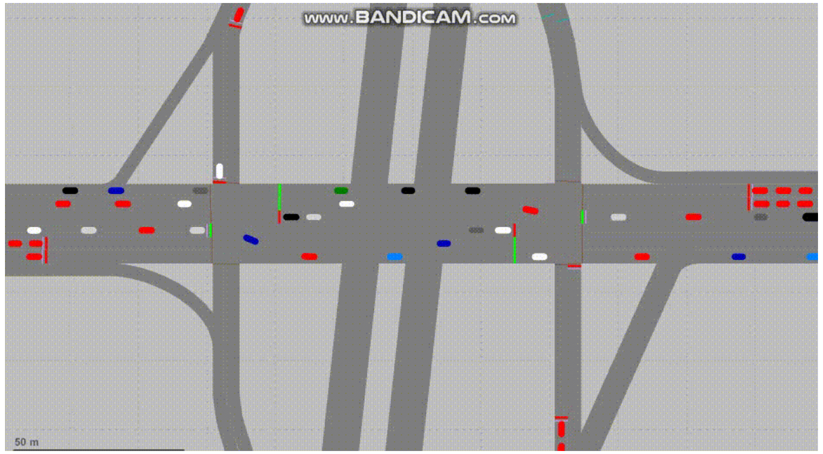
(b) MPR: 100%



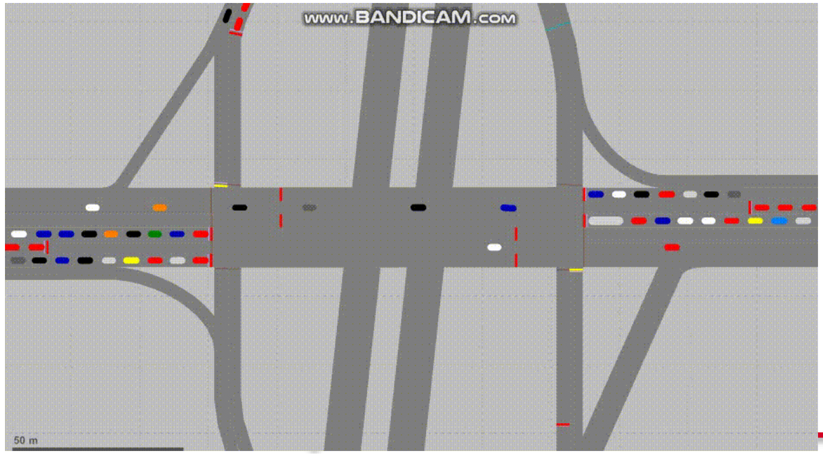
(c) MPR: 25%
MPR: 50% (1 Lane)



(d) MPR: 75%
MPR: 50% (2 Lane)



NIC (75% CAV)



NIC (25% CAV)

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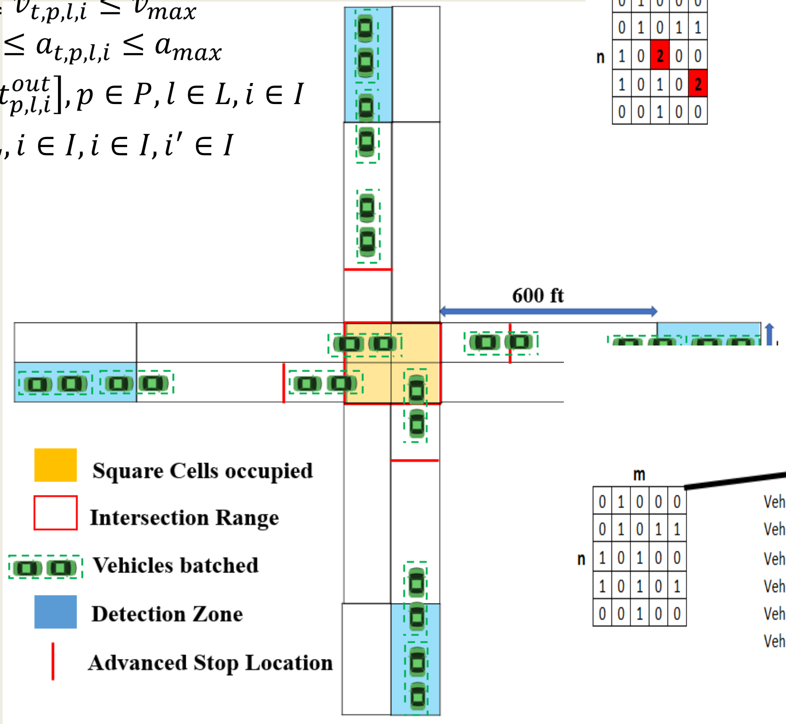
Signal-Free Autonomous Intersection Control

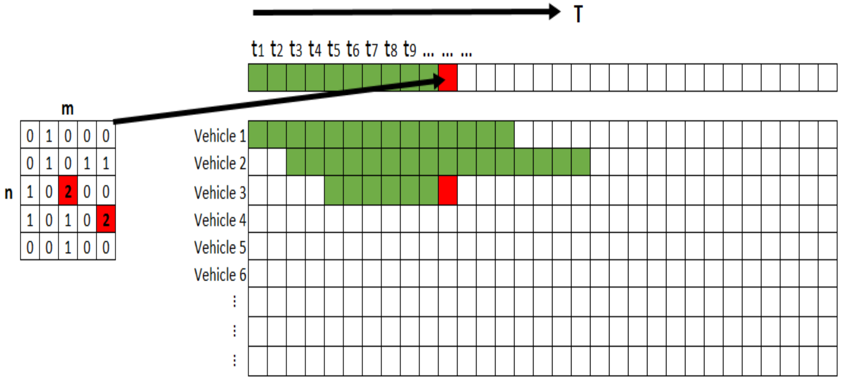
- ❑ **Connected and Autonomous Vehicle Empowered Next-Generation Interchange Control with Improved Operational Efficiency and Energy Consumption (NIC)**
- ❑ Idea is to maximize the utilization of the interchange time-space in terms of cells

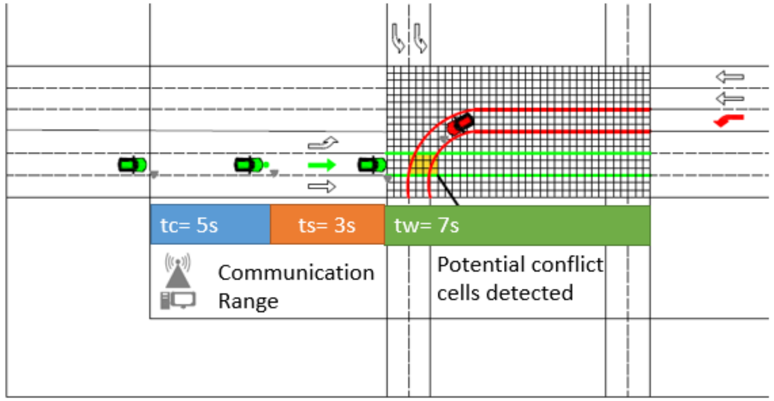
$$\boldsymbol{J} \ : \ minmax \sum_{t \in \left[t_{p,l,i}^{in}, t_{p,l,i}^{out}\right]} \delta_{t,p,l,i}$$

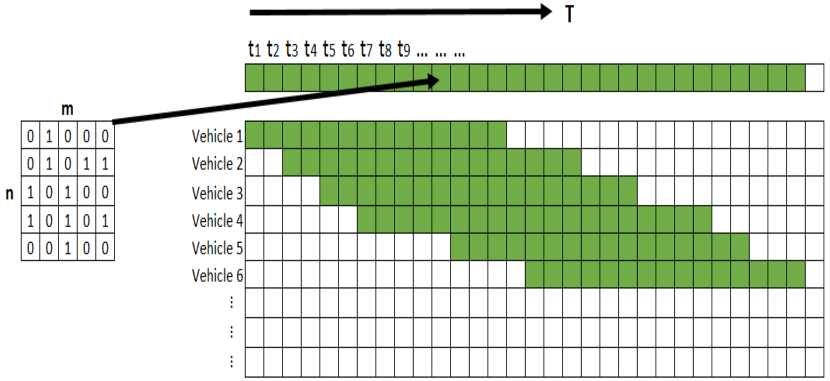
$$s.t.: \begin{cases} 0 \le x_{t,p,l,i} \le X \\ 0 \le v_{t,p,l,i} \le v_{max} \\ a_{min} \le a_{t,p,l,i} \le a_{max} \\ \forall t \in \left[t_{p,l,i}^{in}, t_{p,l,i}^{out}\right], p \in P, l \in L, i \in I \end{cases}$$

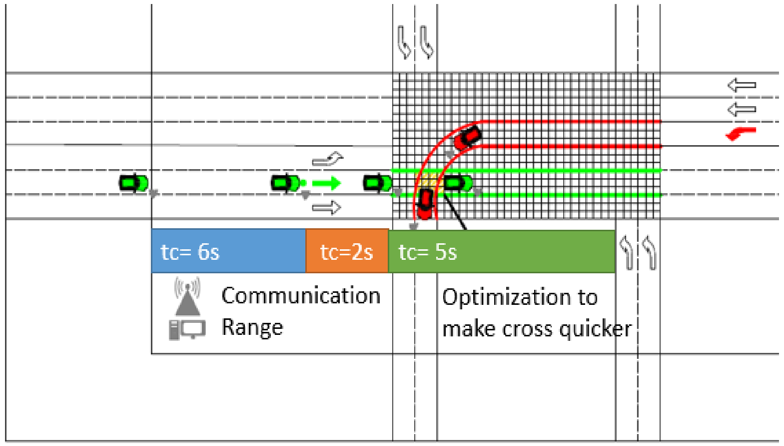
$$\forall p \in P, l \in L, i \in I, i \in I, i' \in I$$



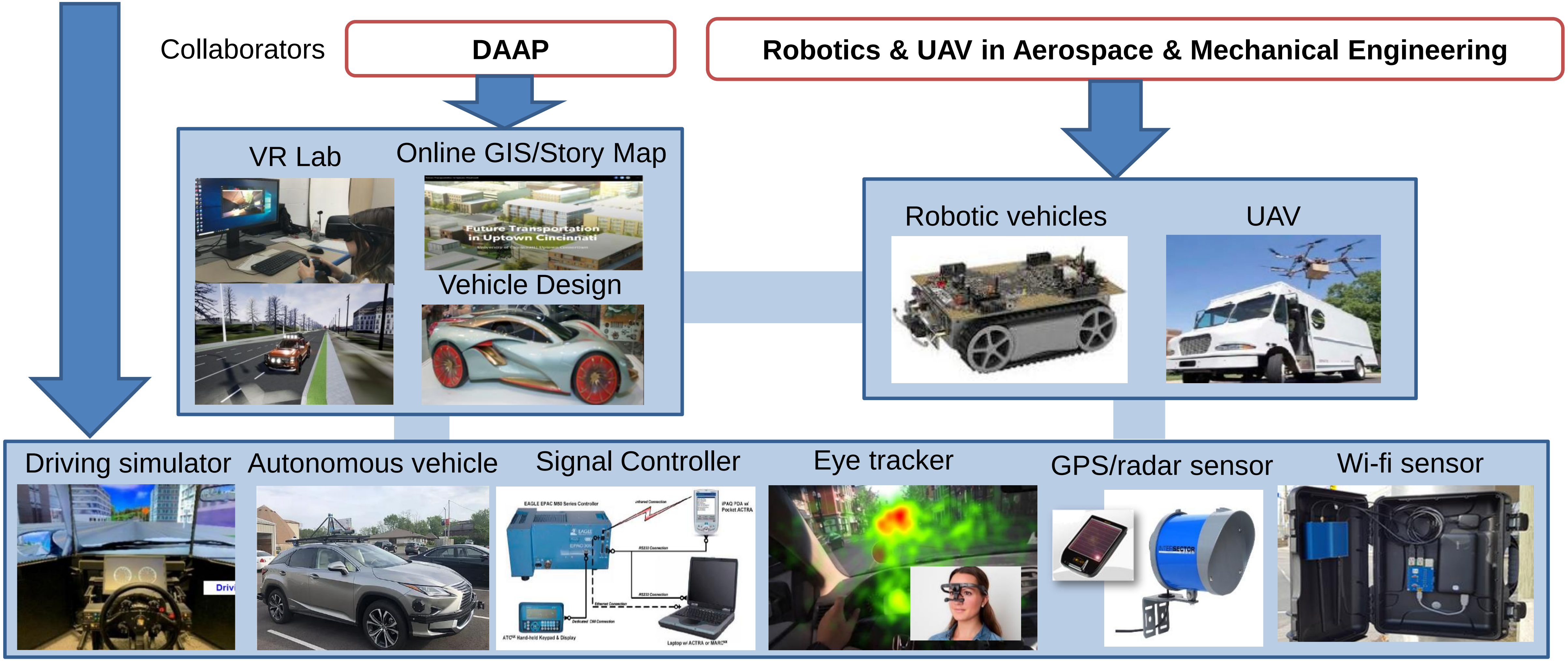








UC Facilities that Supports CAV related Research



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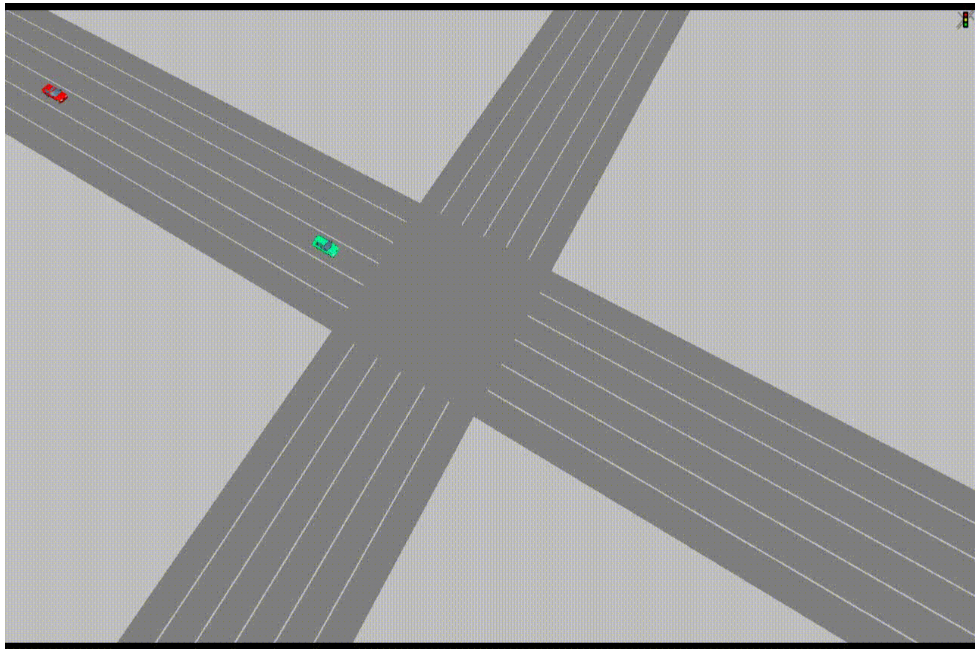
Signal-Free Autonomous Intersection Control

❑ Next Step: Mixed Reality Field Testing using Real CAV

- ❑ Emulated vehicles with Hardware in the loop simulation
- ❑ Real CAV (Lexus) applied and generating trajectories and applied in simulation

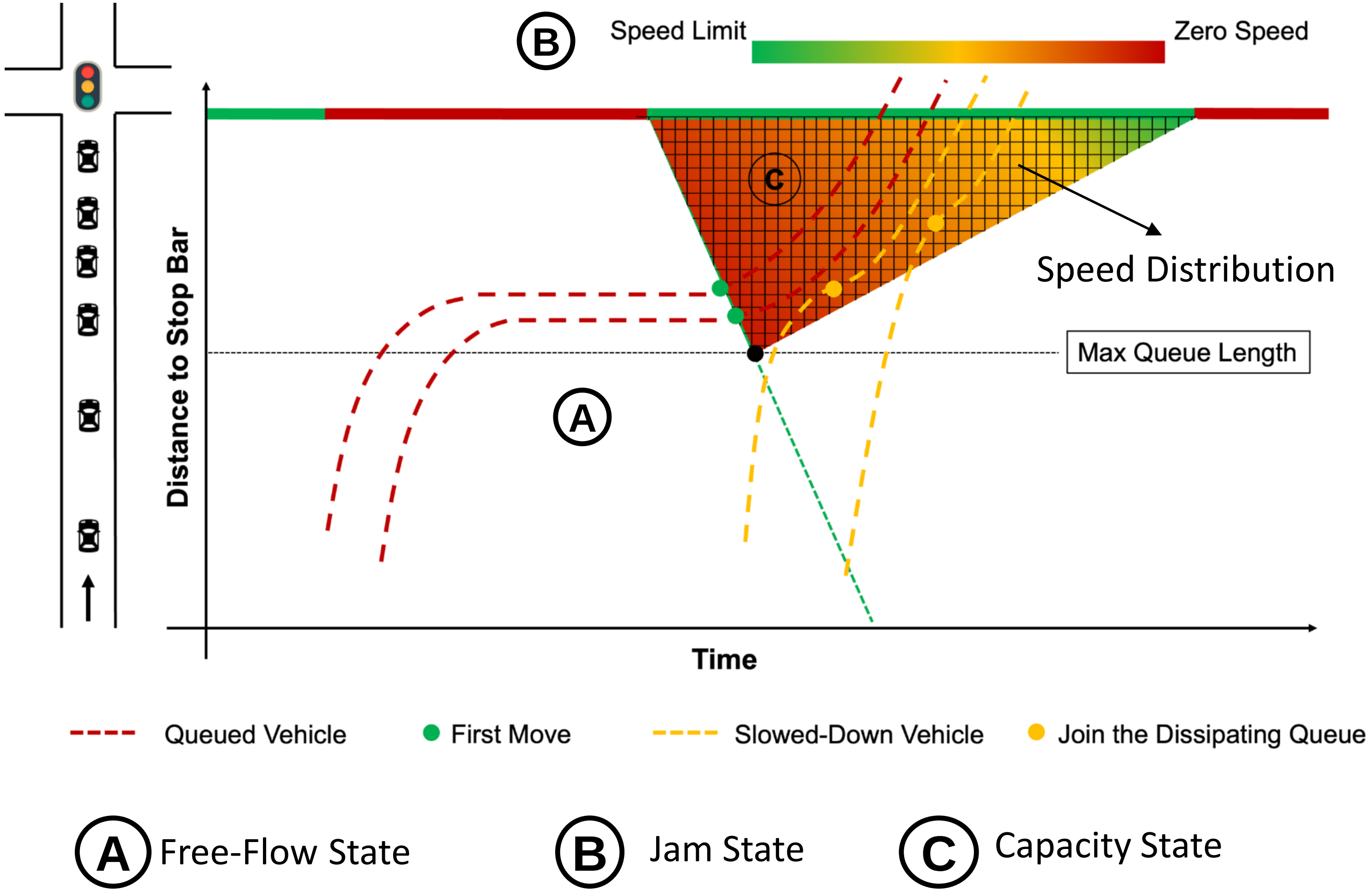
Single-tile ACUTA



CV Trajectory Data in Support of Adaptive Signal Control

- With CV Real-time traffic flow pattern can be accurately estimated using only 10% penetration rate of CV.
- The speed distribution of the queued vehicles inside the capacity state is uniform.
- The slowed-down vehicle decreases its speed closer to the queued vehicle and then increases it.
- The speed distribution indicates the speed if a queued vehicle exists at that point.

To achieve adaptive signal control, real-time estimation of queue length and traffic volume data is required.



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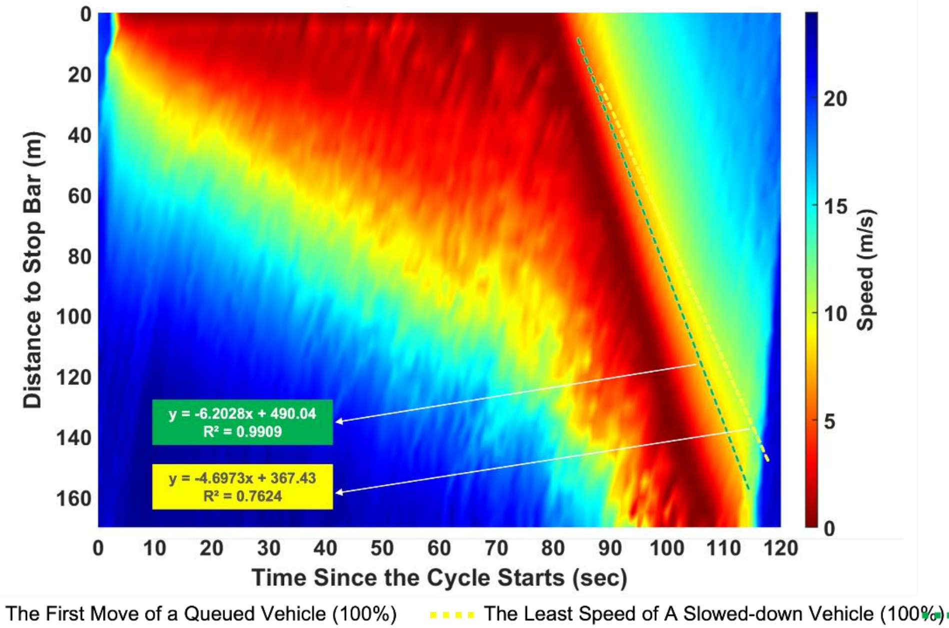
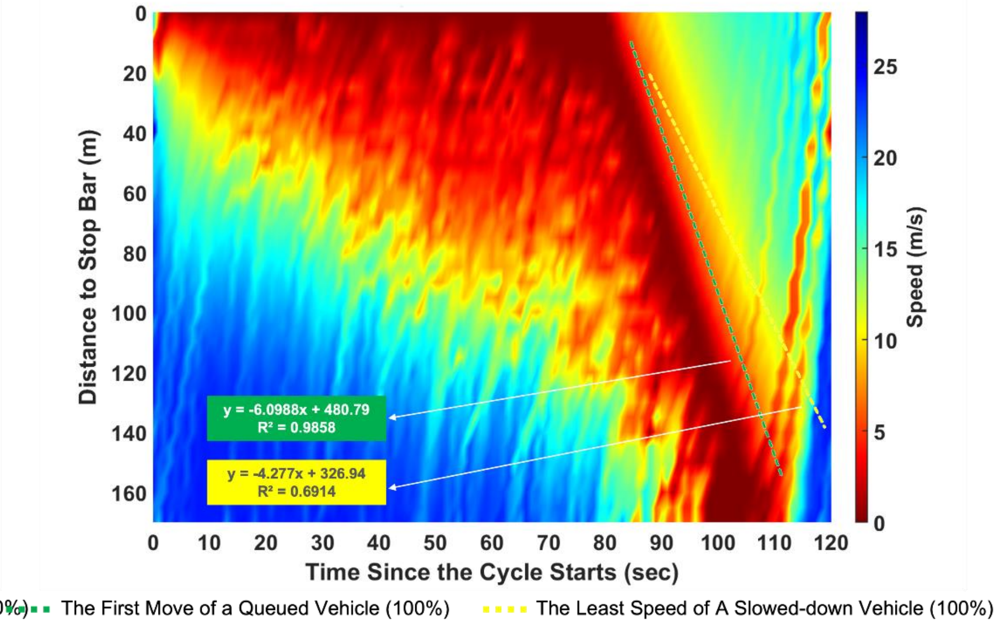
CV Trajectory Data in Support of Adaptive Signal Control

- The regression of the first move of queued vehicles is plotted.
- The regression of the least speed of the slowed-down vehicles is plotted.
- The two regressions have similar slopes
- The sampled data (10%) demonstrates the same shockwave profile



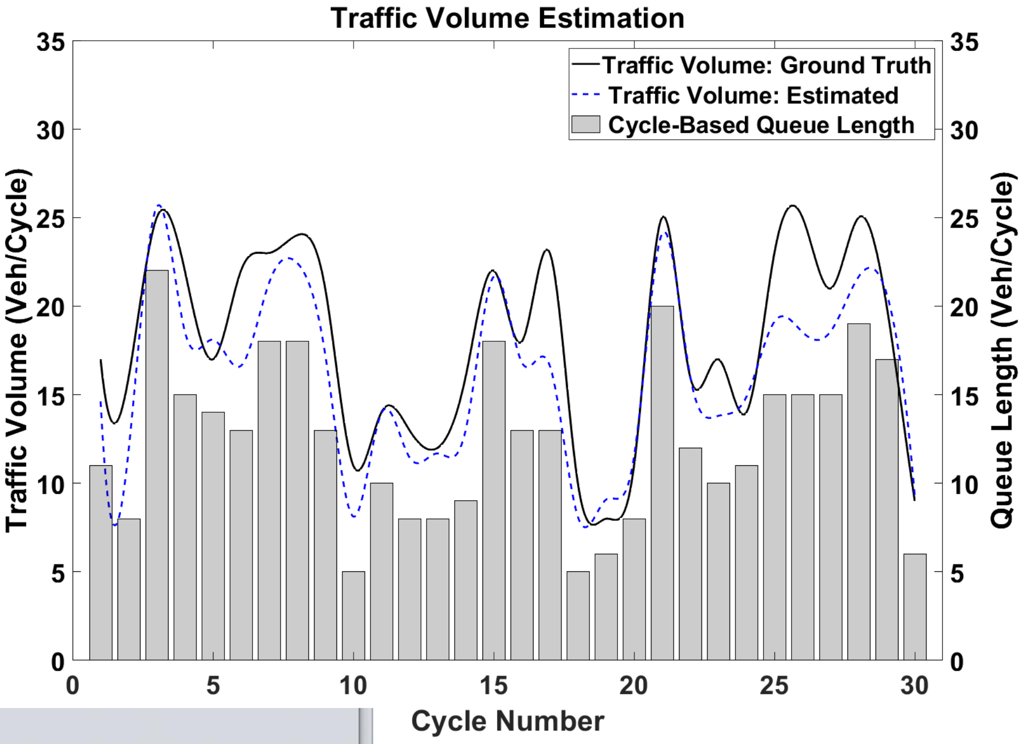
Prior Dataset (MPR: 100%)

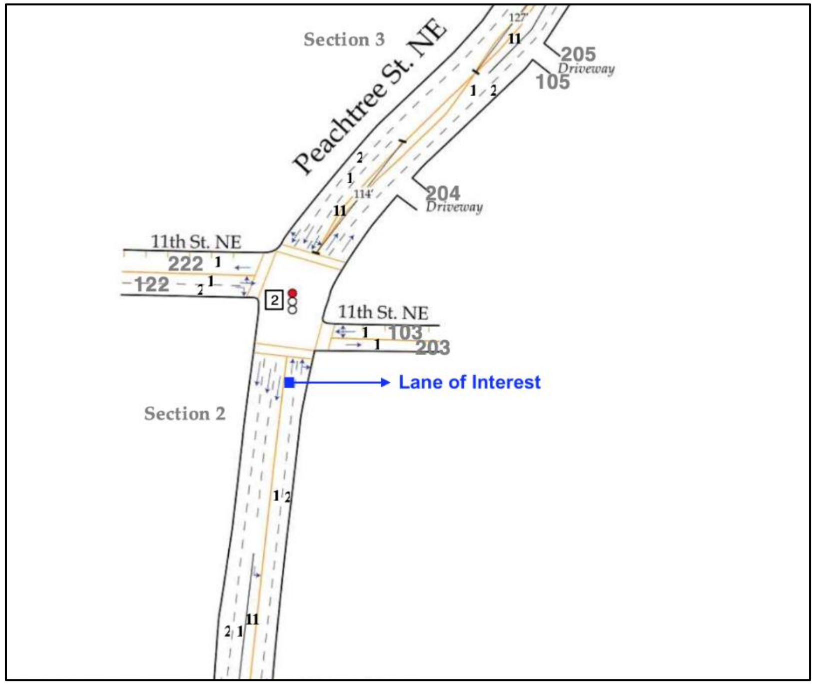


Prior Dataset (MPR: 10%)

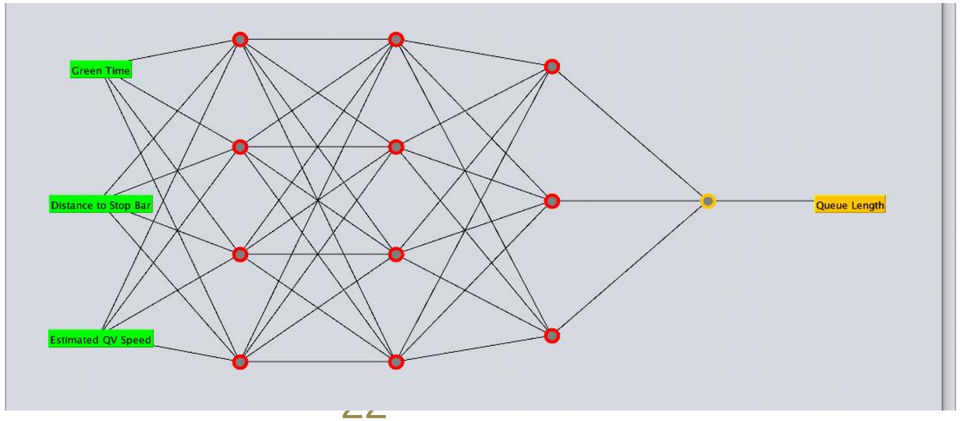
CV Trajectory Data in Support of Adaptive Signal Control

- Two simulation experiments for the estimation models of the queue length and the traffic volume
- The traffic signal cycle is 100 seconds with 32-sec green time.





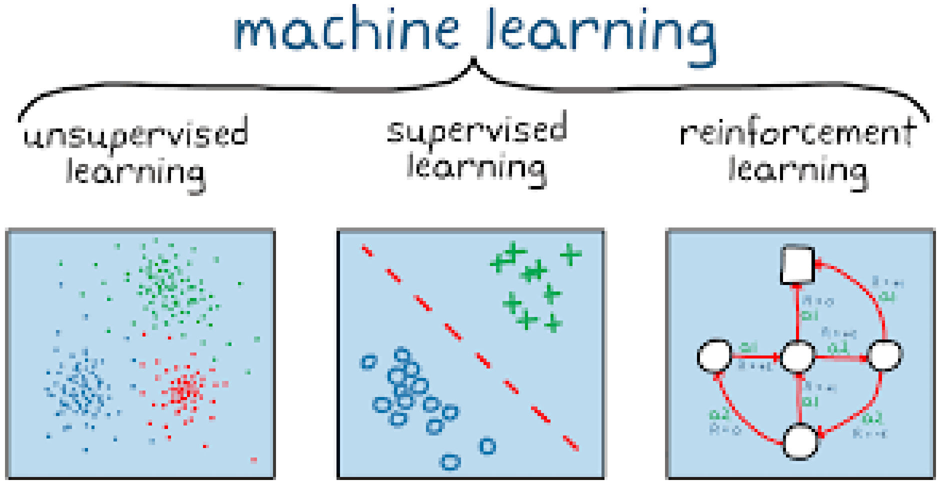
NGSIM data from (Atlanta, GA)

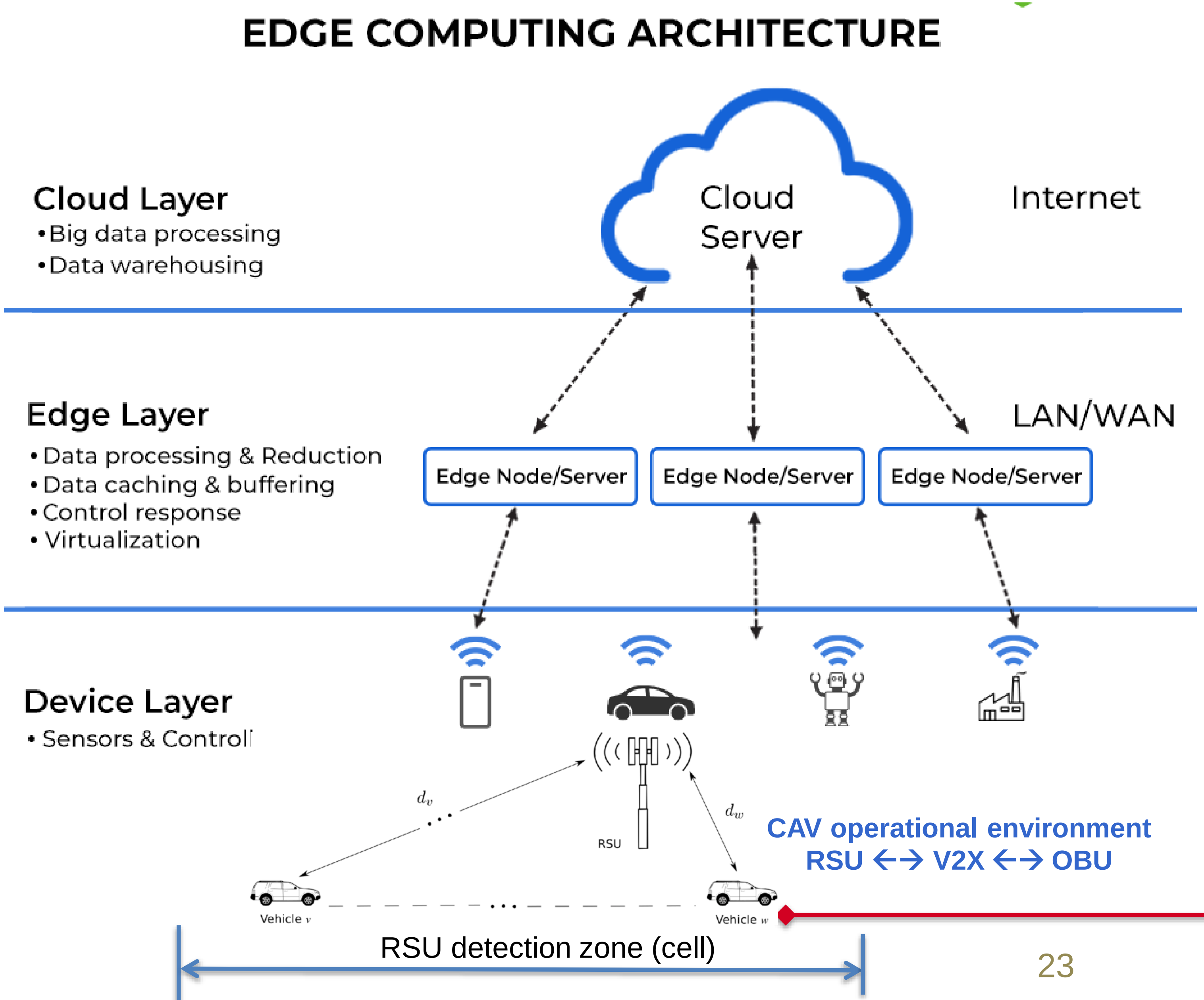


Accuracy = 88.15%

AI/ML/IoT Technologies in Support of SoCAT-C: Operations & Performance Monitoring

- Adopting and deploying AI-based tools to improve the efficiency and effectiveness of internal processes and research as well as citizen-facing services, including natural language processing, computer vision, and machine learning-based predictive analytics.





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AI/ML/IoT Technologies in Support of SoCAT-C: Operations & Performance Monitoring

Background: Cyber-physical system in Transportation (CPS-T) is marked by CAV technology that will generate diversity of real-time data sources ubiquitously available over roadway networks.

Research Question: How to transform vast quantities of CAV datasets to enable feedback-based interoperability between transportation cyber system and physical infrastructures, towards maximized traffic safety, efficiency, energy saving and emission reduction?

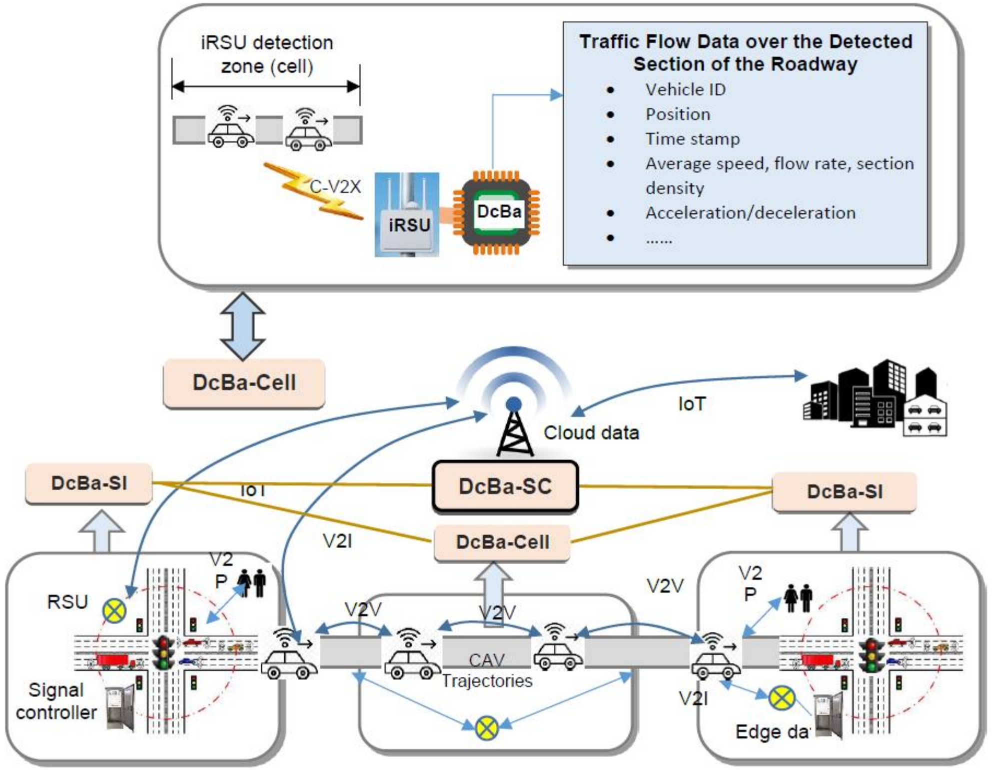
Challenge: Lack of core analytics could impede CAV integration and delay their safe introduction.

Solution:

Distributed Computing Brainbox Analytics (DcBa-X) Data Fusion to process and manage the CAV probe mobility data source, through integrating cyber-physical data flows among roadside units (RSUs), CAVs' on-board units (OBUs) and V2X-enabled signal controller.

Merits:

- Enable spatiotemporally CAV distributed mobility data available, much more than traditional fixed-point sensor data;
- Scalable and flexible to locations towards a bigger vision;
- Enable data intelligence transformation for actively monitoring/ measuring/evaluating efficiency, safety, energy and environmental impacts; and
- No road traffic interruptions during maintenance.



WEI's CAV Flow Modeling Framework

Wayside Equipment Integration for Signal Control Adaptation of Vehicle Flows

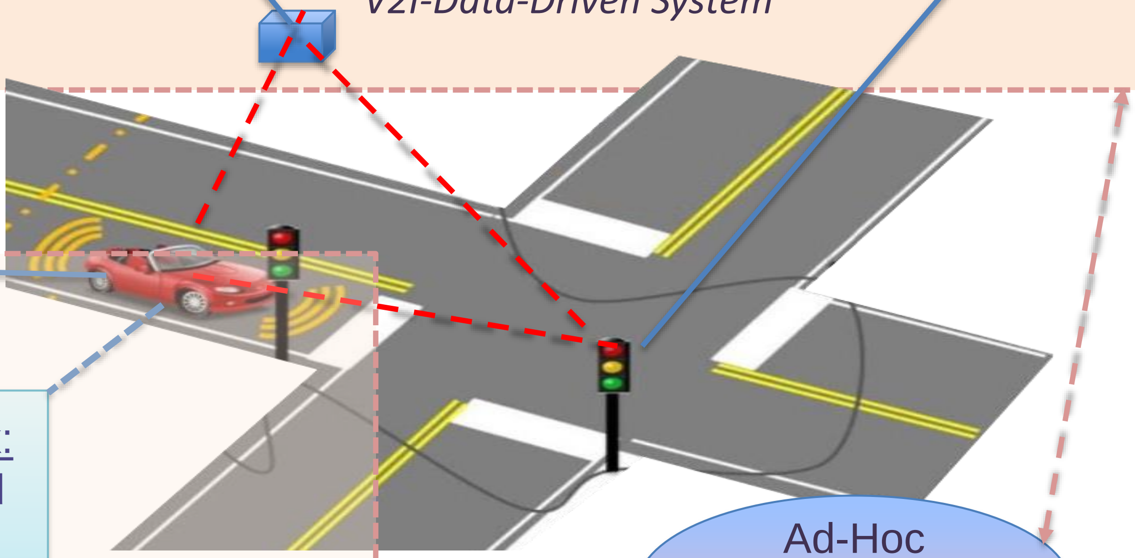
Module 1: CAV and SPaT Data via V2I

Module 2: Aggregate Variables/ Traffic Parameters

Module 3: Arrival Type/ Traffic State Estimation/ Planning

Module 4: Adaptive Signal Optimization & Feedback

V2I-Data-Driven System



Future Work: Harmonized Clustering Flow via V2V

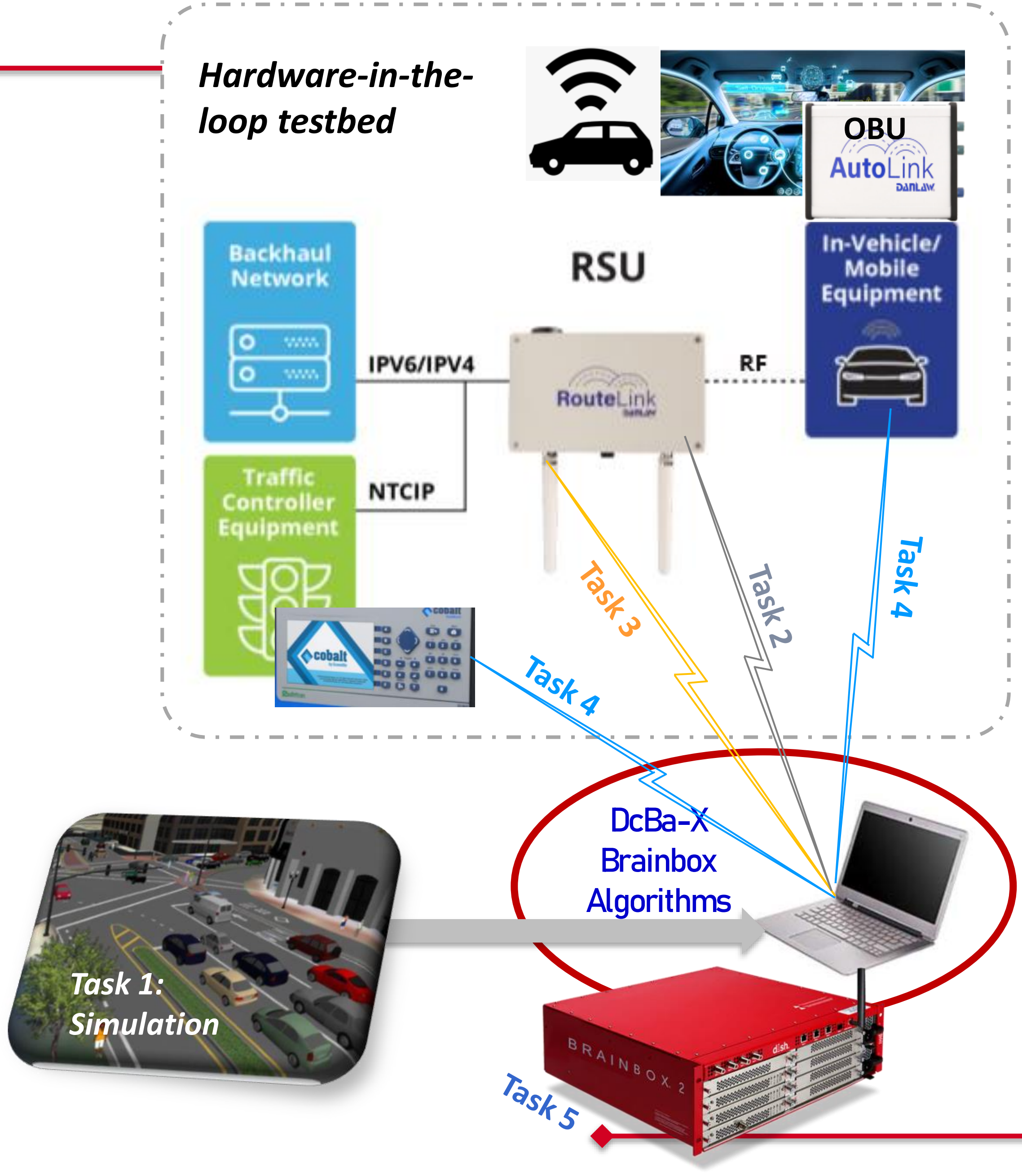
V2V-Data-Driven System

Ad-Hoc Control Cell Center

To integrate roadside equipment with controller for transforming the raw CAV trajectory data via on-board-unit into the process of identifying the traffic flow state, on the basis of which the adaptive traffic signal control scheme is dynamically optimized to achieve the maximum throughput with performance feedback in a timely manner.

On-going Research Steps

- Task 1: Simulation proof-of-concept study of WEI's CAV Flow (Wayside Equipment Integration for Signal Control Adaptation of Vehicular Flow) framework.
- Task 2: Refine algorithms and purchase equipment and devices.
- Task 3: Embed DcBa-X algorithms into RSUs to construct iRSU.
- Task 4: Test/calibrate/validate DcBa-X brainbox in the hardware-in-the-loop testbed.
- Task 5: Develop paradigm/mechanism to formulate a connected CPS-T through integrating iRSUs into a realistic CPS-T.



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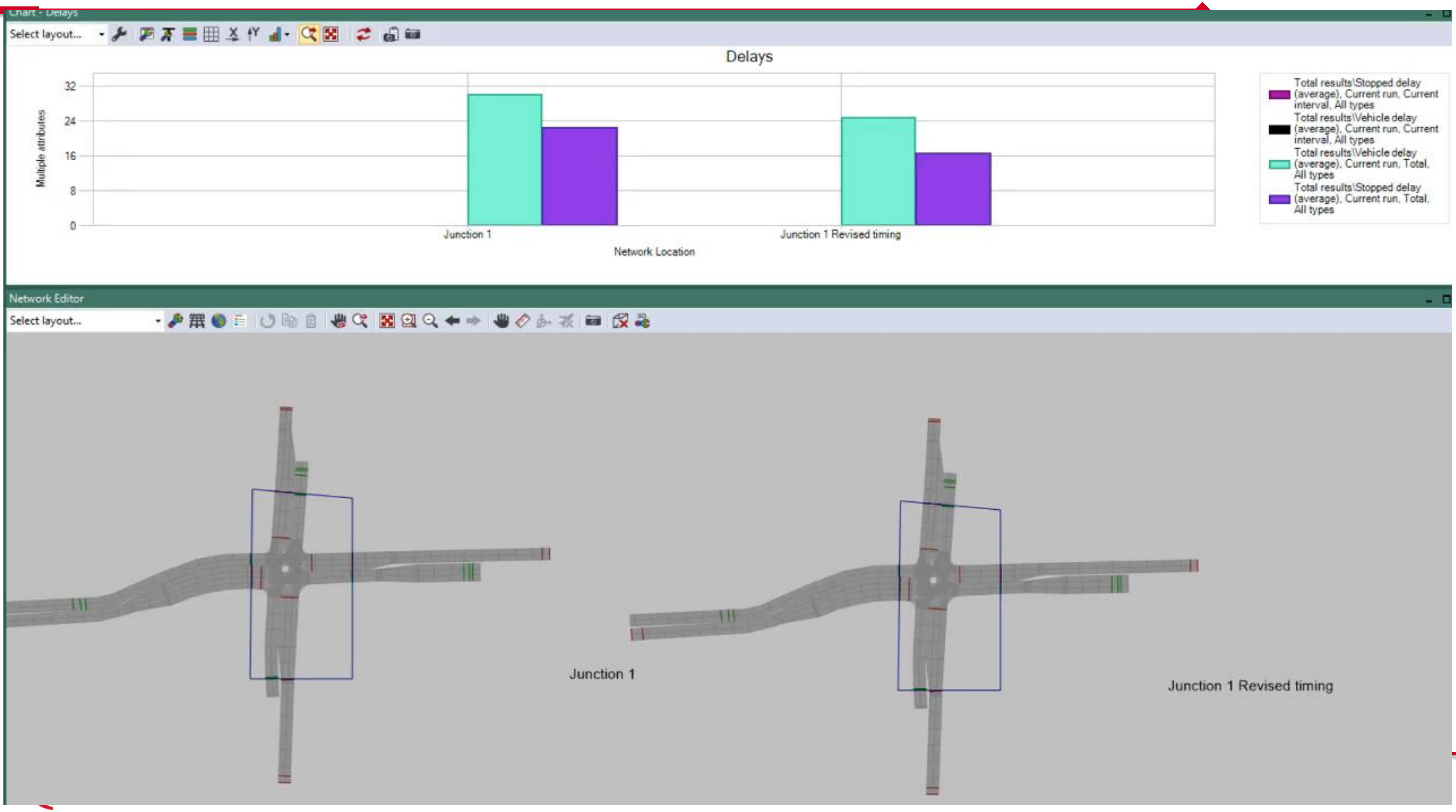
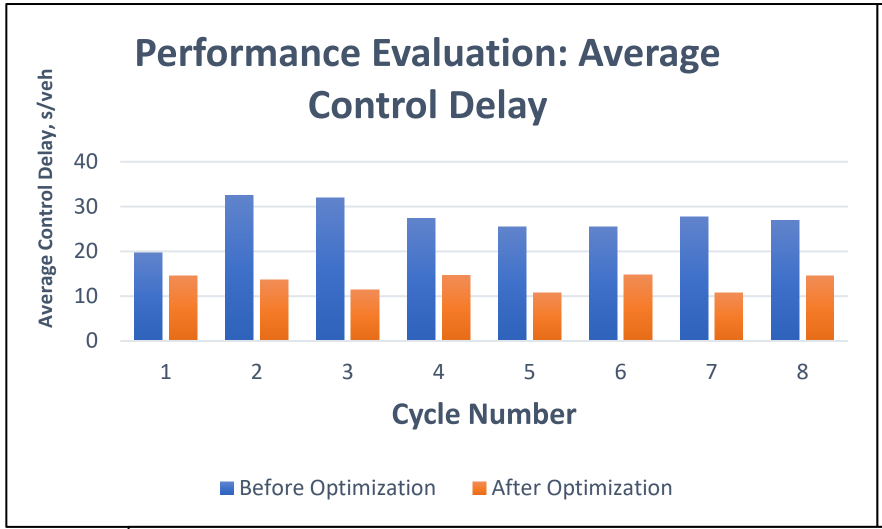
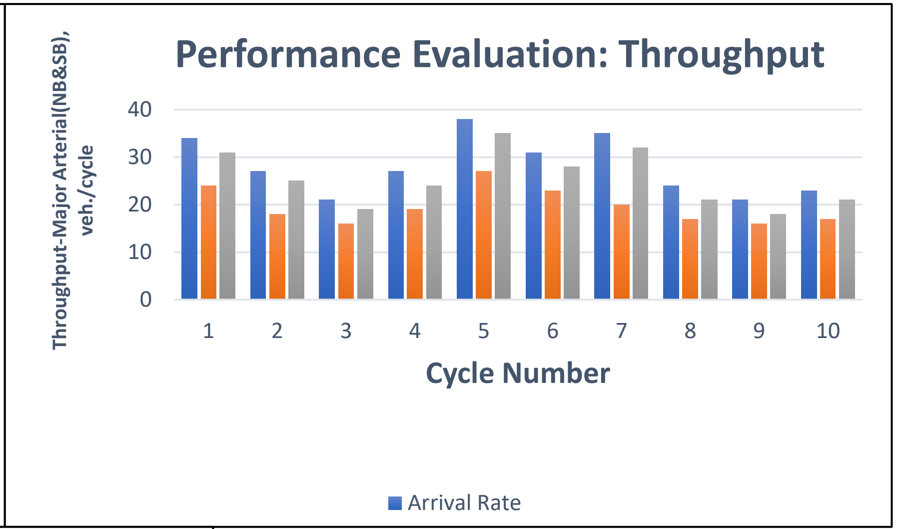
Before-and-After Performance Evaluation

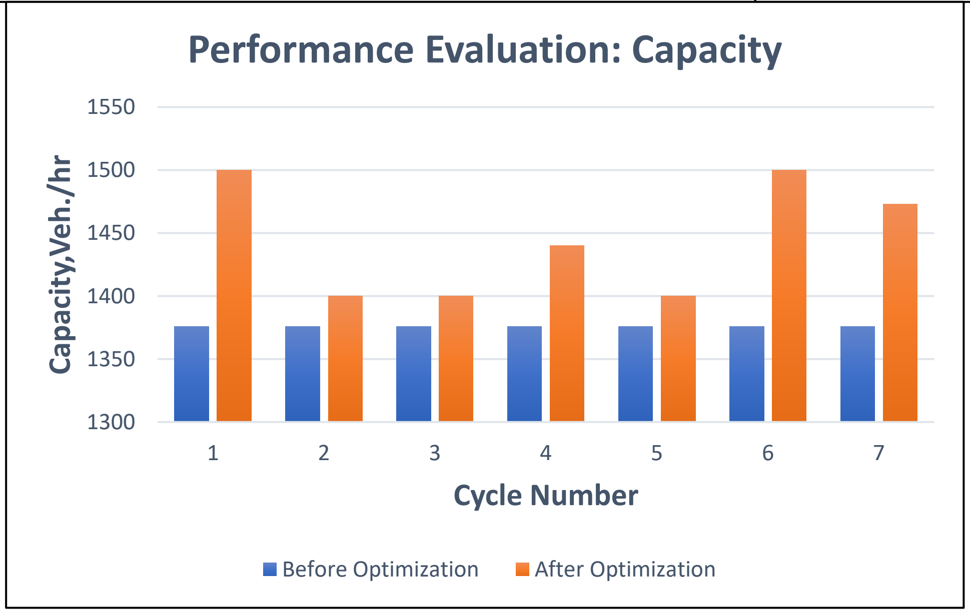


Before-and-After Performance Evaluation





- "WEI's CAV Flow" Framework can process the raw trajectory data from connected vehicles and SPaT data from traffic signal controllers to identify multiple traffic flow parameters or variables



- Accurately identifying traffic state plays a significant role to achieve the goal of signal control strategies. The theory of traffic state identification can better aid designing signal control strategies against various traffic conditions (six arrival types as defined in HCM, 2016 – see the next slide).
- This research does not restrict itself to implement adaptive signal control strategy along isolated intersections. However, it aims at exploring the viability across multiple intersections to optimize the signal control along a corridor.

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Modeling and Algorithm for Identifying Arrival Type/Traffic State

"Arrival Type" (AT) is used to describe the quality of progression for vehicles arriving on each approach. Based on Highway Capacity Manual (2016), there are six defined arrival types, 1 through 6, with AT 1 representing the worst progression quality and AT 6 representing the best progression quality.

If the proportion of vehicles arriving on green can be computed from the field data or the space-time graph, then AT is computed as:

$$AT = 3 * P / (g_i / C) \qquad (11)$$

where: P = Proportion of vehicles arriving on green, decimal;
g_i = effective green time for movement, s;
C = cycle length for movement, s.

Arrival Type	Progression Quality
1	Very poor
2	Unfavorable
3	Random arrivals
4	Favorable
5	Highly favorable
6	Exceptional

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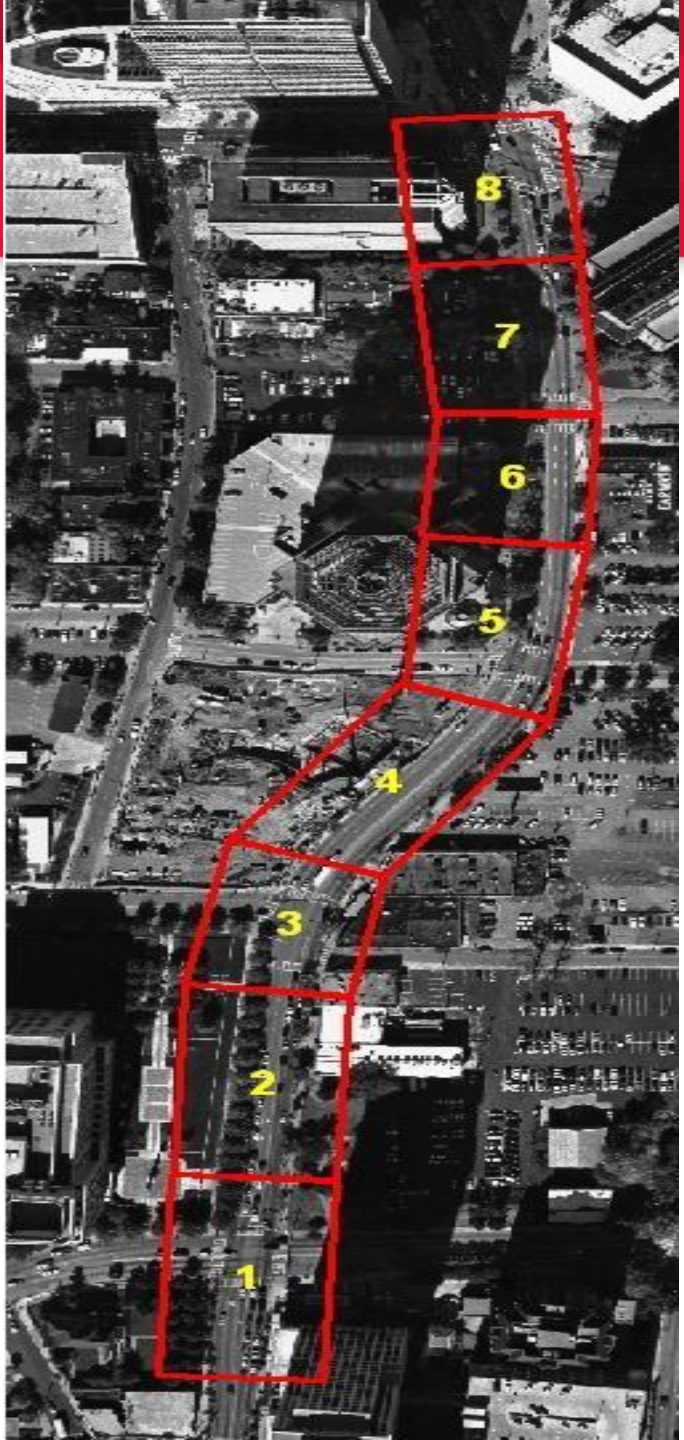

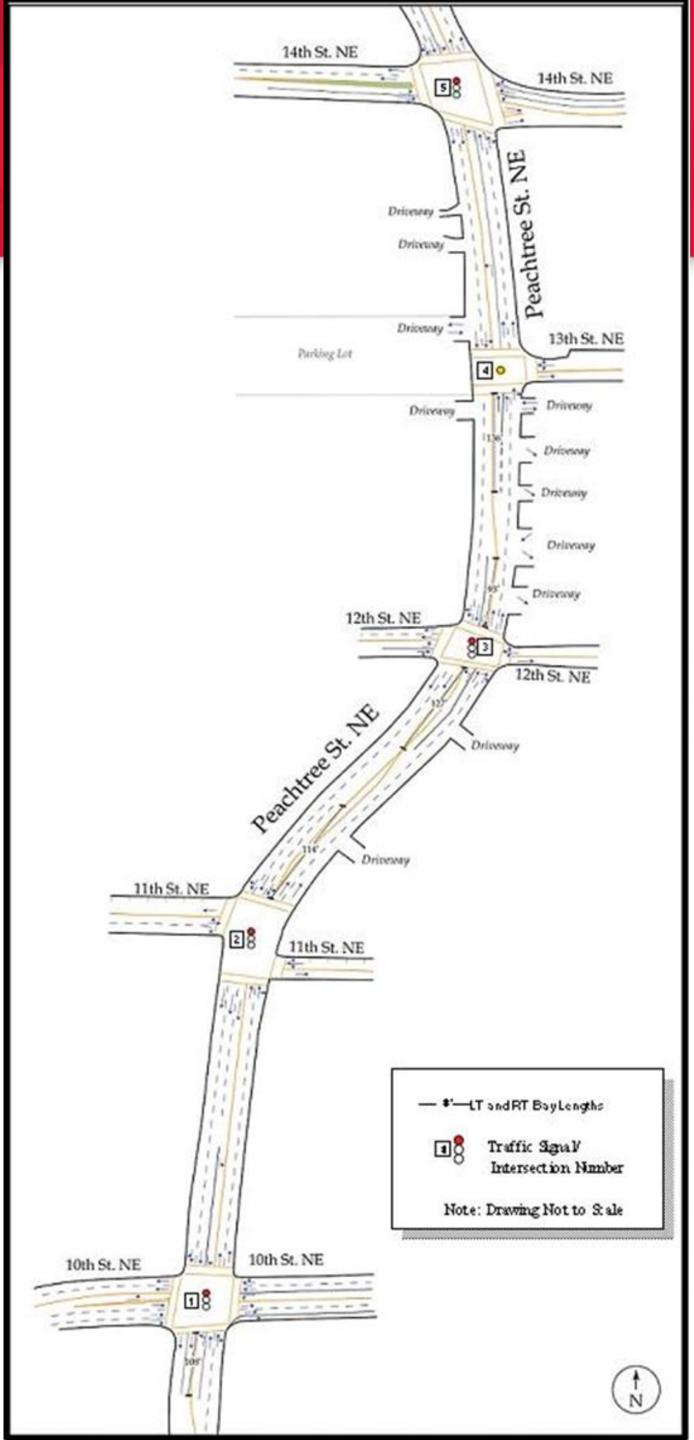

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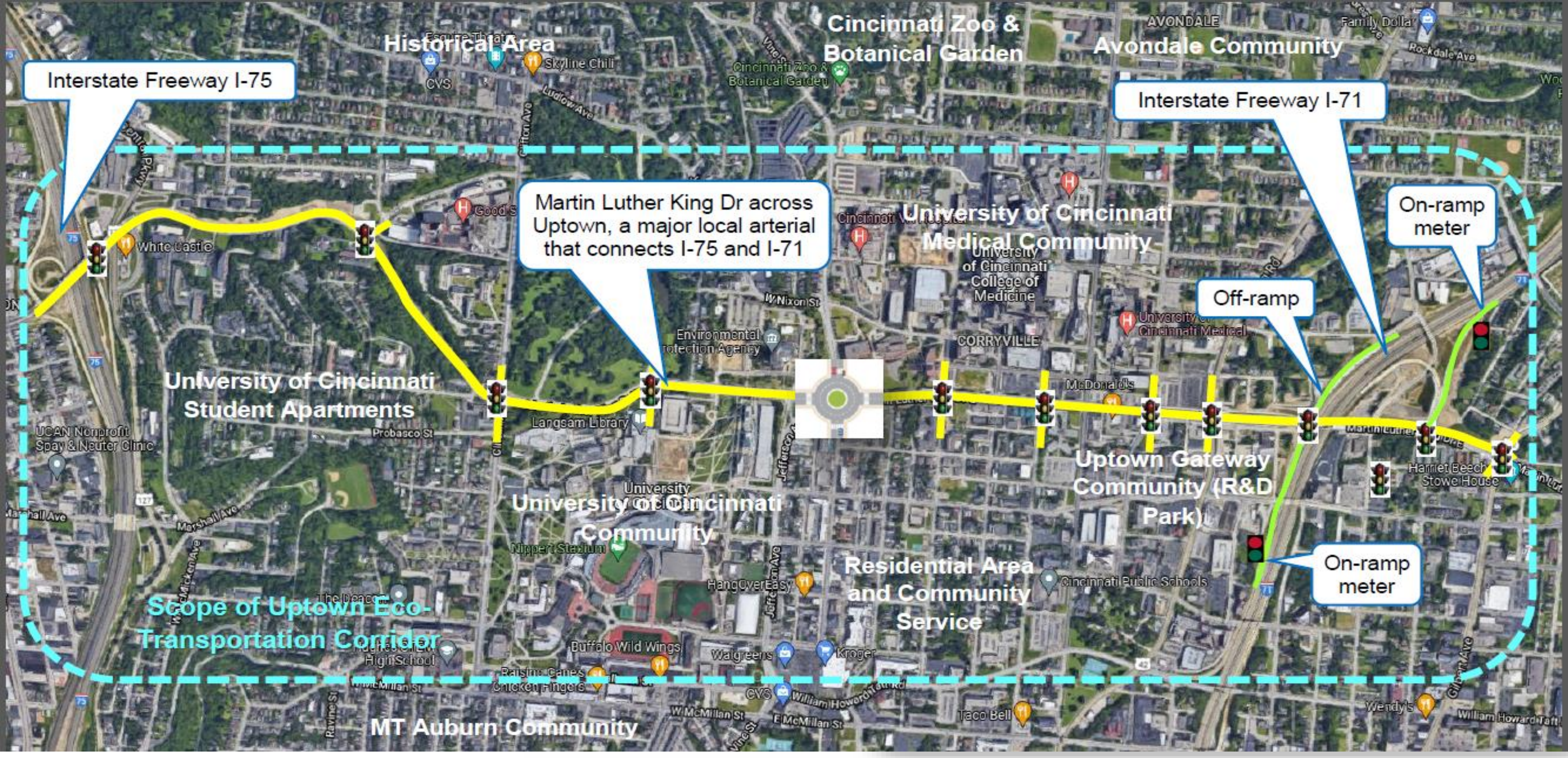
Proof-of-Concept Study Site for A Signalized Corridor

Data Source: Next Generation Simulation (NGSIM) program at Peachtree Street, Atlanta, GA

Real-Time Simulation for Measuring Performance of An Entire Corridor

Lin*, W., and **Wei, H.** (2023). Cyber-physical models for distributed CAV data intelligence in support of self-organized adaptive traffic signal coordination control. *Expert Systems With Applications* 224 (2023) 120035. https://doi.org/10.1016/j.eswa.2023.120035



How to do? Develop a series of DcBa-X algorithms via integration of an underlying cell of the iRSU (iRSU-Cell) with control modules residing in associated physical infrastructures (e.g., controller, ramp metering). X refers to a specific type of facility.

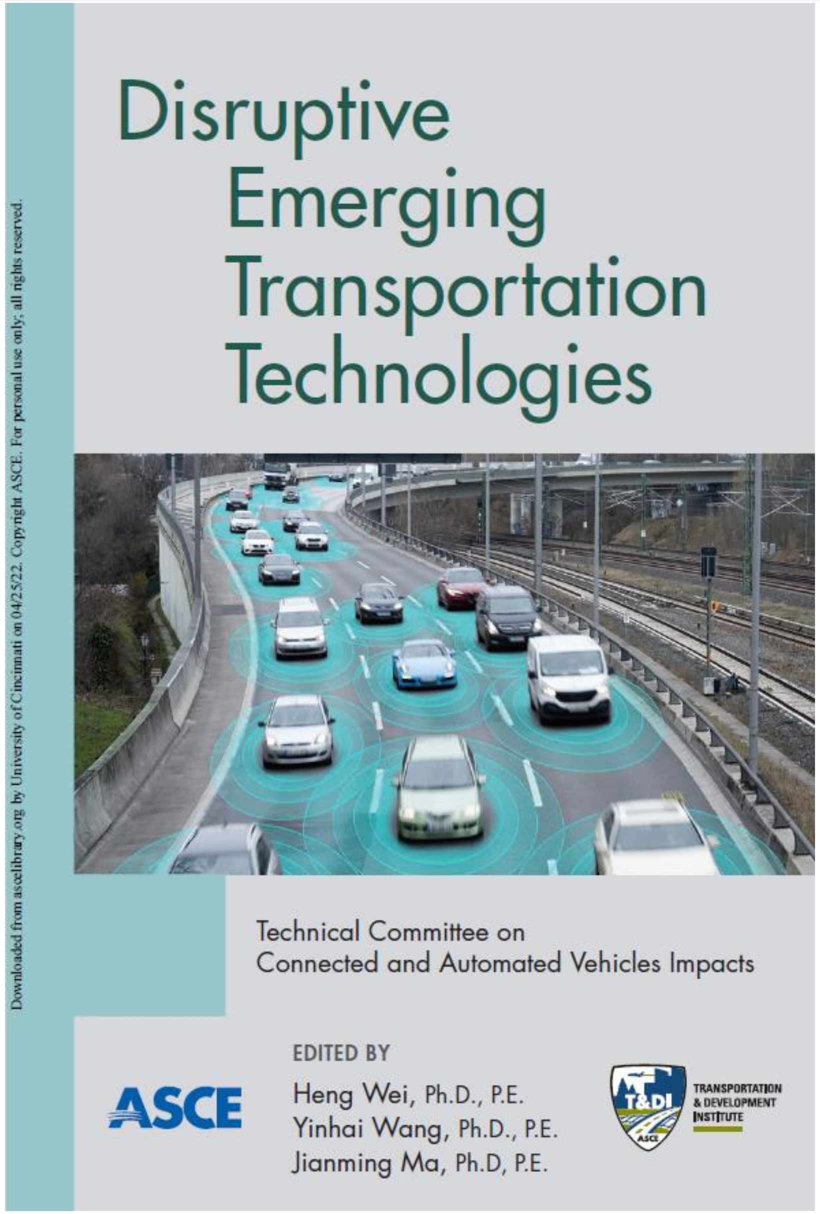
New Book: *Disruptive Emerging Transportation Technologies*

The Overall Goal of the Book

- Motivation of ASCE T&DI's Technical Committee on CAV Impacts
- Critical understandings of 4IR technologies
- Be prepared for adapting to the potential changes
- A critically valuable reference for relevant educators
  - ✓ re-imagine their roles
  - ✓ update or redesign their curricula
  - ✓ adopt new pedagogical strategies

The Target Audience

- Educators
- Researchers
- Students
- Professionals of public and private sectors (engineers, managers, planners, policy-makers, and specialists)
- Other broader interested audience



https://ascelibrary.org/doi/book/10.1061/9780784415986

Structure of the Book

- ❑ Chapter 1: Emerging Technologies Impacting the Future of Transportation
- ❑ Chapter 2: Surface Transportation Automation
- ❑ Chapter 3: Autonomous Vehicle Testing
- ❑ Chapter 4: Emerging Mobility Service
- ❑ Chapter 5: Shared Sustainable Mobility
- ❑ Chapter 6: Cooperative and Automated Traffic Control
- ❑ Chapter 7: UAV and VTOL Technologies

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Appreciate your time!