Improving Network-Wide Fuel Economy and Enabling Traffic Signal Optimization Using Infrastructure and Vehicle-Based Sensing and Connectivity

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2021 DOE Vehicle Technologies Office Annual Merit Review

College of Engineering

Project ID: EEMS107

Overview

Timeline

- Start: October 2020
- End: September 2023
- Percent Complete: ~15%

Budget

- Total project funding
  - $1,421k Federal Share
  - $499k Cost Share
- FY 2020 - $881k (Current)
- FY 2021 - $523k

Barriers and Technical Targets

- Estimating energy/emissions savings in future mobility scenarios
- Quantifying benefits of Active Traffic Management with and without Connected and Automated Vehicles
- Artificial Intelligence/Machine Learning based tools for traffic/vehicle control optimization.

Partners

- Oak Ridge National Laboratory
- Alabama DOT – West Central Region
- Project lead: The University of Alabama

Relevance

Big Picture Potential for Energy Cost Reduction

- Given an awareness of real-time traffic flows, there is an opportunity to optimize traffic system operations and reduce system wide fuel consumption
- Through connectivity, traffic system operational strategies can incorporate individual vehicles to further realize reduced fuel consumption

Impact of Project on EEMS program objectives

From USDRIVE Vehicle-Mobility Systems Analysis Roadmap, this project directly supports goals of:

- Estimating fuels savings potential in future connected transportation scenarios and management
- Demonstrating potential for real-time data collection and system modeling
- Evaluating AI/ML approaches for traffic and vehicle control

Relevance (cont.)

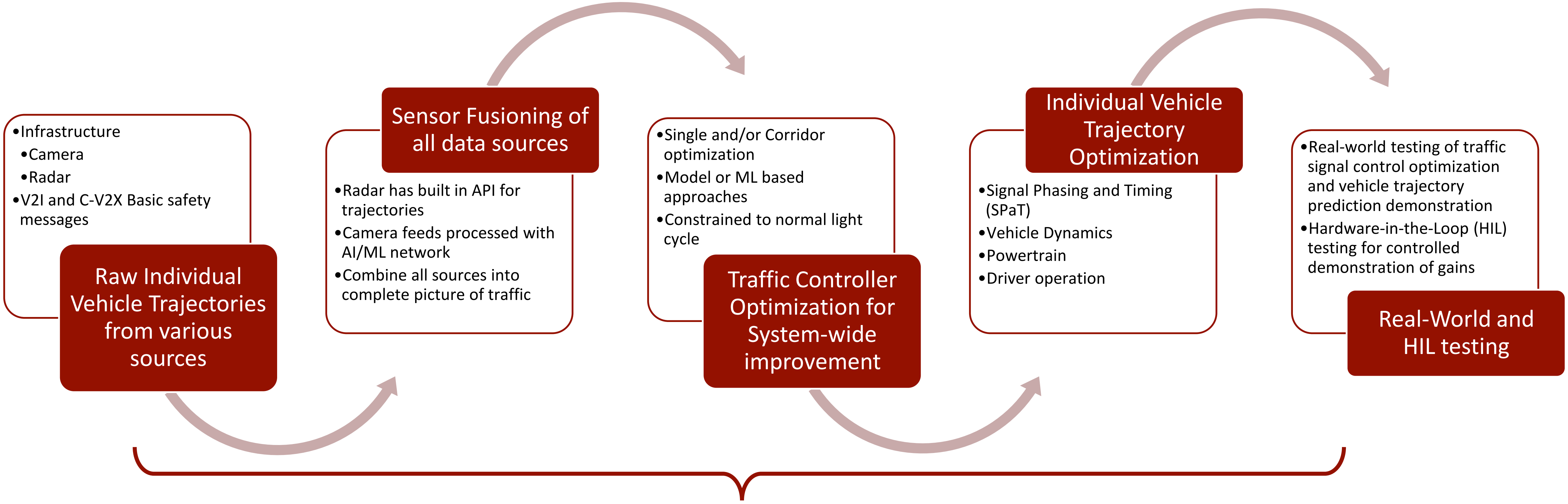
Specific Project Objectives

- Research, develop, and validate traffic signal and vehicle optimization approaches to demonstrate a system-wide reduction in fuel consumption and emissions of ≥20% in real-world testing.
- Evaluate infrastructure-based detection and sensor fusioning with CAVs upon which AI/ML techniques can optimize traffic flow for reduced fuel consumption

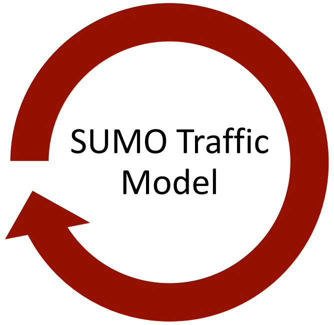
Progress in Past Year

- Developed microtraffic simulation to serve as platform for optimization method development.
  - Model is of real-world testbed with advance detection and logging capabilities, and is calibrated to USDOT guidelines
- Preliminary Sensor Fusion, DSRC/C-V2X Evaluation, and Probe Vehicle Instrumentation

Approach Flowchart



The development of each step is enabled first by real-world data sources, but developed in an overall traffic network microsimulation using Simulation of Urban Mobility (SUMO)



- Real-time AND Post Processed
  - Estimated fuel consumption
  - Evaluate Controller performance
- Traffic details for HIL input

Approach Goals

1. Demonstrate network-wide fuel economy improvements through real-time signal optimization
2. Ability to impact traffic flow at low penetration levels.
3. Individual vehicle optimization enabled via signal phasing and timing (SPaT) information.
4. Evaluation of various V2X communication pathways.
5. Real-world demonstrations and rigorous HIL validation of improvements.

<u>Unique Capability and Methods enabling team to overcome technical barriers</u>

1. Existing real-world connected infrastructure test bed which includes 85 intersections in Tuscaloosa area equipped with data logging & C-V2X/DSRC radios
   - Developed in close partnership with local city, county, state and federal DOT stakeholders
2. Enhance selected corridor with radar and camera-based detection systems funded through this project
   - Combined with V2I/V2X data from connected vehicles this provides holistic view of traffic flow

Milestones and Go/No-Go

FY 2020

Milestone	Type	Description
Traffic Model Complete (COMPLETED)	Technical	Traffic model of corridor is completed and fully functioning and capturing historical traffic data with acceptable quality of match as determined based on US DOT calibration procedures in FHWA-HRT-04-040 report.
Lab-scale DSRC/C-V2X testing completed (COMPLETED)	Technical	Lab scale testing of DSRC/C-V2X radios are complete. Ideal latency, bandwidth, and ranges are available and reported for inclusion in the traffic modeling.
Probe vehicles instrumented for real-world data collection	Technical	Probe vehicles instrumentation (including fuel/energy consumption, location, and appropriate radio units) is updated and functional. On-board radar system integrated (used to provide heading of nearby vehicle). Initial trajectory data through corridor provided.
Hardware deployment completed, preliminary sensor fusion demonstrated, and simulations running correctly	Go/No Go	Infrastructure hardware field deployment will be completed to serve as the primary data source for sensor fusioning in real-world demonstrations. Lab-scale sensor fusioning should be demonstrating $\geq$90% detection to give confidence in likely success of the real-world effort in the next phase. Demonstrate the functionality of traffic models incorporating advanced vehicle dynamics models based on $\leq$10% error from probe vehicle test drive trajectories.

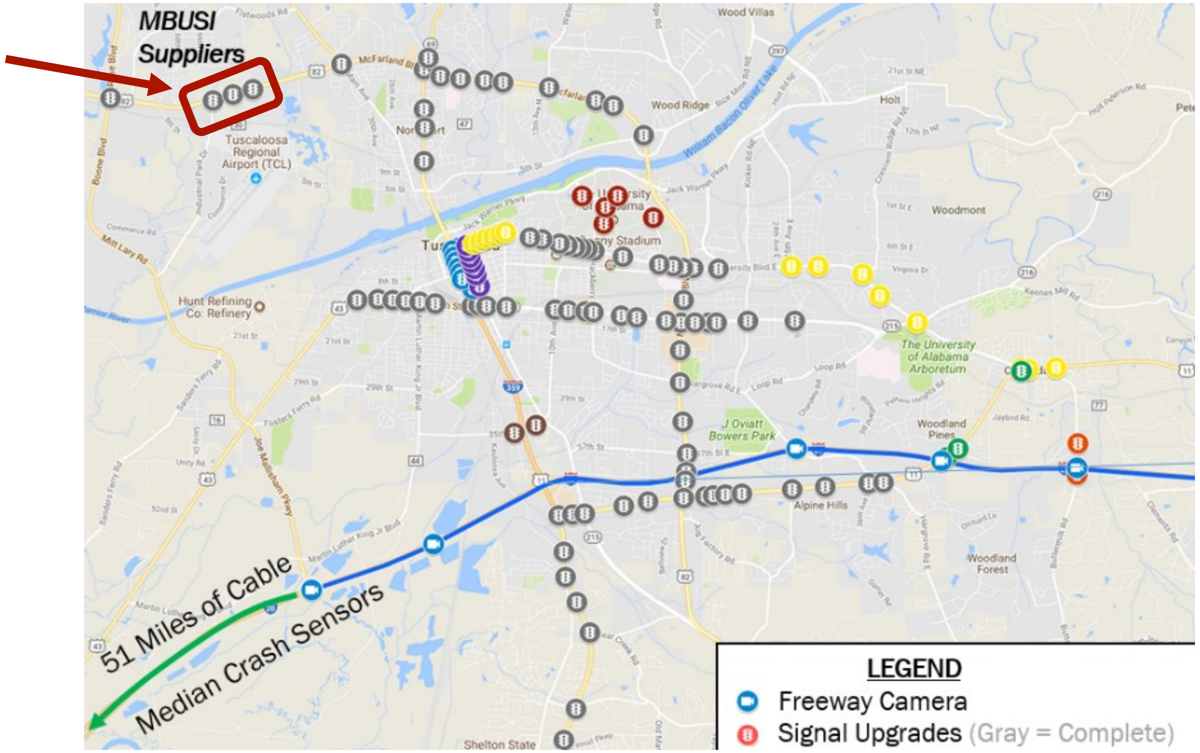
FY 2021

Milestone	Type	Description
Real-world data Collection Complete	Technical	High fidelity real-world data obtained from the deployed infrastructure-based sensor suite. Manual observations will serve as initial validation that all vehicles are captured and available for supporting sensor fusion development
Traffic Model for CAVE Lab Testing is Complete	Technical	Traffic model and 3D environment in CARLA have been updated and integrated for testing in CAVE Lab at ORNL.
Single Intersection Control Optimization Demonstrated	Technical	Static intersection control optimization has been completed and is demonstrating $\geq$5% reductions in local fuel consumption. Results based on simulations with real-world traffic data and calibrated vehicle trajectory models.
Optimizations of intersection operation is demonstrating significant corridor-wide energy reductions in simulation	Go/No Go	Achieve a $\geq$10% corridor-wide fuel consumption reduction in simulation.

Technical Accomplishments and Progress

Deployment corridor identified and final infrastructure detection equipment on order

- Coordinated with city and Alabama DOT to identify locations and commitment
- Trucking, shopping, and residential demand serviced by three intersections
- Expected installation by mid-Q3 2021
- Includes V2N backboard for cellular based connectivity options

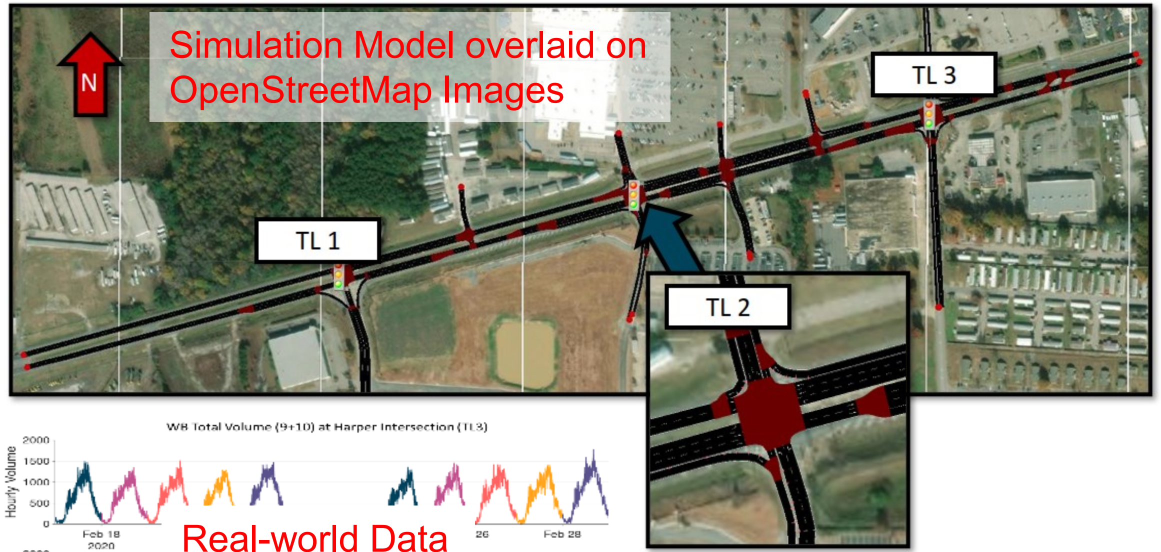


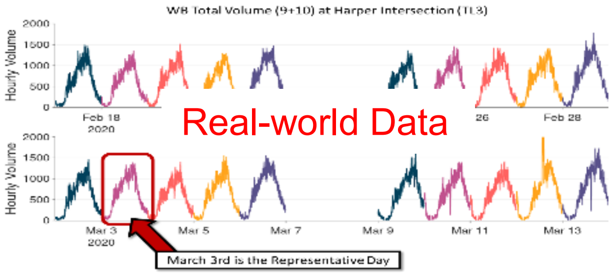
Connected Infrastructure deployment locations in and around Tuscaloosa area

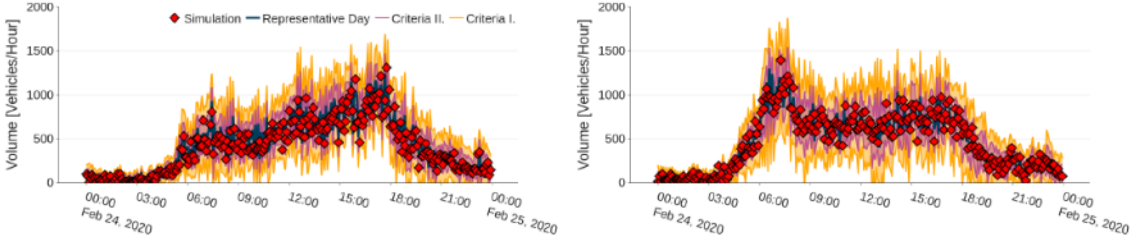
Technical Accomplishments and Progress

Milestone #1 Complete

- Microsimulation model of deployment corridor generated and configured
- Historical real-world data (vehicle detectors and signal status) reviewed and nominal month long period selected (Feb – March 2020)
- Model calibrated to USDOT Procedures[1] at all detectors and approaches







(a) TL2-WB (b) TL2-EB

Calibrated Model Results

[1]Wunderlich, K., et al.., 2019. TAT Volume III: Guidelines for Applying Trac Microsimulation Modeling Software 2019 Update to the 2004 Version (FHWA-HOP-18-036). USDOT & Noblis, Washington, DC, 4.

Technical Accomplishments and Progress

Milestone #2 Report In progress

- Installed C-V2X/DSRC On-board unit (OBU) radios in probe vehicles for real-world controlled testing
- Communications with road-side unit evaluated for latency and packet loss as impacted by line-of-sight (LOS) and non-LOS configurations

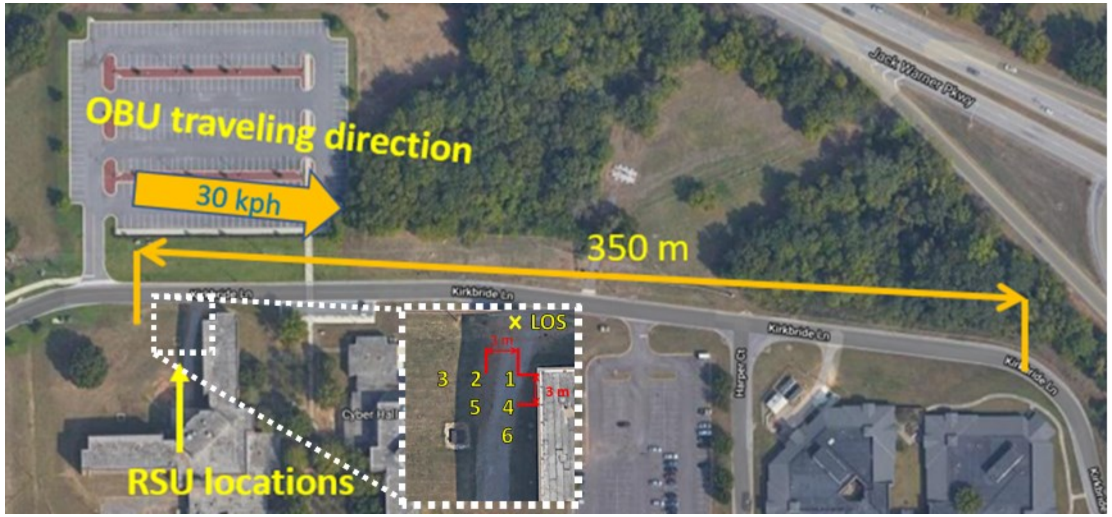
Road Side Unit (RSU)

Roof-top antenna for OBU

OBU Radio temporarily installed in vehicle

Technical Accomplishments and Progress

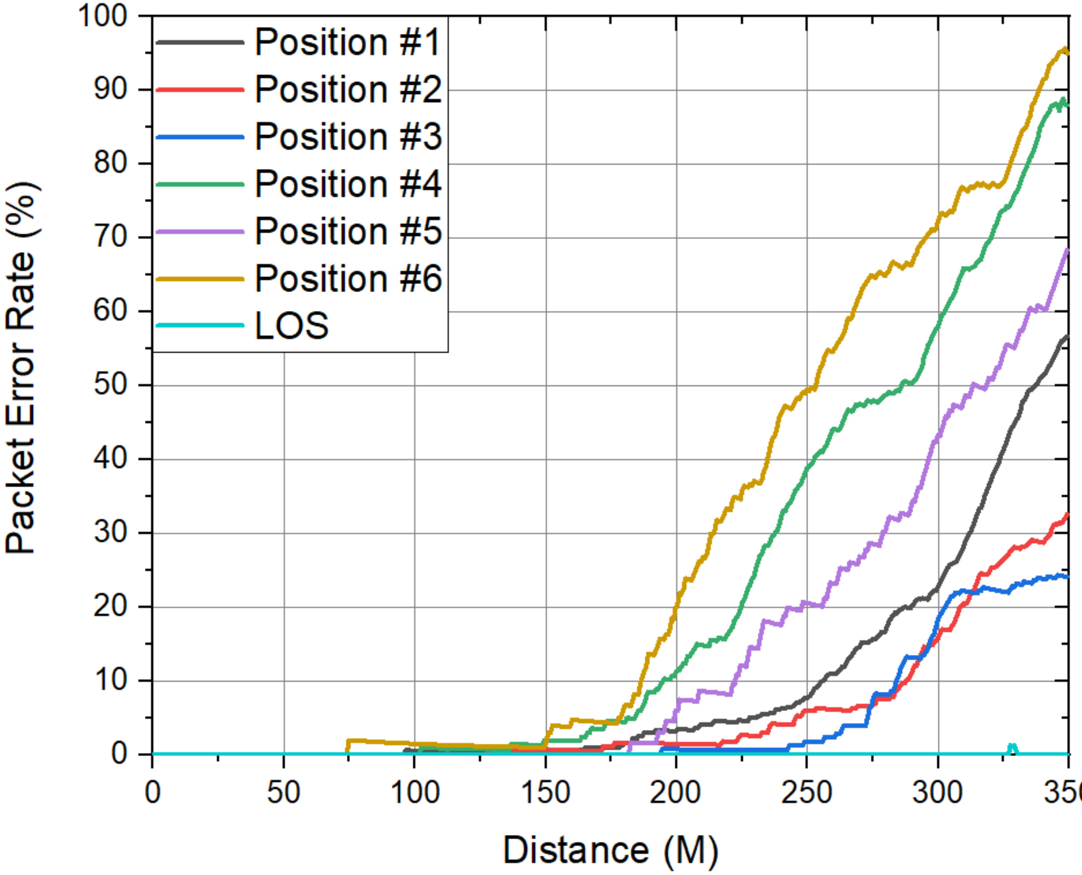
- Tested building obstruction impact on signal quality in initial configuration shown.
- As expected, latency is unaffected by distance and LOS/non-LOS conditions (data available in technical backup slides)
- More complex obstructions, including on-road testing, will be pursued to assess effectiveness of V2I communications in aiding traffic signal control optimization.



Road test configuration Schematic for RSU locations from LOS to non-LOS positions

Technical Accomplishments and Progress

- Increased Packet error rate (PER) is primary effect of LOS obstructions.
  - A packet error occurs when receiving unit detects error in data received
  - This will potential impact timing of vehicle trajectory information being received in road-side traffic signal control optimization system.
  - The range and probability of error will be incorporated into microsimulations and support optimization algorithm development.



Technical Accomplishments and Progress

- Milestone #3 is on Schedule
  - Probe vehicle instrumentation upgrades are installed.
    - OBDII Datalogging,
    - Dash cameras
    - AVL Plutron fuel consumption
    - Cohda Wireless DSRC & C-V2X radio/GPS units
  - Integration with on-board data-logging systems are in progress

Technical Accomplishments and Progress

- Image shows composite results of video with data streams.
  - Currently includes:
    - Location (top left)
    - Fuel Consumption and Total (top right)
    - Vehicle Speed and Pedal Position (bottom right).
  - Future additions will include DSRC/C-V2X performance data and V2I messages

Responses to Previous Year Reviewers' Comments

- This is the first year that the project has been reviewed.

Collaboration and Coordination with Other Institutions

Highly Interdisciplinary Team at UA:

- Transportation system operations, sensing, and traditional optimization
- Transportation system modeling
- Sensor Fusioning
- DSRC/C-V2X Radio Performance Evaluation
- Machine Learning/Artificial Intelligence Methods applied to traffic signal operation optimization
- Vehicle Performance characterization and power train optimization

Critical Partner at ORNL:

- Support enhanced vehicle modeling for more accurate traffic system predictions
- 3D Virtual Environment Development and Integration to enable controlled Hardware in Loop Testing.

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Remaining Challenges and Barriers

- Obtaining complete picture of traffic flow will be critical to developing optimization approaches
  - Preliminary efforts are underway (see future work) to develop sensor fusioning in road-side hardware
- Effectively developing optimization requires accurate models including vehicle and virtual sensing/communications in the micro traffic simulation
  - Development of frame work of virtual sensing, communications, and AI/ML based control interfaces are on-going
- Real-world demonstration depends on ability to interface with traffic controllers in real-time
  - Close communication with DOT partners regarding plans and requirements is maintained
  - Meeting safety and operational requirements prior to testing will be critical.

Proposed Future Research

<u>FY21: Research Optimization Methodology</u>

Remainder of currently approved work

- Deploy infrastructure based detection and communications hardware enhancements to the corridor
- Complete probe vehicle instrumentation and data integration (Milestone #3).
- Go/No-Go Point:
  - Present acceptable lab-scale sensor fusioning results
  - Present calibrated probe vehicle model based on real-world trajectories
  - Hardware deployed

<u>FY22: Develop Optimization Methodology</u>

- Collect exhaustive real-world data from infrastructure detection and probe vehicle
- Support preparations of the simulation environment for HIL testing at ORNL
- Demonstrate single, and corridor level optimization of traffic signal control in simulation
  - Targeting 10% reduction in fuel consumption at this stage. Final goal is 20% reduction in system (all vehicles) fuel consumption.

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

Summary

<u>Big Picture Potential:</u>

Future Looking Integration of vehicles and traffic control system through C-V2X/ DSRC/ V2N at various penetration levels can enable gains now rather than waiting (algorithms will be the same regardless of data source).

<u>Impact toward EEMS Objectives:</u>

There is opportunity to dramatically reduce transportation system fuel consumption (targeting 20%) based on combined V2I and infrastructure based sensing of traffic flows in real-time and AI/ML based controller optimization.

<u>Accomplishments:</u>

- Interdisciplinary team and collaboration between teams at UA and ORNL is making good progress and on schedule
- Built traffic simulation model that will serve as foundation for off-line vehicle and traffic controller optimization development.
- Instrumented probe vehicle to support complex vehicle model development
- Performed preliminary C-V2X testing to provide performance metrics as model input
- Working closely with ALDOT to deploy infrastructure hardware to test corridor for real-world data collection and optimization demonstrations

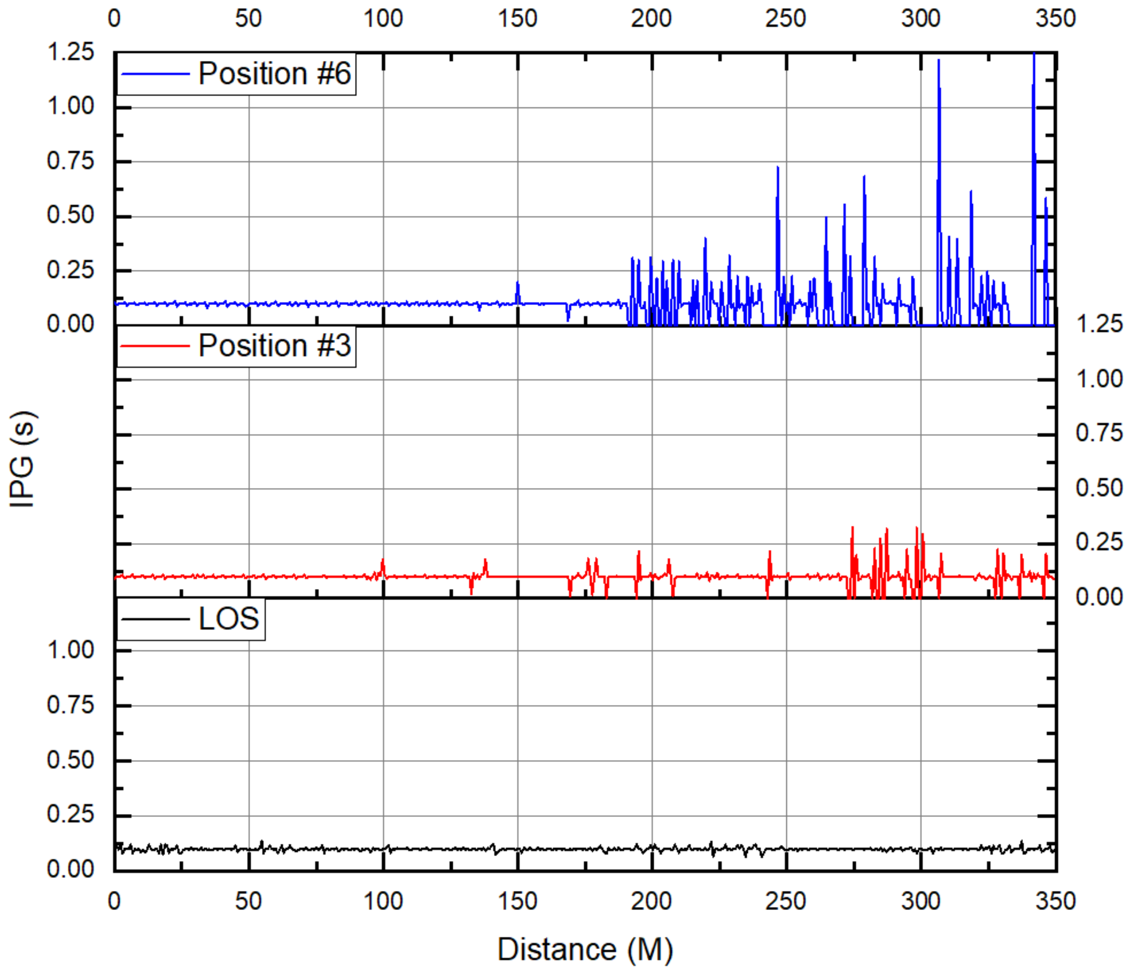
Technical Back-Up Slides

The following slides contain additional supporting technical details.

Additional C-V2X Testing Results

Inter-packet Gap (IPG) is the time between received data packets.

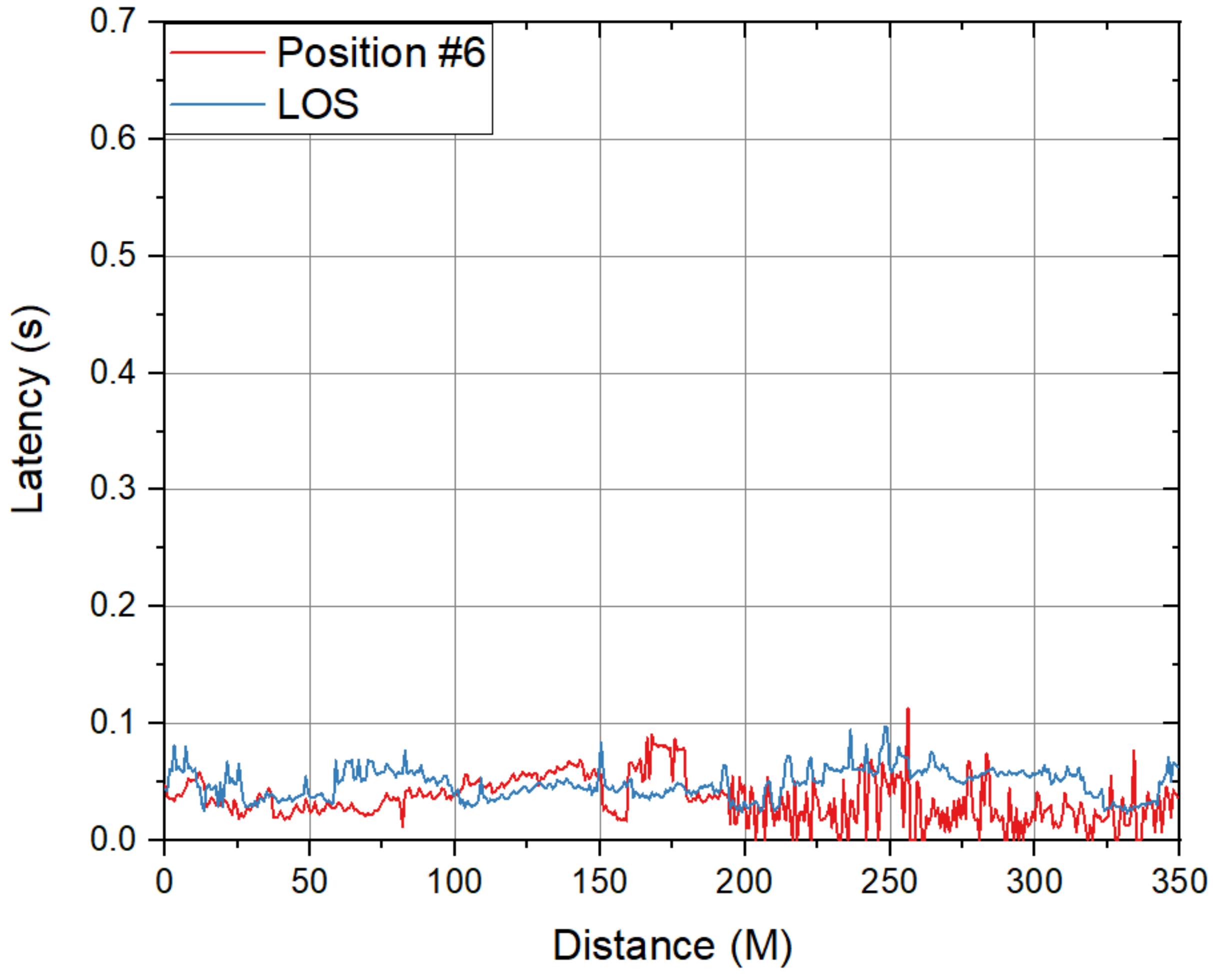
- Radios configured for 10 Hz, or 0.1 s per message
- This IPG is observed until packets start to be missed at increased distance and/or obstruction.



Additional C-V2X Testing Results

Latency is measured as time between message sending from RSU and receiving in OBU (or visa versa).

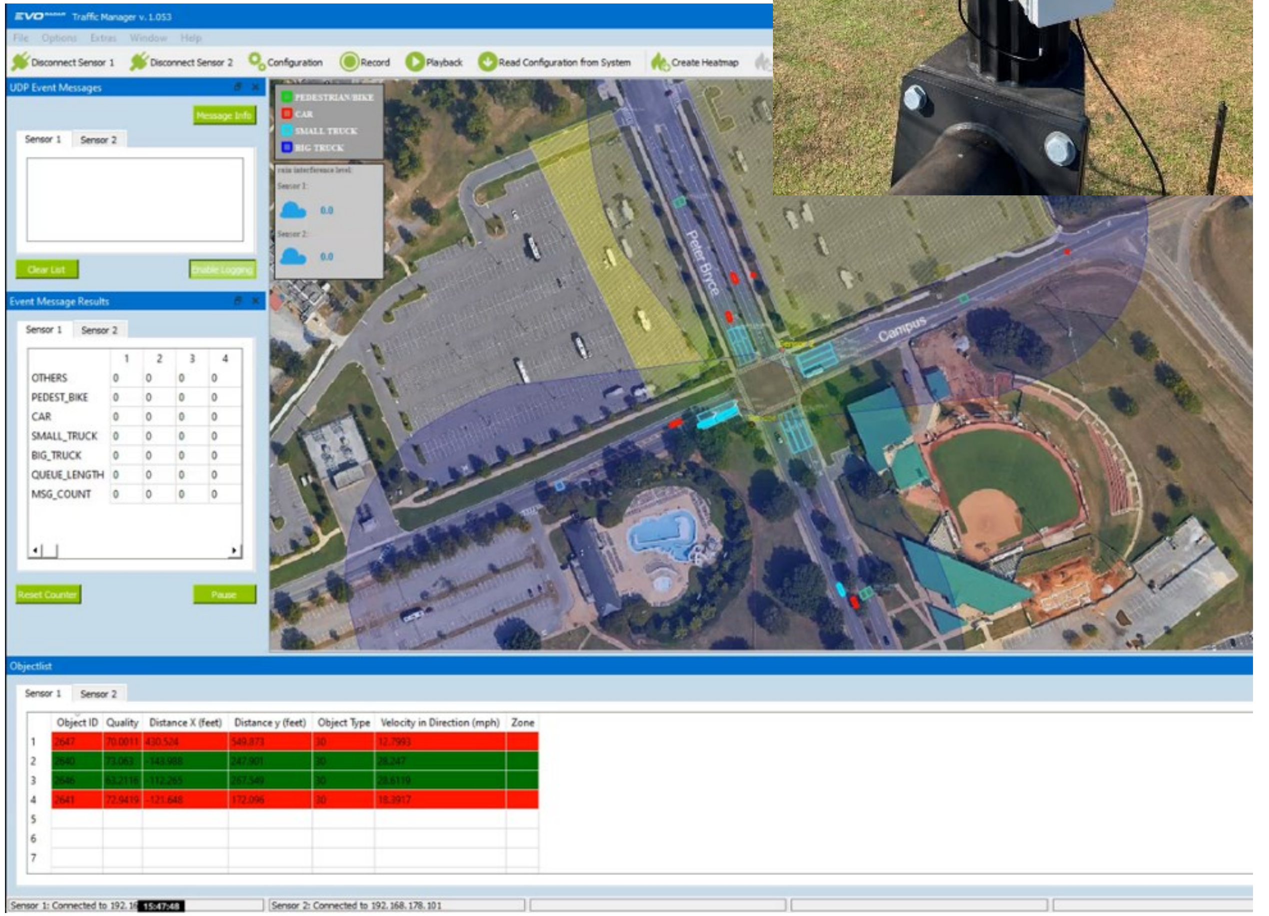
- Messages include GPS based timestamps and thus can be compared between message contents and timestamp at receipt.
- Latency is primarily due to message generation/buffering as speed of light over 300m is negligible.
- As such, latency is unaffected by distance or obstruction when messages are properly received.



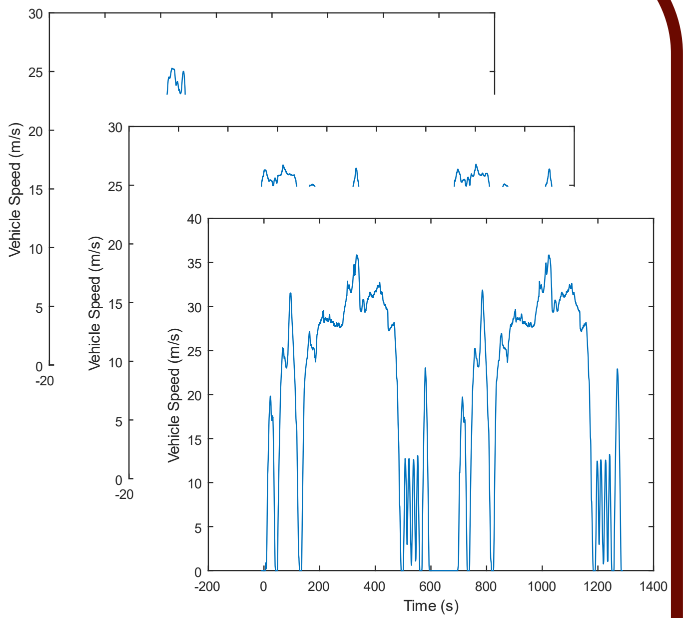
Camera/Radar Sensor Fusion

We are using pilot deployment of chosen radar system at a single intersection to gain experience interfacing with radar and camera systems.

- Top shows radar head mounted on signal pole
- Image shows vendor interface for dual-head radar system overlaid field of view and objects
- Bottom table provides location and trajectory information



Vehicle Modeling Progress



Transient Test Data will be used as input to generate generic vehicle models based on classification.

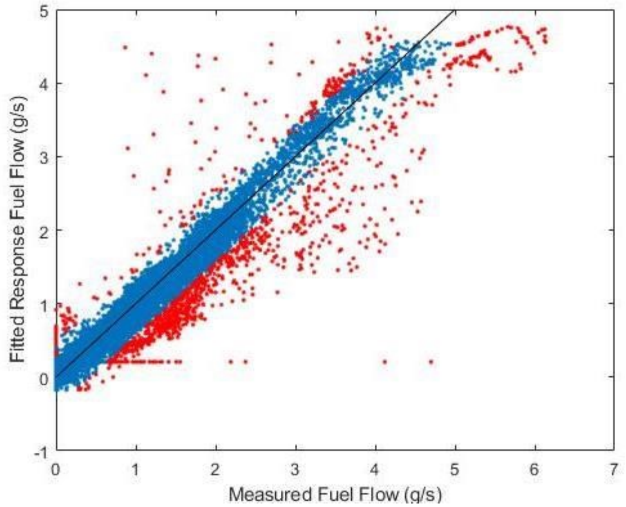
$$\dot{m}_f = aP_{traction} + b$$

Linear Relationship to Traction Power

$$\dot{m}_f = \sum_{i=0}^{m}\sum_{j=0}^{n} K_{i,j} v^i a^j$$

Polynomial Response Surface with Velocity and Acceleration Inputs

Fit Multiple Models



$$AIC = 2k - 2\ln(\hat{L})$$

Akaike Information Criterion

Compare and Select Best Model and customize for microsimulation