Developing an Energy-Conscious Traffic Signal Control System for Optimized Fuel Consumption in Connected Vehicle Environments

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2021 DOE Vehicle Technologies Office Annual Merit Review

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Project ID: eems106

Overview

Timeline

- Start Date: October 2020
- End: December 2023
- Percent Complete: 15%

Barriers

- Data availability, sources, accuracy, and their frequency
- Multidisciplinary nature of the project
- Single simulation coordination among multiple universities/ a national lab

Budget

- Total project funding: $1.893M
  - UTC: $778K
  - University of Pittsburgh: $414K
  - Georgia Tech:$350K
  - ORNL: $300K
  - City of Chattanooga: $50K

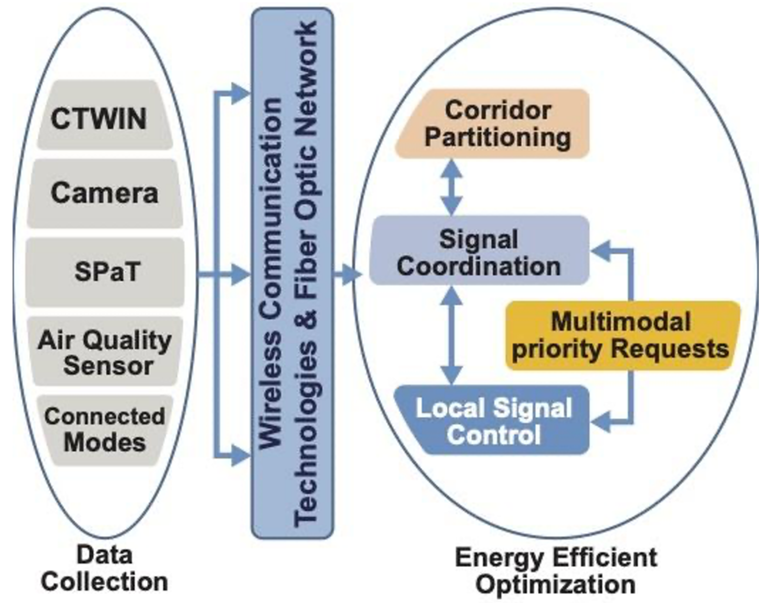
Partners

- University of Tennessee at Chattanooga
- University of Pittsburgh
- Georgia Institute of Technology
- Oak Ridge National Laboratory
- City of Chattanooga
- Applied Information & Temple, Inc.

Relevance

Impact

- Improve corridor-level fuel consumption and GHG emissions in mixed traffic environments (CVs and UCVs) by ≥20%
  - Capitalize on CV and CI technologies to enable an Ecological Adaptive Traffic Control System (Eco-ATCS)
  - A bi-level signal control system: lower-level at local intersections and global-level enables coordination along a corridor
  - A flexible priority system ready to accommodate transit signal priority (TSP), emergency vehicle preemption (EVP), and vulnerable road users (VRU)



Objectives

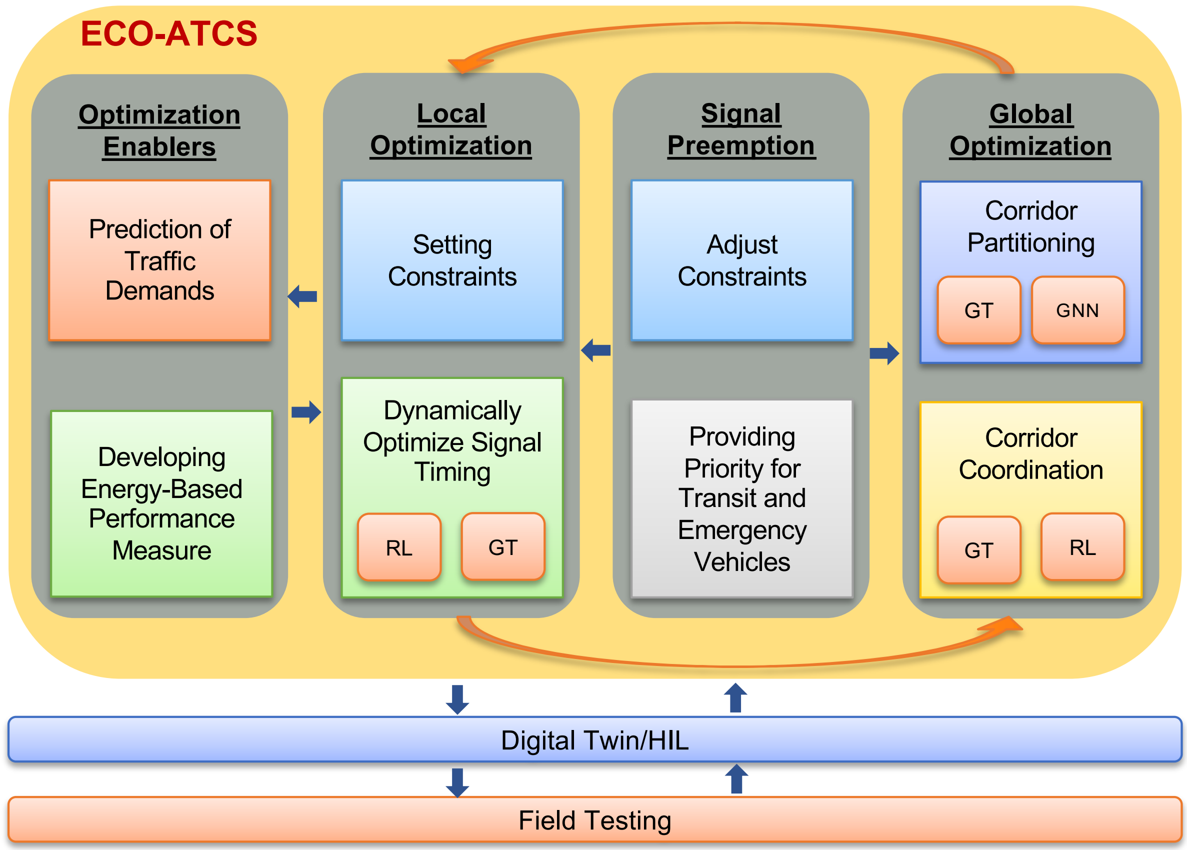
- Develop energy-efficient signal control algorithms that capitalize on wireless communications and traditional and emerging data sources
- Develop a multi-modal priority system that can deal with simultaneous priority requests from various modes in an energy-efficient fashion
- Demonstrate capabilities and evaluate the portability of the proposed technology through high-fidelity simulation and field testing.

Milestones

Month/ Year	Description of Milestone or Go/No-Go Decision	Status
January 2021	- Completed and approved project management plan - Completed coordination and collaboration plan of ORNL	Complete
April 2021	- Mathematically validated Eco-PI metric for fuel consumption and GHG emissions optimization. - A technical report/memo with a clear description of the methodology used to develop Eco-PI metric and impacts of various factors contributing to the Eco-PI	Complete
July 2021	- Fully functioning data infrastructure to ingest and store data from the MLK Smart Corridor testbed for validation in simulation and baseline quantification - High-accuracy traffic state prediction models at intersections based on offline/historical data	On Target
October 2021	Fully developed optimization algorithms for fuel consumption and GHG emissions optimization	On Target
December 2021	Functional time-critical components of ECO-ATCS (optimization and priority request response algorithms) that operate in real time	On Target
Go/ No-Go	Various components of Eco-ATCS (optimization and priority request response algorithms) are individually developed, tested, and fully functional for real-time application. What is the minimum computational requirement for running the algorithms in real time?	On Target

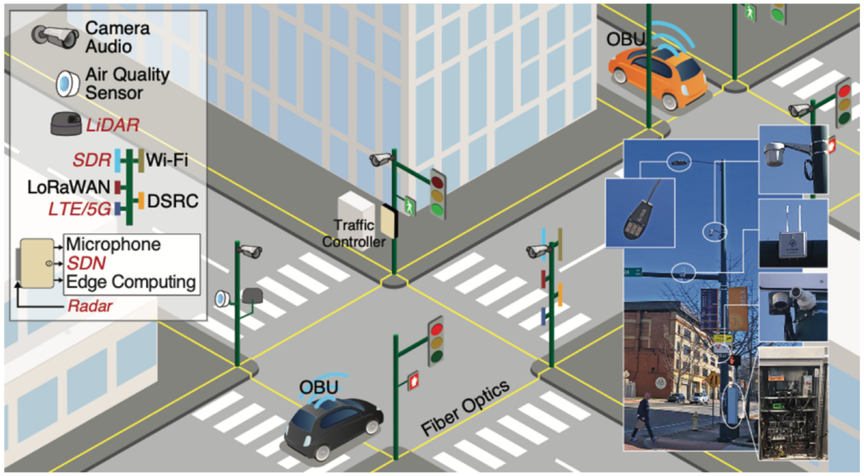
Approach

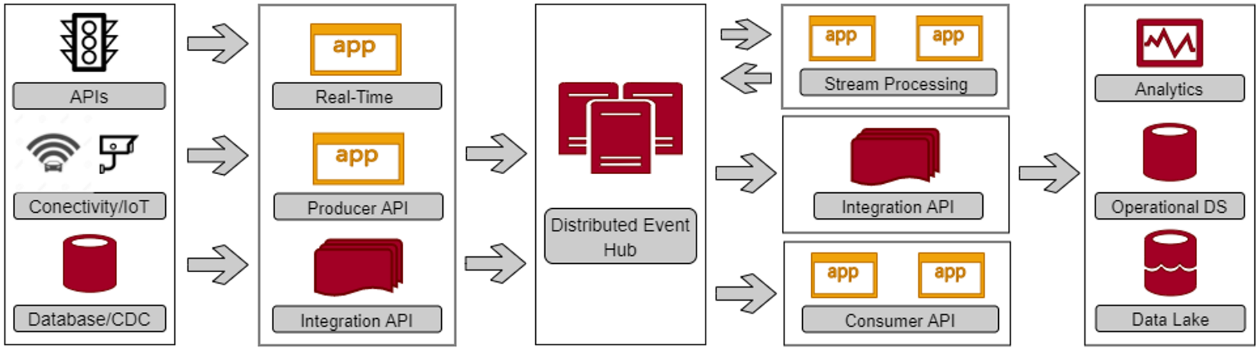
- Build a digital twin of the urban testbed in Chattanooga using real-time and historical data from the field
- Multi-objective optimization: Eco-PI and multimodal priority system
- Artificial Intelligence based optimization for localized traffic signal controllers
- Corridor partitioning and signal coordination using game theory and graph neural networks
- Optimize fuel consumption and emissions at local intersections and along a corridor
- Implement and validate the Eco-ATCS in the digital twin and integrate HIL and high-fidelity simulation capability
- Implement and validate the Eco-ATCS on the MLK Smart Corridor



Technical Accomplishments and Progress

- System Architecture
  - Development and reconfiguration of data collection system to improve data quality and usability.
  - Development of automated daily data processing for dataset generation.
  - Ingestion of 10,000,000+ events per day.





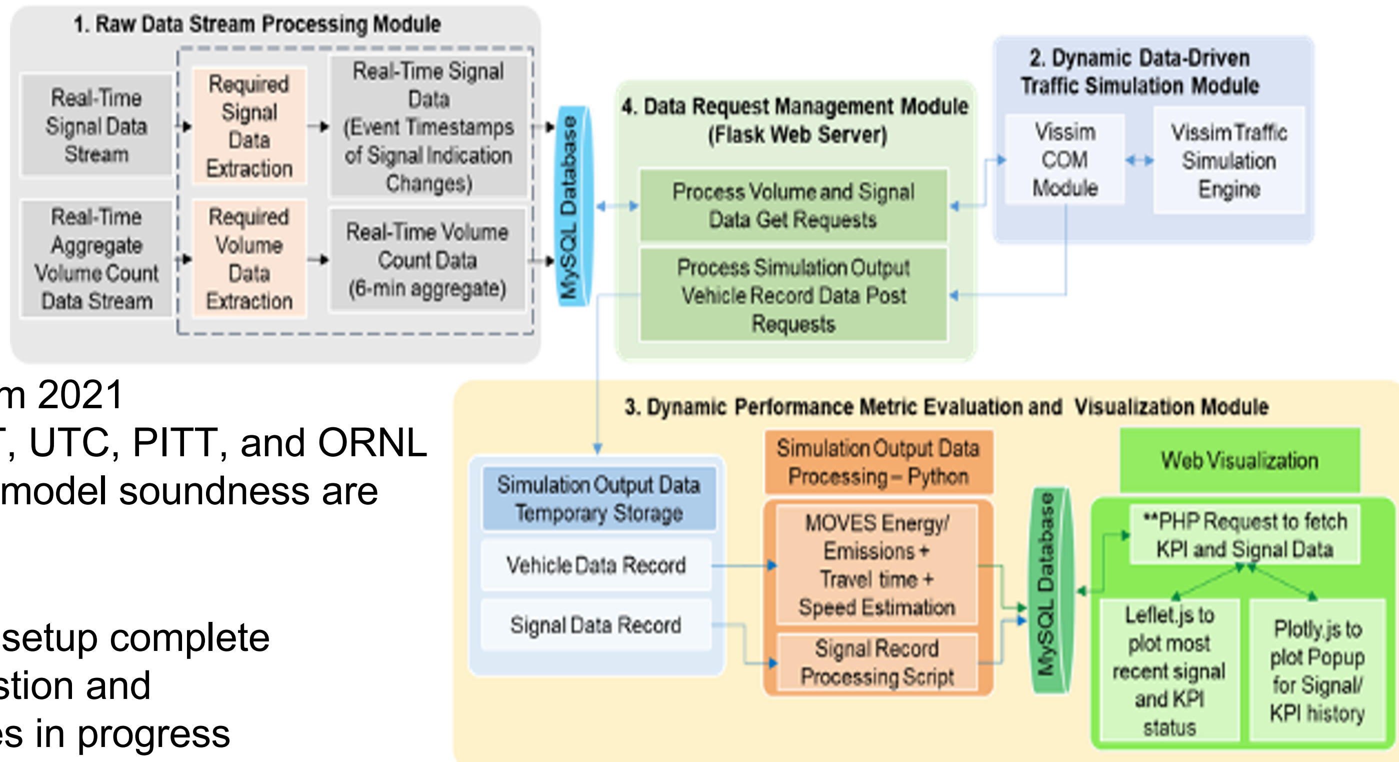
Technical Accomplishments and Progress

- Data analysis & model development
  - Meta-data analysis and accuracy checks for verification of usability
  - Meta-data and usability analysis
  - Create and update zone Ids for data usability.
  - Develop intersection schematics documentation
- Data Collection
  - Video data collection for field-data accuracy verification
    - Vehicle Counts
    - Traffic Composition
    - Travel-Time
  - Signal Phasing & Timing (SPaT)
  - Automated Traffic Signal Performance Measures (ATSPM)
  - GridSmart Data and Reports

Technical Accomplishments and Progress

Digital Twin

- Model leverages corridor data to simulate real time traffic conditions and provides performance measure estimates
- Traffic simulation model
- Under development, using Vissim 2021
- Cooperative development by GT, UTC, PITT, and ORNL
- Initial operational tests to check model soundness are in progress
- System architecture
- Storage and compute hardware setup complete
- Flask server setup for data ingestion and
- communication between modules in progress
- Development of optimal database architecture for real-time computation responsive design is in progress



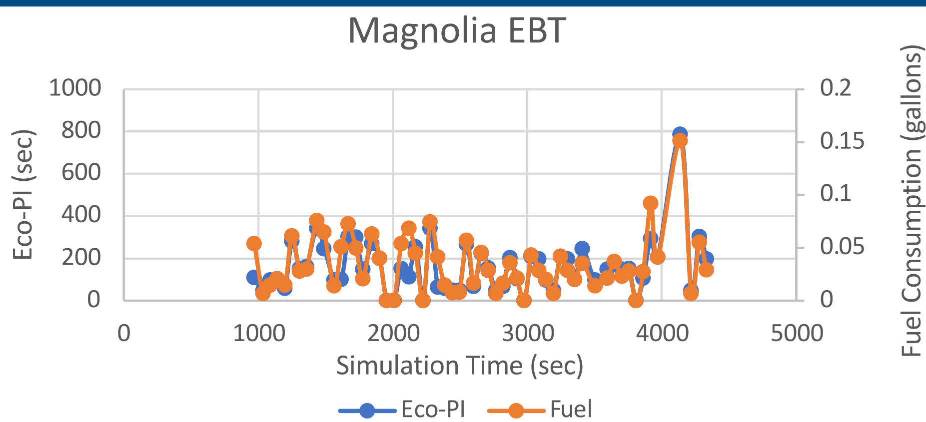
**Note: All components in the architecture run continuous except PHP requests in Web Visualization that are on-demand

Technical Accomplishments and Progress

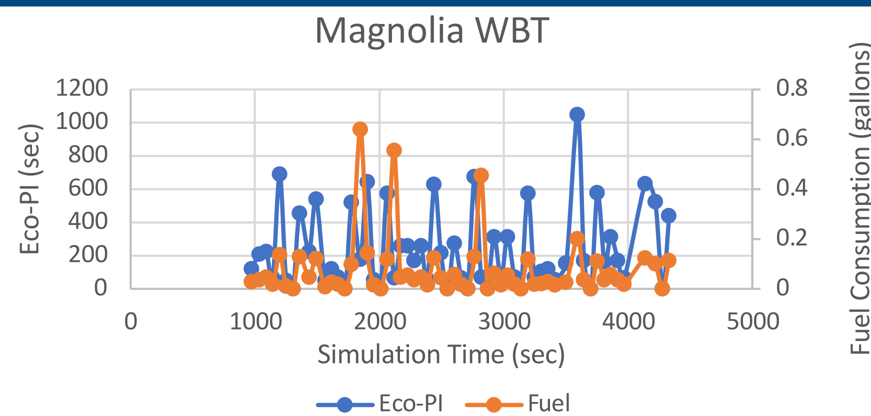
Eco-PI

- Eco-PI takes in consideration multiple factors that impact excess fuel consumption caused by traffic signals
- Versatile performance measure that is easy to compute based on traditional data but can be enhanced to include high-resolution CV data
- The Eco-PI has been developed and tested – it fairly depicts excess fuel consumption without the need to actually measure consumed fuel

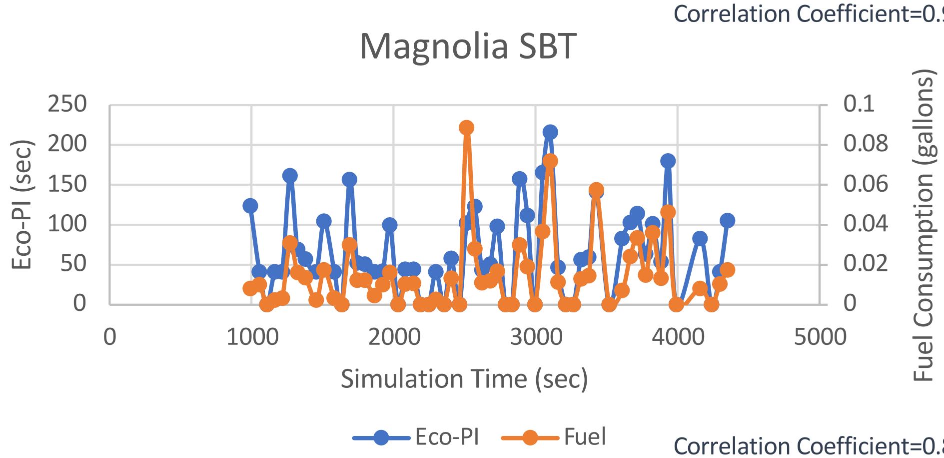
Correlation Coefficient between Eco-PI and Fuel Consumption at Martin Luther King Blvd and Magnolia St



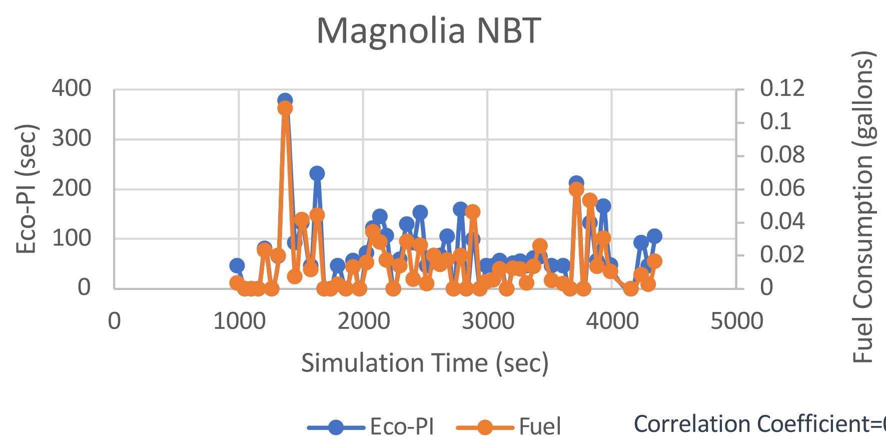
Correlation Coefficient=0.9



Correlation Coefficient= 0.3



Correlation Coefficient=0.8



Correlation Coefficient=0.9

Technical Accomplishments and Progress

Local Optimization of Traffic Signals Based on Eco-PI

- Requires fundamentally different approach that looks at traffic signals beyond their capacity-based performance
- Requires online (near real-time) estimation of Eco-PI
- Progress has been made to capture real-time Eco-PI and establish fundamental prerequisites for local optimization

Direction	Broad	Carter	Central	Douglas	Georgia	Houston	Lindsay	Magnolia	Market	Peeples
EBT	0.93	0.92	0.96	0.95	0.31	0.94	0.95	0.90		0.33
EBR	0.96	0.82	0.98	0.95	0.94	0.87	0.88	0.95	0.88	0.50
EBL	0.99	0.95	0.99	0.99	0.83	0.94	0.26	0.41	1.00	0.46
WBT	0.92	0.94	0.98	0.95	0.53		0.30	0.27	0.93	0.94
WBR	0.95	0.97	0.99	0.99	0.98		0.95	0.51	0.87	
WBL	0.80	0.98	0.99	0.96	0.62		0.96	0.93	0.99	0.50
NBT	0.27	0.69	0.93	0.12	0.68	0.39	0.40	0.91	0.91	
NBR	0.88	0.97	0.96	0.98	0.77	0.89	0.74	0.73	1.00	0.94
NBL		0.94	1.00	0.88	0.70	0.59	0.88	0.54		0.57
SBT	0.93	0.90	0.87	0.90	0.75	0.12	0.85	0.80		
SBR	0.97	0.95	0.98	0.74	0.91	0.97	0.36	0.85		
SBL		0.53	0.99	0.41	1.00	0.94	0.96	0.93		

Correl≥0.8

0.5 ≤ Correl< 0.7

Correl<0.5

0.7 ≤ Correl< 0.8

No vehicle on the movement

Correl= Correlation Coefficient, r value

Technical Accomplishments and Progress

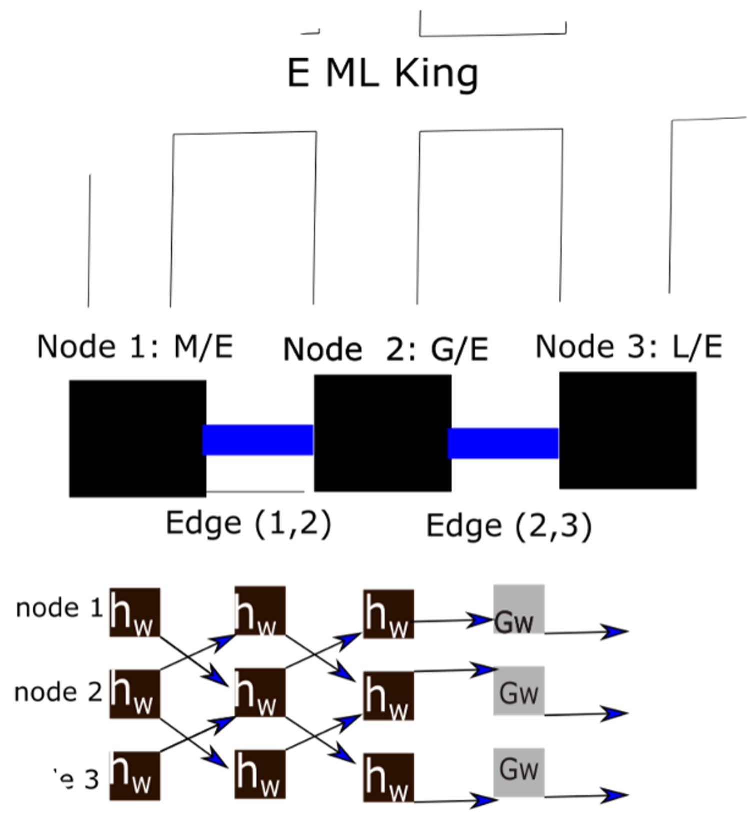
Multi-modal priority system

- Energy impacts of transit vehicle (bus) trajectories in the corridor
- Dynamic computation of potential energy consumption
- Integration in traffic-signal optimization logic
- Incorporation of bus occupancy to prioritize people mobility over vehicle mobility in the cost-function

Technical Accomplishments and Progress

Traffic State Prediction

- Graph Neural Networks was applied to
- estimate traffic flows at an intersection
- using information from upstream and
- downstream intersections
- Preliminary results showed promising
- performance with a RMSE value of 1.4
- Future steps will include adding a lookback
- window to predict flows (5, 10, 15 minutes)
- in the future and expanding the network to
- include all intersections in the corridor



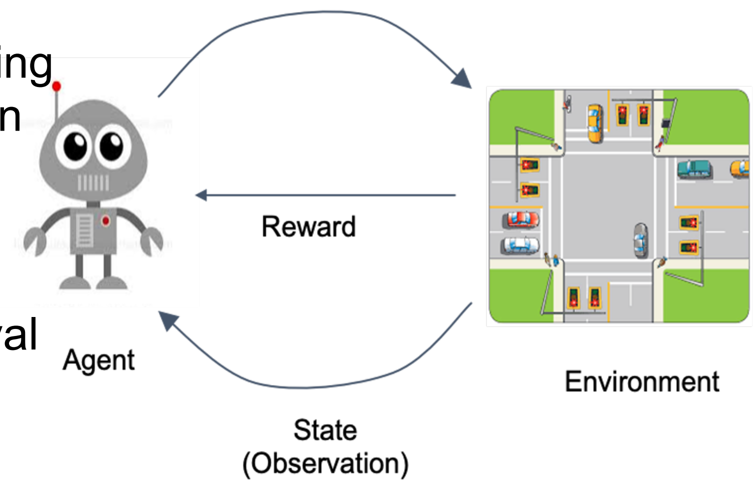
Technical Accomplishments and Progress

Local Optimization

- Based on the available data, the local traffic signal optimization has been formulated as a reinforcement learning (RL) problem associated with the following Markov Decision Process (MDP):

$$< \boldsymbol{S}, \boldsymbol{A}, \boldsymbol{P}, \boldsymbol{R}, \boldsymbol{\gamma} >$$

  - State: $s_t \in S$, queue length
  - Action: $a_t \in A$, choose the phase for the next time interval
  - State transition: $P(s_{t+1}|s_t, a_t): S \times A \rightarrow S$
  - Reward: $r_t \leftarrow R(s_t, a_t)$: $S \times A \rightarrow \mathbb{R}$, Eco-PI
  - Discount factor: $\gamma \in [0,1]$
  - Goal: $G_t \coloneqq \sum_{i=0}^{\infty} \gamma^i r_{t+i}$, the discounted sum of rewards

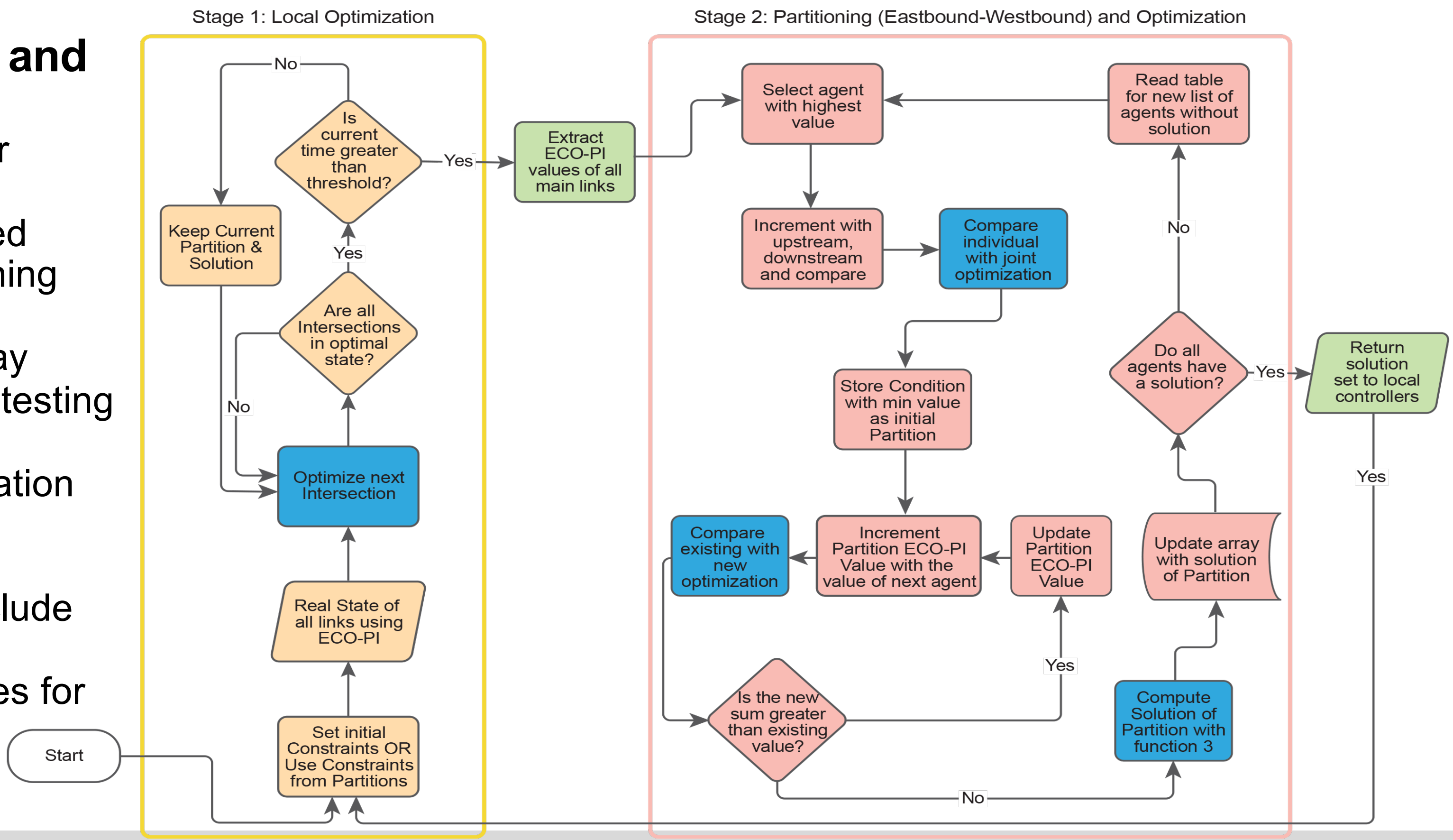


- A Q-learning algorithm is been developed to dynamically set proper phase signal to 'green' at every time interval to deal with different traffic situations and maximize the expected Eco-PI.

Technical Accomplishments and Progress

Corridor Partitioning and Coordination

- Methodology for corridor partitioning and coordination is developed
- Encoding of the partitioning and coordination methodology is underway
- Future work will feature testing formulating the partitioning and coordination problem considering GT
- Future work will also include testing of the developed methodologies for real-time application



Collaboration and Coordination with Other Institutions

- **UTC** *(prime - Mina Sartipi, Osama A. Osman, Dalei Wu, Yu Liang, Austin Harris, and Thanh Nam Doan)*
  - Data Collection, predictive analytics, localized traffic signal controller optimization, partitioning and coordination
- **University of Pittsburgh** (*sub - Aleksander Stevanovic*)
  - Eco-PI, local signal control module, design simulation test and field test scenarios, analyze optimization techniques
- **Georgia Tech** *(sub - Michael Hunter, Angshuman Guin, Abhilasha Soraj)*
  - Develop multimodal priority system, digital twin, establish baseline for current systems, develop test plan for field test
- ***ORNL*** *(sub - Dean Deter, Adian Cook)*
  - Encode MLK Smart Corridor in simulation, HIL and high-fidelity simulation
- **City of Chattanooga** *(sub, Kevin Comstock)*
  - Field test

THE UNIVERSITY OF TENNESSEE CHATTANOOGA

University of Pittsburgh

Georgia Tech

OAK RIDGE National Laboratory

CITY OF CHATTANOOGA CORPORATION SEAL TENNESSEE

Remaining Challenges and Barriers

- Approvals for foreign nationals
- Traffic Controller - Interface

Proposed Future Research

- FY-2021 : Algorithm Development
  - Continue developing a local signal control module
  - Continue developing a multimodal priority and control module
  - Continue developing predictive analytics for the traffic state
  - Continue developing optimization algorithms (local and corridor-level)
  - Analyze optimization techniques for the integrated system
- FY-2022 : Simulation Implementation and Validation
  - Continue developing digital twin
  - Develop communication modeling
  - Integrate HIL and high-fidelity simulation
  - Establish a baseline for the current system
  - Run simulation and collect data
  - Refine Eco-ATCS, as needed

Any proposed future work is subject to change based on funding levels.

Summary

- Developed a novel performance measure referred to as **Ecological Performance Index (Eco-PI)**
  - Eco-PI characterizes impact of signal timings on excessive fuel consumption and vehicular emissions at signalized intersections
  - Eco-PI analyses how various operational and traffic conditions impact unnecessary vehicular stops at controlled intersections
  - Eco-PI is a scalable performance measure that can be estimated on various spatial levels
    - Eco-PI for a specific traffic movement (related to a signal phase)
    - Eco-PI for a whole intersection (in order to be able to find the right balance for various traffic movements)
    - Eco-PI for the entire road network.
- Incorporating multi-modal priority module into the objective constraint in addition to Eco-PI
- Developing optimization algorithms at local level using artificial intelligence
- Developing partitioning and coordination techniques for corridor-level optimization
- Developing digital twin to implement and validate the proposed algorithms in simulation environment