Real-Time Data and Simulation for Optimizing Regional Mobility in the United States

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Date: 6/2/2020 11:00:00 AM

2020 DOE Vehicle Technologies Office Annual Merit Review

Project ID #: eems061

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Overview

Timeline

- Project Start: Oct. 2018
- Project End: Sept. 2020
- Percent Complete: 75%

Budget

- Total: $2.4M
- FY2019 Funding:
  - ORNL: $1.2M
  - NREL: $800K
- FY2020 Funding:
  - ORNL: $1.2M
  - NREL: $800K

Barriers and Technical Targets

- Disparity, lack of openness, and heterogeneity of transportation data from sensors, controls, and probes leading to lack of observability
- Significant computational complexity for the application of situational awareness, advanced data science, and simulation to impact energy savings at regional scale
- Rigorously identifying control decisions and actions and overcoming technological challenges to implement cyber-physical control

Partners

- Tennessee Department of Transportation (TDOT)
- City of Chattanooga (CDOT)
- University of Tennessee, Chattanooga (M. Sartipi)
- University of Tennessee, Knoxville (S. Chakraborty, A. Kohls)
- Wayne State University (Steve Remias)
- TomTom – Industrial collaborator

Relevance

- **Key target:** Achieve 20% energy savings at the regional level.
  - Highways, linked arterials and freight present an opportunity at the systems level.
  - Framework to be transferable and applicable to other regions.
- **Near real-time situational awareness:** Create a 'Digital Twin' of an entire metropolitan region providing real-time situational awareness for analysis of the entire region
  - Requires data processing at scale across a variety of data sources
  - Demands large scalable computing approaches
- **Near real-time control of traffic infrastructure and vehicles:** Digital Twin forms the basis of a cyber physical control system for control of the highway/road infrastructure and connected vehicles in the ecosystem
  - Fast simulation and algorithmic decisions
  - Orchestration of computational resources on High-Performance Computing resources
  - Data science and artificial intelligence/ machine learning approaches

FY2020 Milestones (ORNL)

Milestone Name/Description	Criteria	End Date	Type
Identify system controls mechanism and develop methods for control utilization	Milestone report documenting the available system controls and methods.	12/31/2019	Quarterly Progress Report **Completed**
Establish observable metrics and develop analysis to measure impact with a focus on energy and traffic mobility as per MAP-21 both at regional and corridor levels.	Milestone report documenting observable metrics in CTwin and analysis with focus on energy and traffic mobility as per MAP-21 measures.	3/31/2020	Quarterly Progress Report **Completed**
Prototype control algorithm testing with hardware-in-the-loop in a lab setting	Milestone report documenting prototype testing in lab setting	6/30/2020	Quarterly Progress Report
Deploy simulation/AI informed control input in a real-time cyber-physical environment along a corridor and measure observables	Milestone report documenting implementation results of real-time cyber-physical controls	9/30/2020	Quarterly Progress Report

FY20 Milestones (NREL)

Milestone Name/Description	Criteria	End Date	Type
Identify system controls and develop methods for control for utilization by Regional TMC to impact energy use and freight.	Milestone report documenting the available system controls and methods.	12/31/2019	Quarterly Progress Report **Completed**
Identify observables and develop ML/AI algorithm to analyze observables and measure impact in regional transportation focused on energy and freight.	Milestone report documenting observables and measures.	3/31/2019	Quarterly Progress Report **Completed**
Augment digital twin (HPC simulation, optimization and situational-awareness tool) with near real-time observables and measures impacted by controls focused on energy and freight.	Milestone report documenting augmentation of situational awareness tool.	6/30/2019	Quarterly Progress Report
Develop and prototype near real-time cyber-physical control informed by situational-awareness, simulation and optimization focused on energy and freight.	Milestone report documenting near real-time cyber-physical controls	9/30/2019	Quarterly Progress Report

Technical Approach

- Create multi-institutional collaboration of transportation science, data science and simulation researchers to build a 'digital twin", enabled by high-performance computing.
- Engage the broader to bring to bear transformative approaches to impact mobility at a Regional Scale.

CTwin – 'Digital Twin' for Regional Mobility, Chattanooga, TN

Situational Awareness from real-time data feeds → Allows observability at a regional scale

+

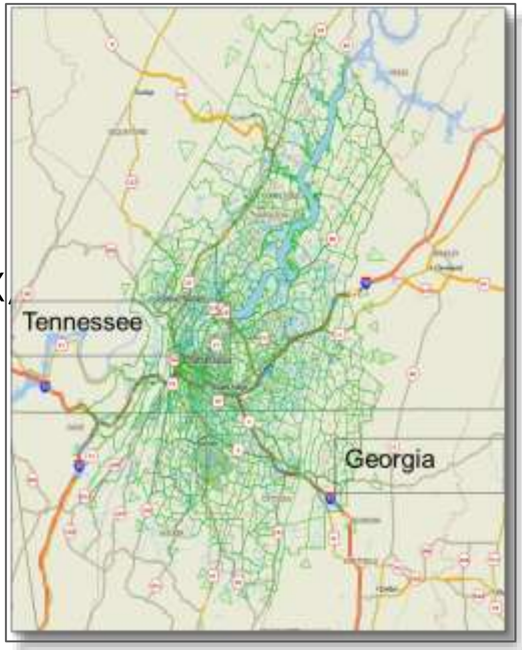
Simulation and Modeling, and Machine Learning → Identifies and evaluates improvements
Demonstrates feasibility/ anticipated outcomes

+

Cyber-Physical control actions → Algorithmically actuates hardware

Real-Time Data

- Data from partner stakeholders is key
- Data partners: City of Chattanooga, Tennessee Department of Transportation, Multiple other agencies: MPO, GA-DOT, Titan, INRIX, TomTom, HERE, ATRI, etc.
- Reference/dynamic data: characteristics of infrastructure/ data collected by sensors
- Significant complexity in variety and nuances of the data, and in the systems that serve the data



Study region


Traffic signals locations in region.


RDS locations in the region

City of Chattanooga

- GridSmart cameras
  - 72 + 70 planned
- Signalized intersections
  - 350 intersections; ~275 signal control, 1/10th second
- Incident data
  - 911, ETRIMS, Waze

TDOT

- Radar Detector Sensors - ~280
  - Located every ½ mile on average
  - Receiving daily 2GB file once a day
  - 30s data from RDS sensors
  - Lane occupancy, speed, classification
- Weather sensors
- Dynamic Message Signs

Regional Data from Hamilton County, and other sources

From Hamilton County

- Road network (multiple versions)
  - TAZ/NavTeq
  - Augmented with data from other versions
- Traffic light locations and schedule
- Historic traffic counts
- GridSmart Camera
  - Live traffic volumes, turn statistics
  - Video feed
- Sensys, BlueToad
- Origin/Destination Pairs

- Probe data – ATRI and TomTom
- NREL has access to TomTom and INRIX
- Freight data
  - Data issues in automated classification from TDOT sensors
  - ATRI data obtained
- Incident data
  - Some lag in availability
  - Multiple systems – 911 TITAN, GEARS, DPS, WAZE
- NPMRDS data access available
  - Not real-time; only bulk downloads possible

Priority data sources: RDS sensors along highways, GridSmart cameras at intersections, SPaT controllers for signals, Freight data from ATRI, Probe data from WAZE, and incidents

Accomplishments – High-Level Highlights

- Real-time situational awareness
  - CTwin real-time tool stood up
  - Collaborators given logins
- Metrics
  - Energy, mobility, safety, and MEP implemented
  - MAP21 metrics and ATSPM implemented
  - Real-time regional speed and energy estimation achieved
- Modeling & Simulation
  - Microscopic and mesoscopic simulations and simulation-calibration strategies setup
  - Corridor scale control simulation/ optimization strategy implemented
- Data Science
  - Novel intersection movement visualization developed
  - Emulated traffic flow from RDS derived
  - Signal performance derived from probe data
  - Machine Learning to detect freight prototyped
- Cyber-Physical Control
  - Updated corridor timing implemented through vendor software
  - Direct control through Python program interfacing with the six m60 controllers on Shallowford Rd; additional testing ongoing

Accomplishment – CTwin Real-Time Situational Awareness tool

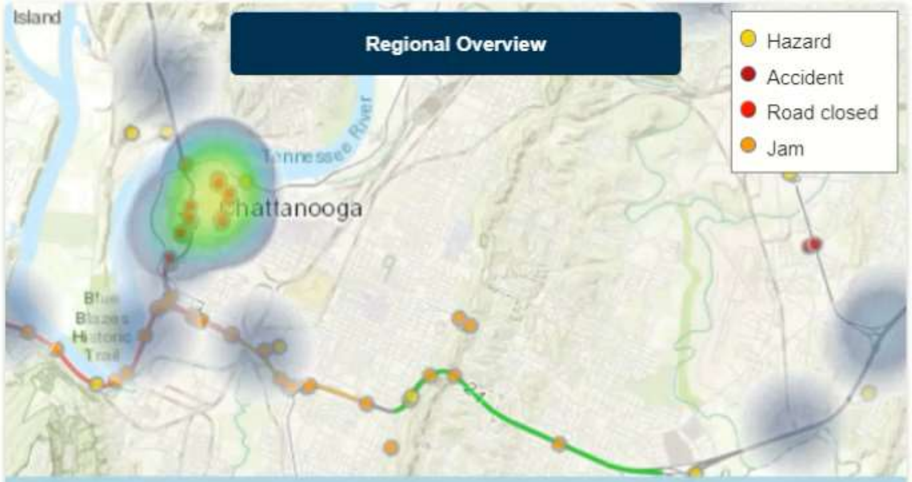
CTwin

Home | Region | Corridors | Incidents | Metrics | Help | admin

Select a Date
1/14/2020

Regional Freeway Speed and Volume

Regional Overview



Real Time From Waze - Last Updated: 2/5/2020 06:18 PM EST

Go to Region View

Road Incidents

Hazard
1/14/2020 11:57 PM

Law
1/14/2020 11:55 PM

System News

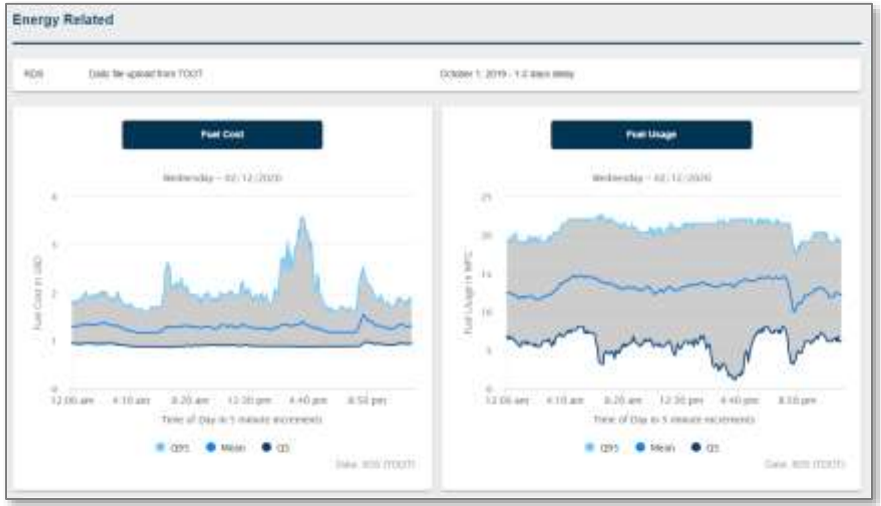
Prototype stood up
7/8/2019 02:36 PM

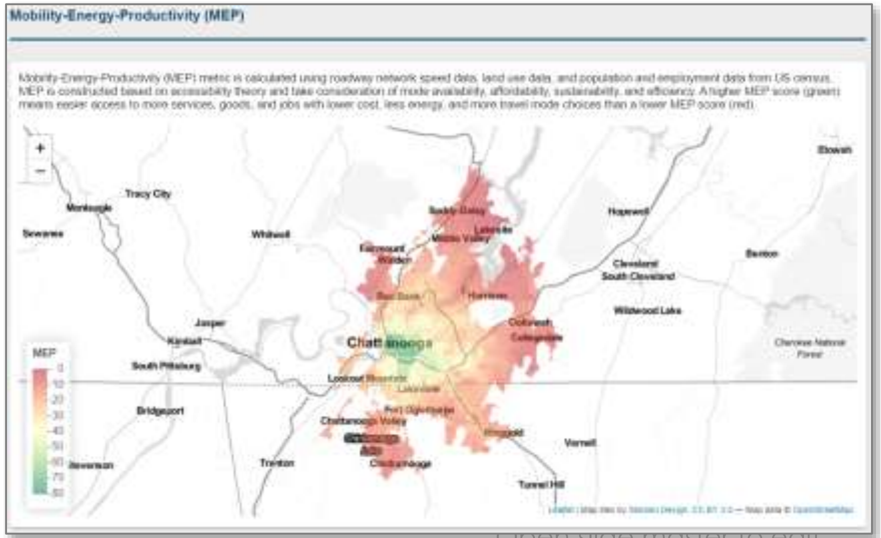
Go To System News

Accomplishment – Metrics

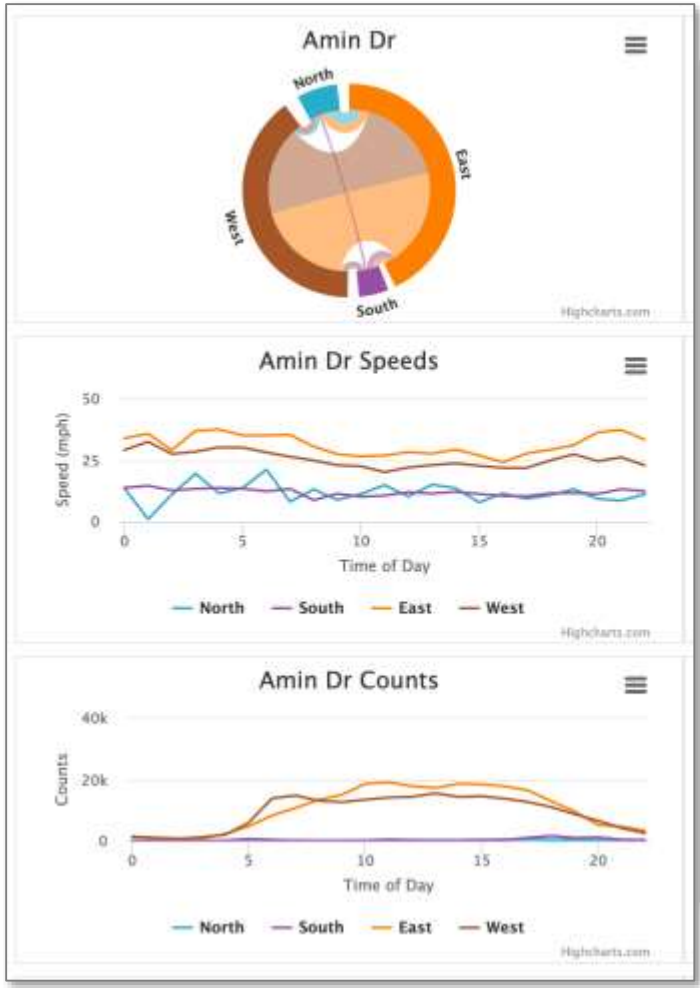
Metrics in CTwin

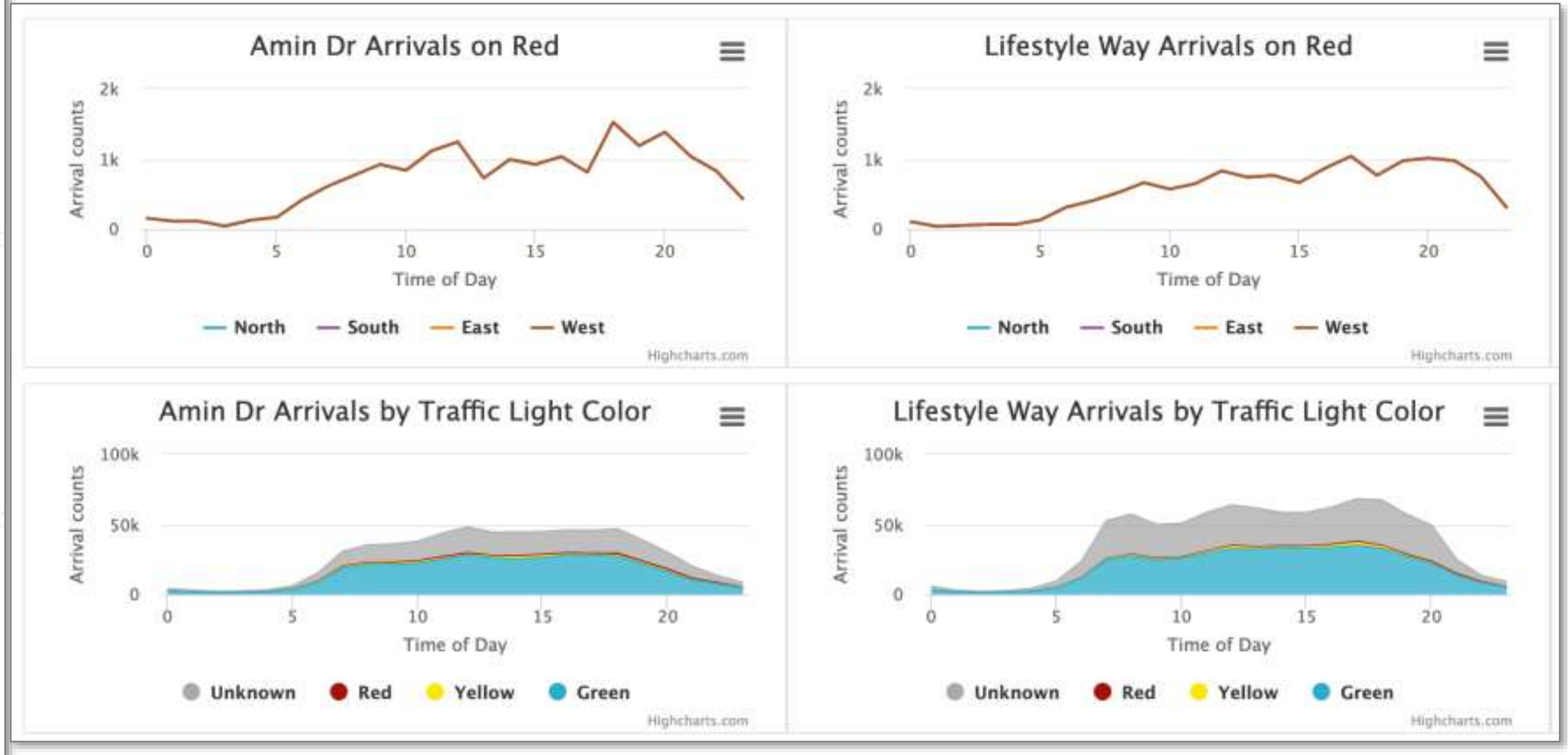
- Mobility Dynamics
  - Macroscopic – Freeway travel time reliability, level of service (average speed and volume to capacity ratio), vehicle miles of travel (VMT) by passenger and freight.
  - Microscopic – Level of service (vehicle delays, queue length and signal delays) from signalized intersections.
- Traffic Safety
  - Roadway segment level – fatalities per capita and serious injuries per capita (crashes per VMT)
  - Intersection level – crashes per 100,000 vehicles
- Energy Usage
  - Minute by minute on-road vehicle fuel consumption & cost
  - RouteE – Energy estimation over roadway segments
- Mobility – Energy – Productivity (MEP)
  - *f(mobility weighted by [energy, cost, trip purpose])*





Automated Traffic Signal Performance Measures from Signal Phase and Timing (SPaT) Data



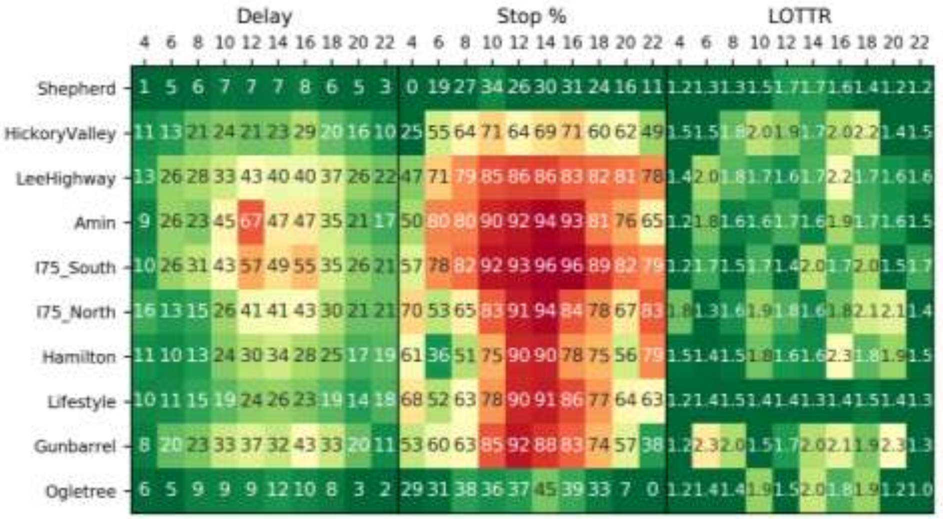


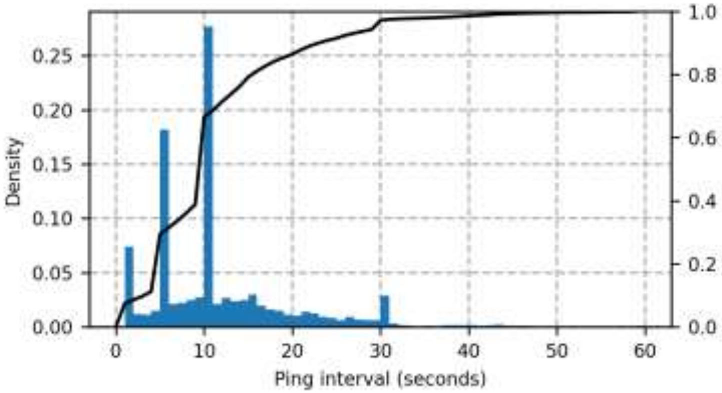
Shallowford Road Trajectory Data Analysis: High Arrival on Red around Noon

- Analysis performed using three months of multi-source trajectory data
- Scalable
- Built on previous effort using Ohio data
- Base Statistics:

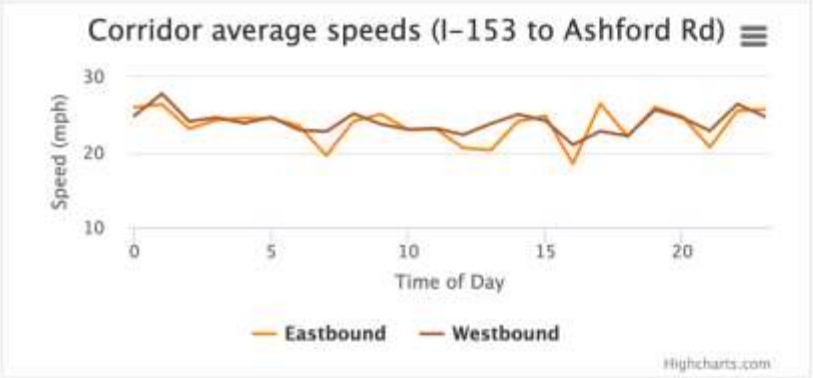
Eastbound
Free Flow Travel Time = 4.6 min.
AM Peak (0700-0800) = 6 min.
PM Peak (1700-1800) = 8.5 min.

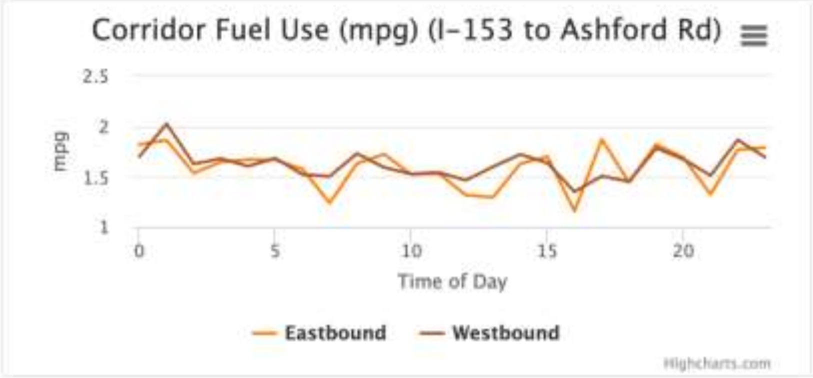
Westbound
Free Flow Travel Time = 4.2 min.
AM Peak (0730-0830) = 6.2 min.
PM Peak (1700-1800) = 7.3 min.



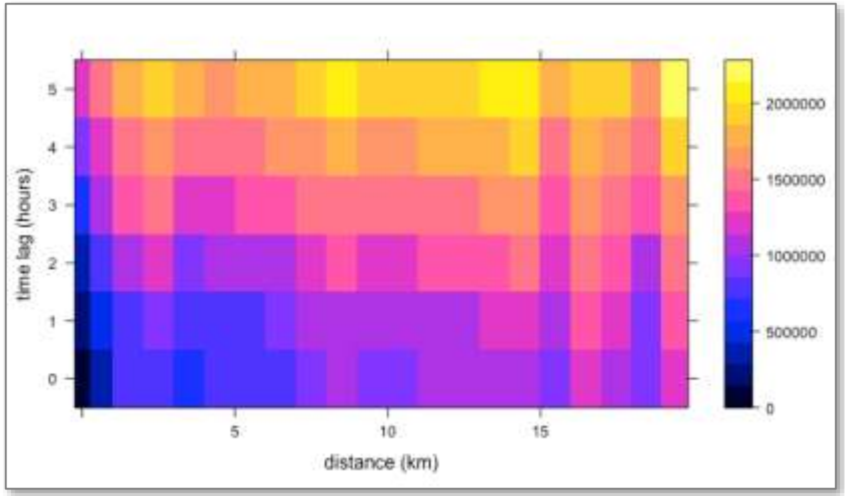


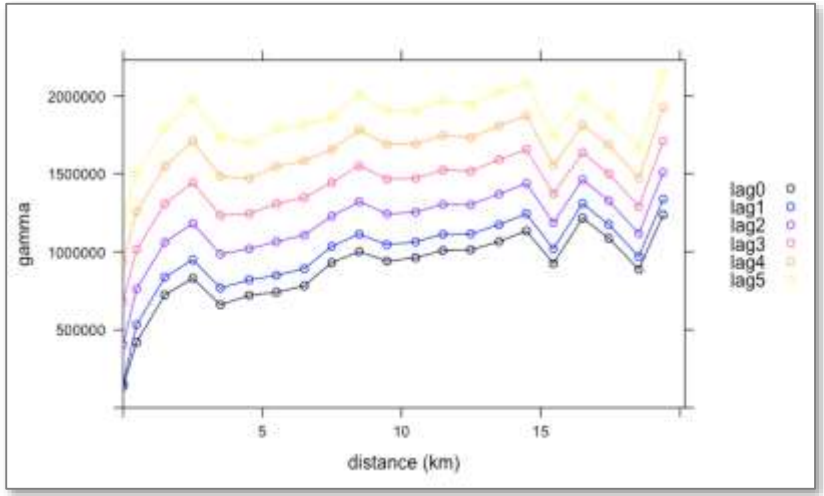
Travel time, speed and fuel use from RDS data





Analysis indicates the spatial relationship of the extent of congestion (about 15 km) and length of time (around 2 hours) that the congestion lasts in the region.





Space-Time matrix of variance and variogram from RDS data

Real-time Regional Speed and Energy

TomTom Data

- Historical probe volume counts and speeds at road segments
- Near real-time speeds

Volume Estimation

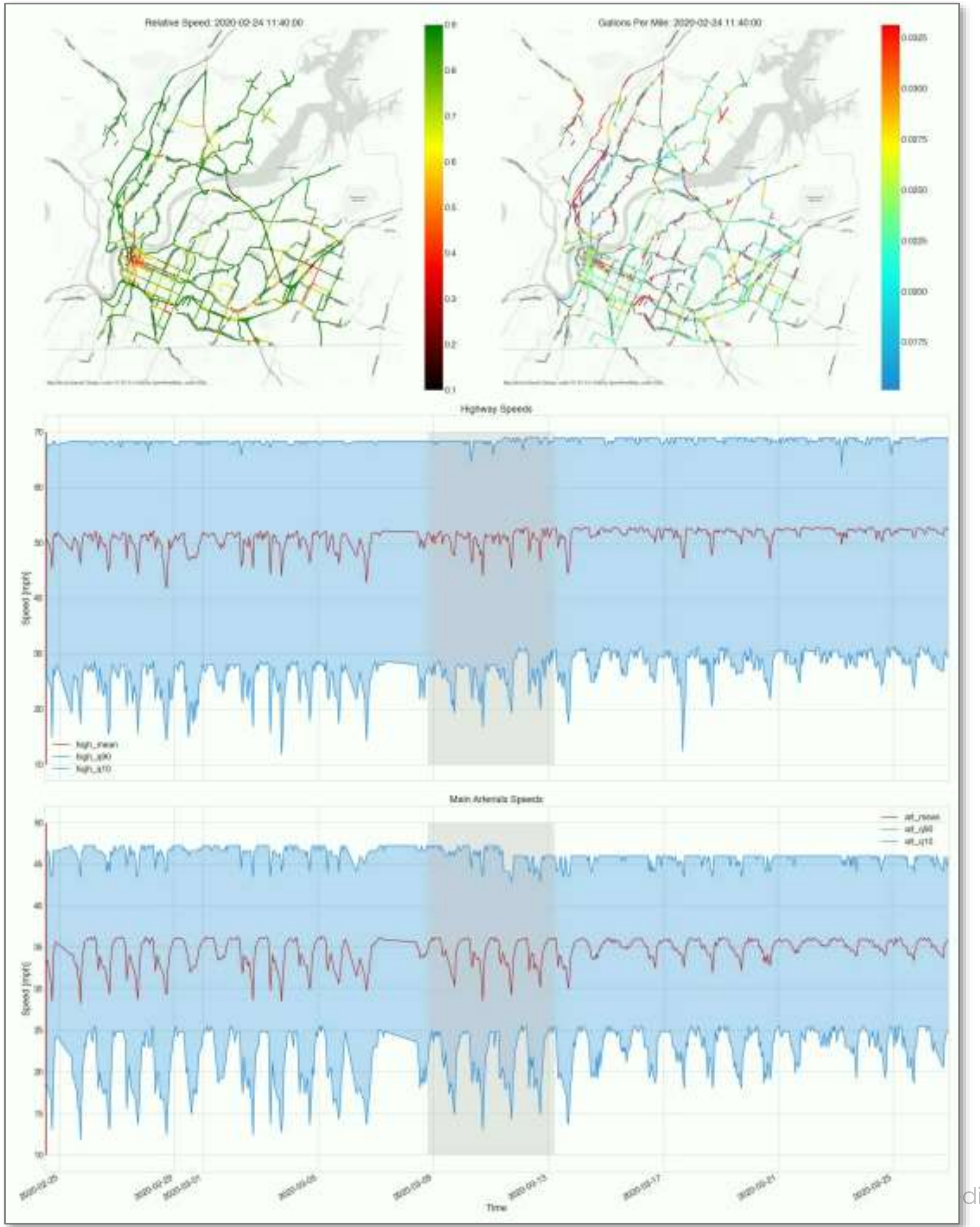
- Machine learning to estimate volume given weather, time of day, day of week, road type, speeds, probe counts

Map Matching

- Match TomTom road network to TPO network for network consistency
- Grid partitioning networks by grids decreased computation time from 2 weeks to 2 hours

Energy Estimate

- Use of machine learning to estimate energy consumption on each road segment
- Estimate is derived from RouteE algorithm



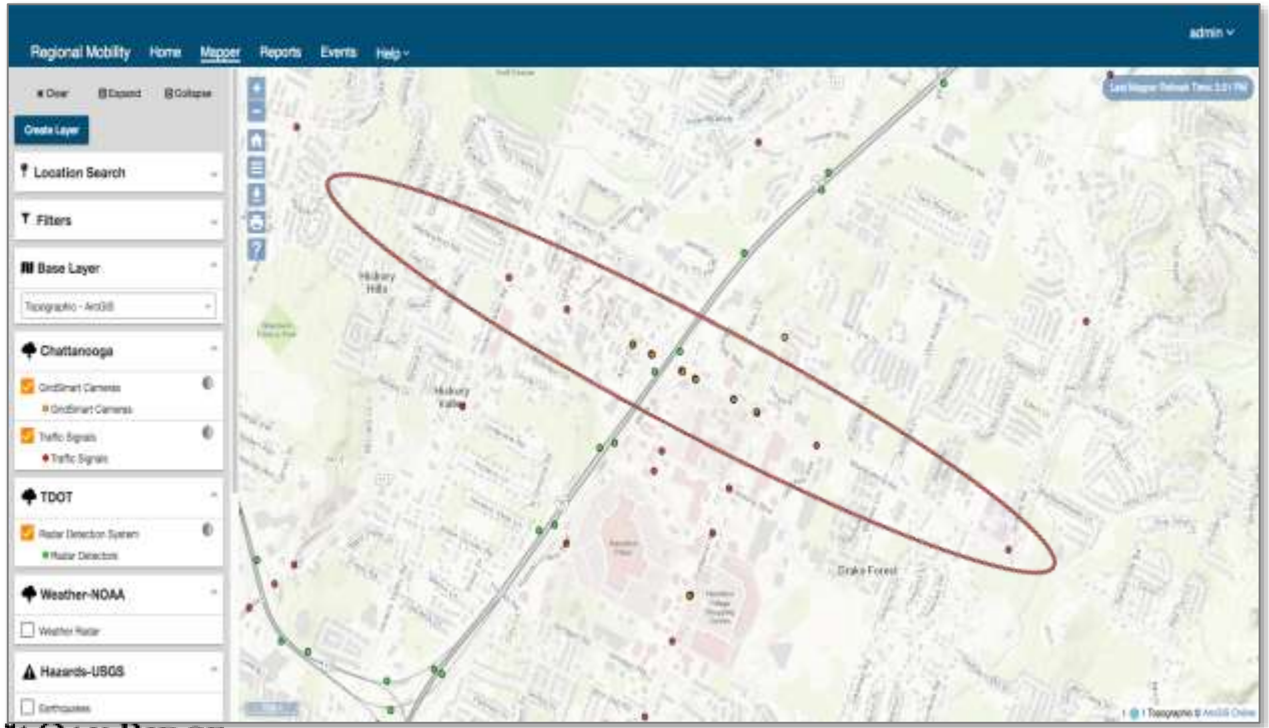
Accomplishment – Modeling & Simulation

Candidate Corridor for Simulation

<u>Shallowford Road Arterial</u> identified for analysis and optimization based on data availability and priority discussion with City of Chattanooga, TN

- GridSmart Cameras
- Signalized Intersections with timing information
- Radar Detection Systems
- Traffic Incidents

Spatial scope: Signalized Arterial



Temporal scope: frequency of adjusting signal settings	Signal settings optimization- standard techniques	Performance -based optimization	Near real-time optimization
5-15 minutes	Yes	No	Yes
Hourly	Yes	No	Yes
Time-of-day	Yes	Flexible	No
Daily	Yes	Yes	No
Weekly	Yes	Yes	No

Simulation for Shallowford Road

- Three newly developed traffic signal control methods to the 8-intersection traffic corridor in Chattanooga:
  - Linear Feedback Control, Linear Quadratic Regulator (LQR) Control, and Bilinear Control
- Evaluated in a microscopic traffic simulation environment, VISSIM

Existing pre-timed control

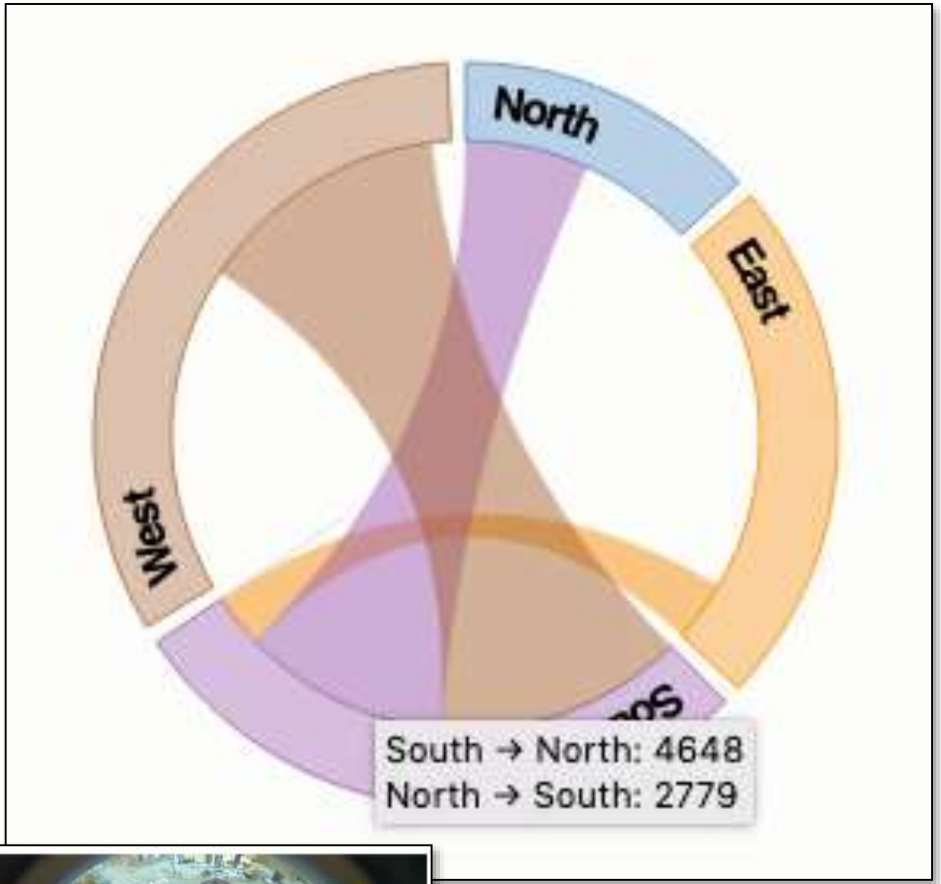
Bilinear control

Traffic control strategies

- Signal timings and optimization
  - In cyber-physical implementation
- Responsive and adaptive traffic signal control
  - In cyber-physical implementation
- Other strategies that CTwin can facilitate:
  - Speed harmonization
  - Real-time Information-Sharing for Traffic Coordination
  - Ramp Metering and Junction Controls
  - Part-time shoulder use
  - Other strategies: dedicated freight lanes, flow restrictions, parking restrictions

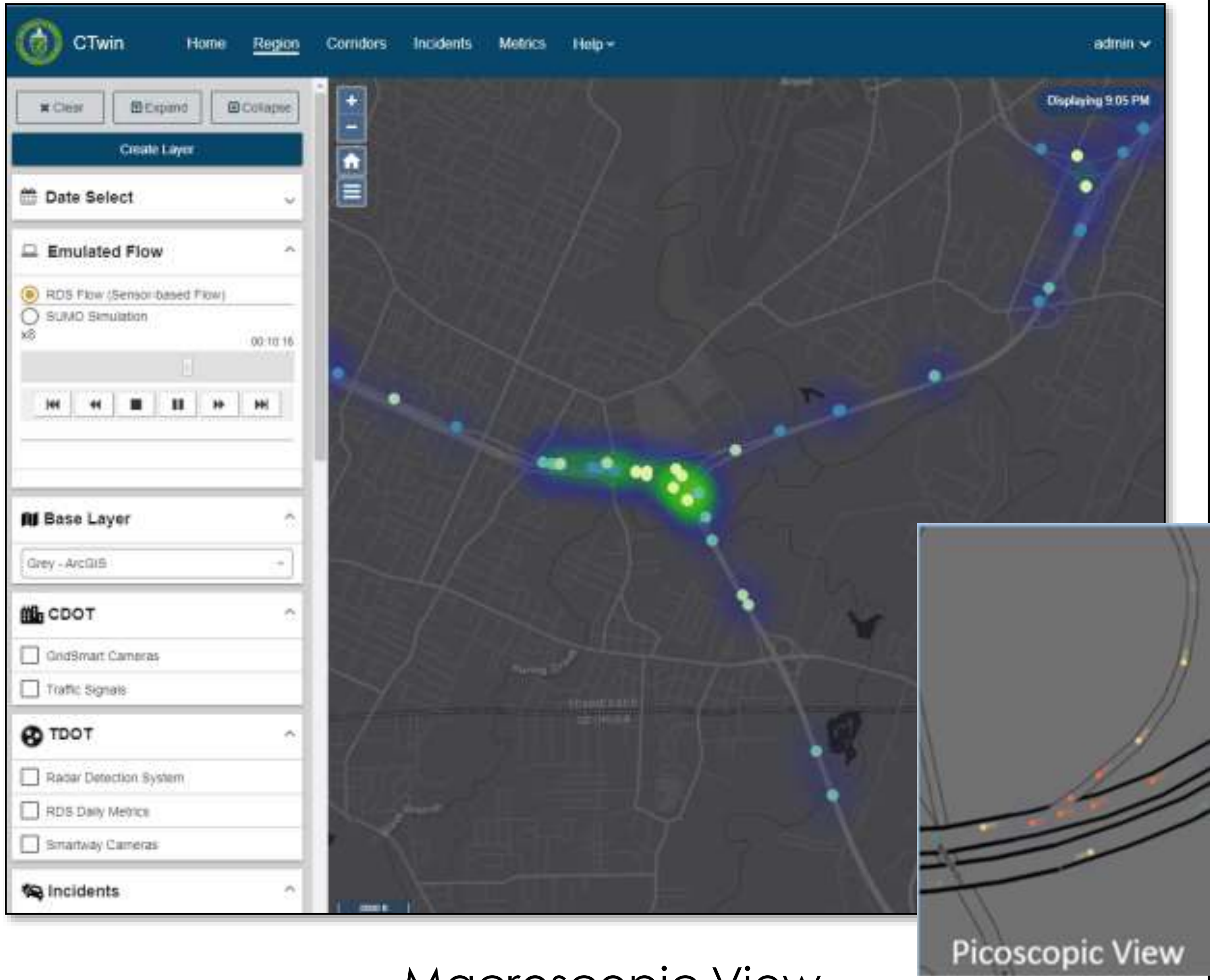
Accomplishment – Data Science

GridSmart data – Novel Turn Movement Visualization

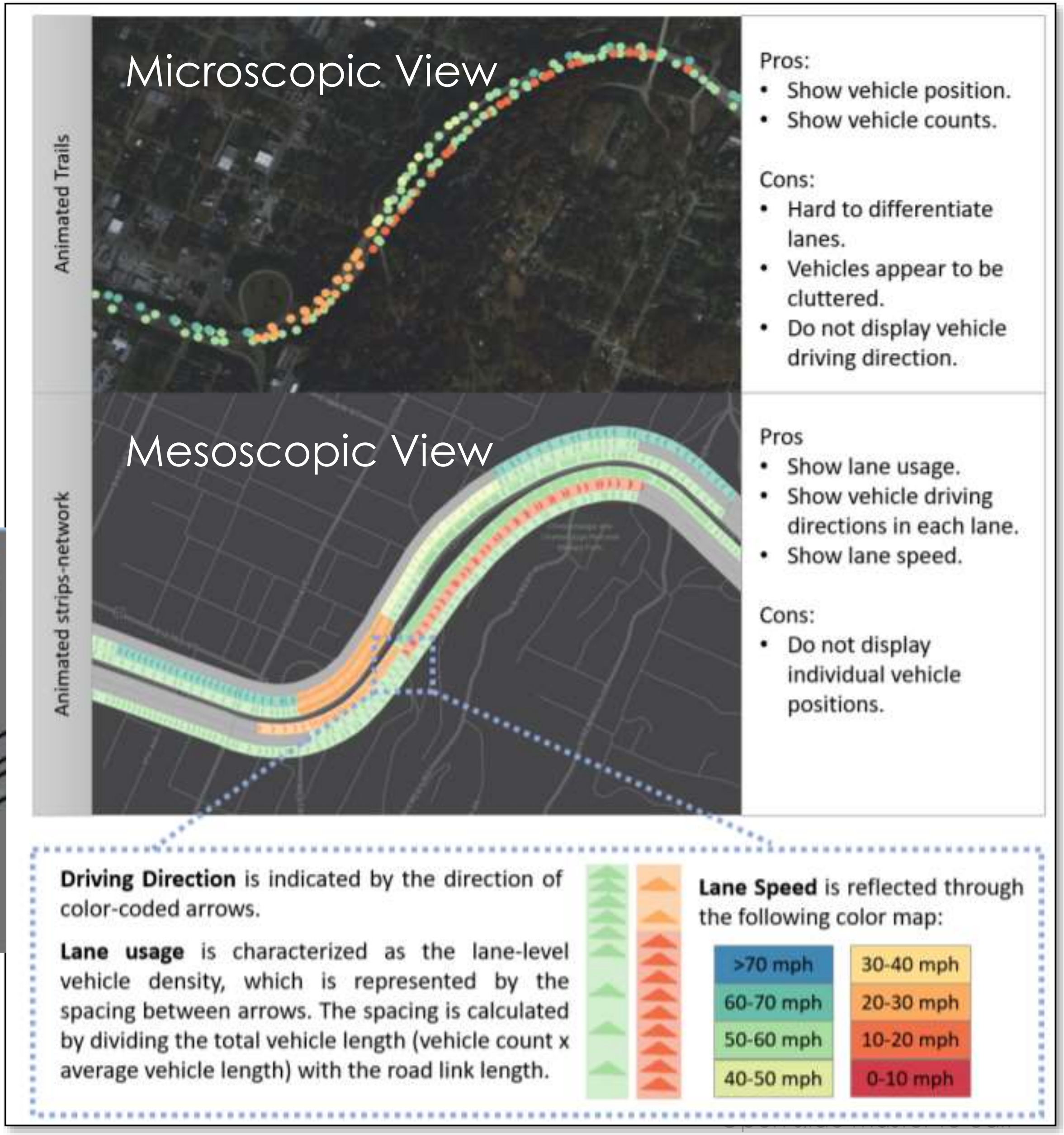


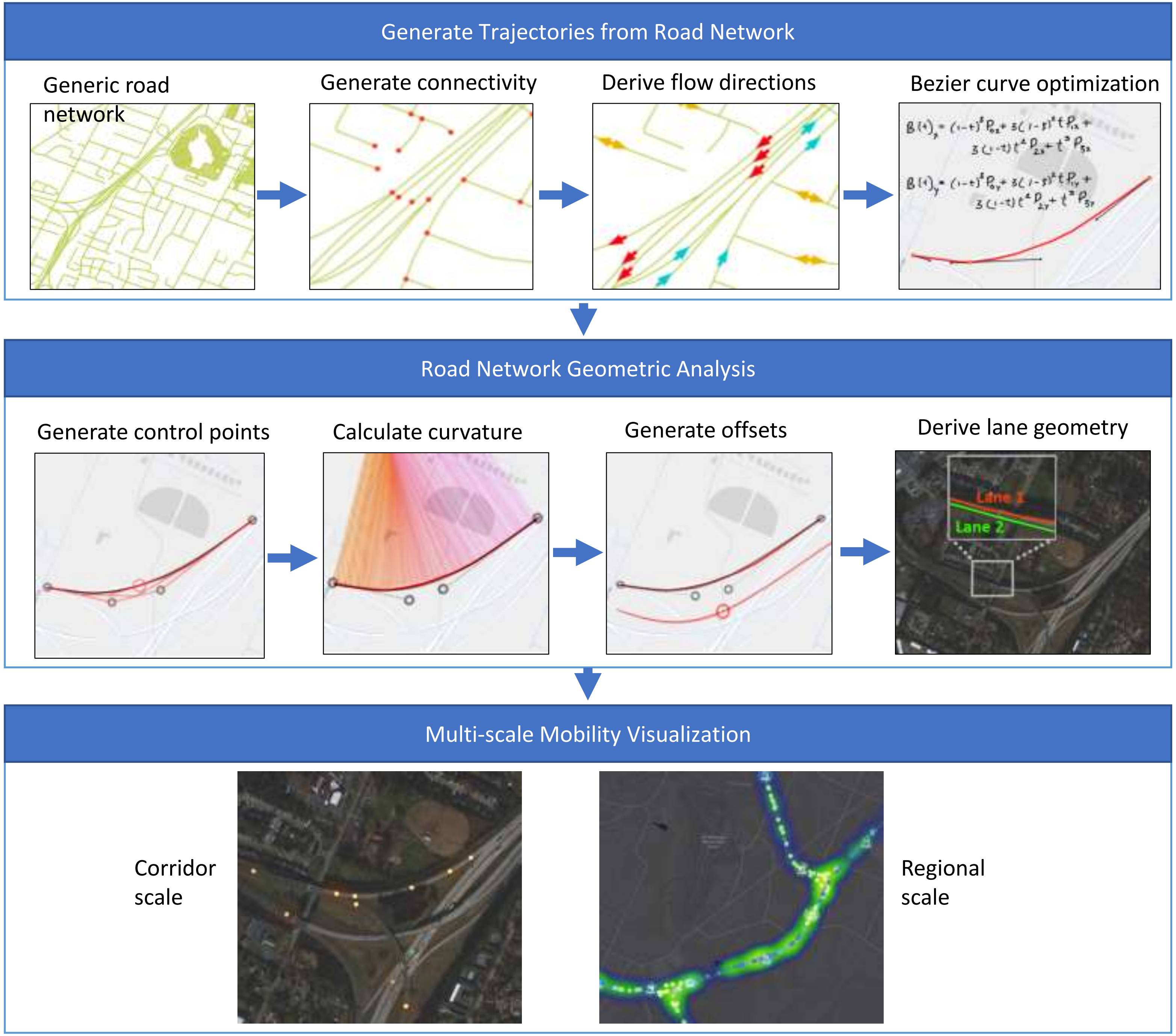
- New visualization of flow
- Automated Site Configuration Analysis
  - Do not use consistent phase numbering
  - Configurations have changed over time
- Implemented site history for any given date
- Easy-to-digest output that lists all phases and turns example : {'approach': 'Eastbound', 'turn': 'Straight'}

Emulated Flow from RDS Data



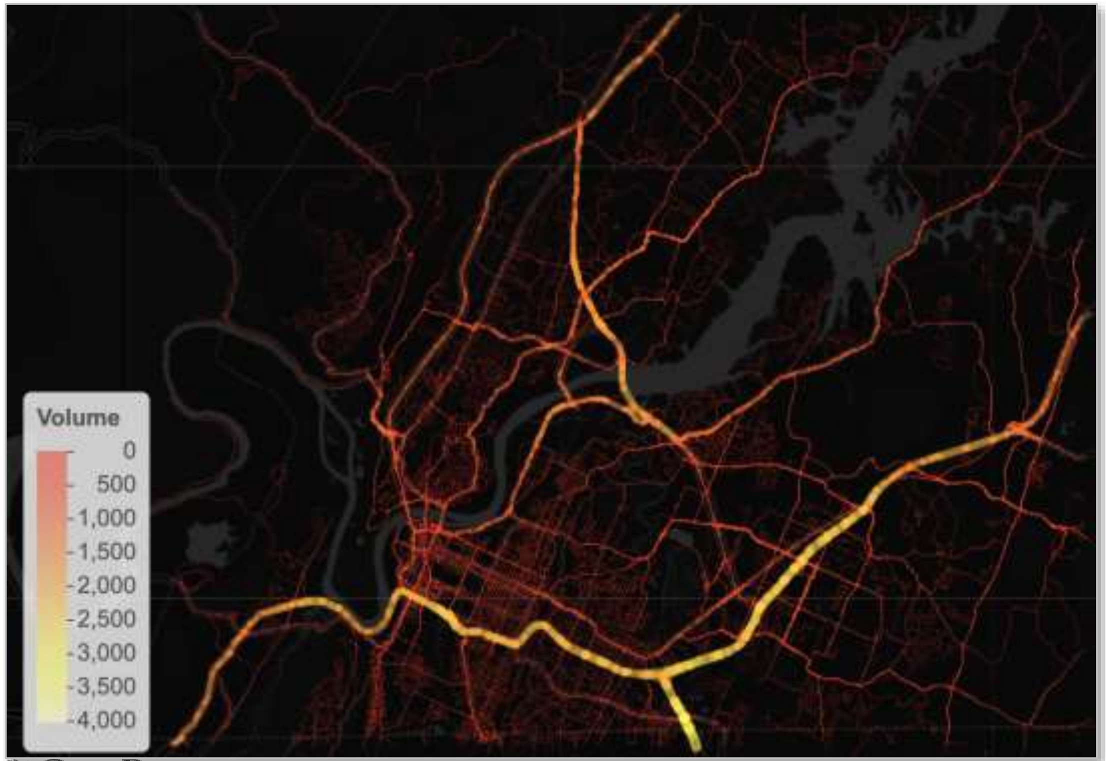
Macroscopic View



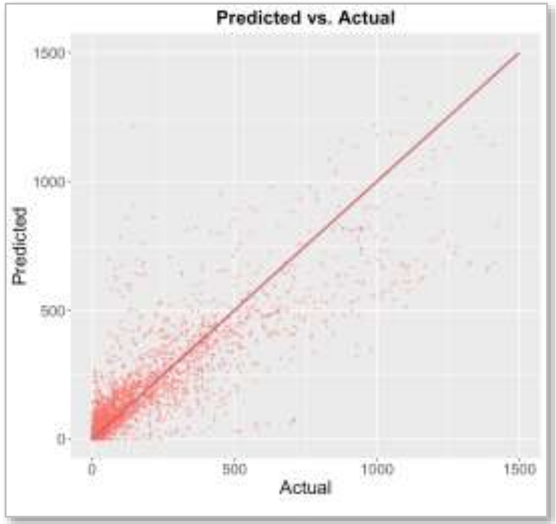

Generate Trajectories from Road Network
Generic road network
Generate connectivity
Derive flow directions
Bezier curve optimization
Road Network Geometric Analysis
Generate control points
Calculate curvature
Generate offsets
Derive lane geometry
Lane 1
Lane 2
Multi-scale Mobility Visualization
Corridor scale
Regional scale

Accurate Traffic Volume Estimation, including Non-Interstate Traffic and Special Events

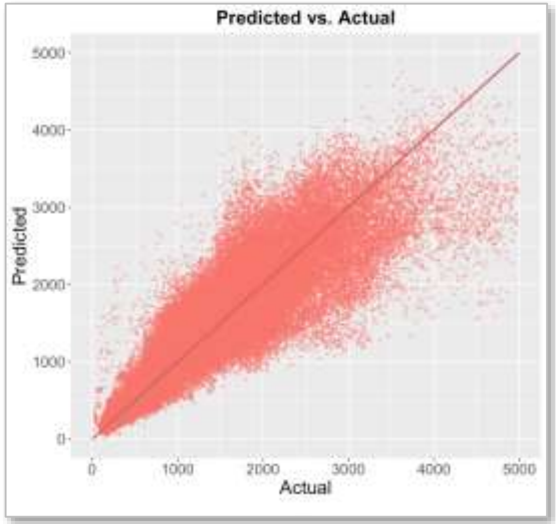
	R-squared	MAE (vh/hour)
Interstates	0.80	284
Non-interstates	0.77	81

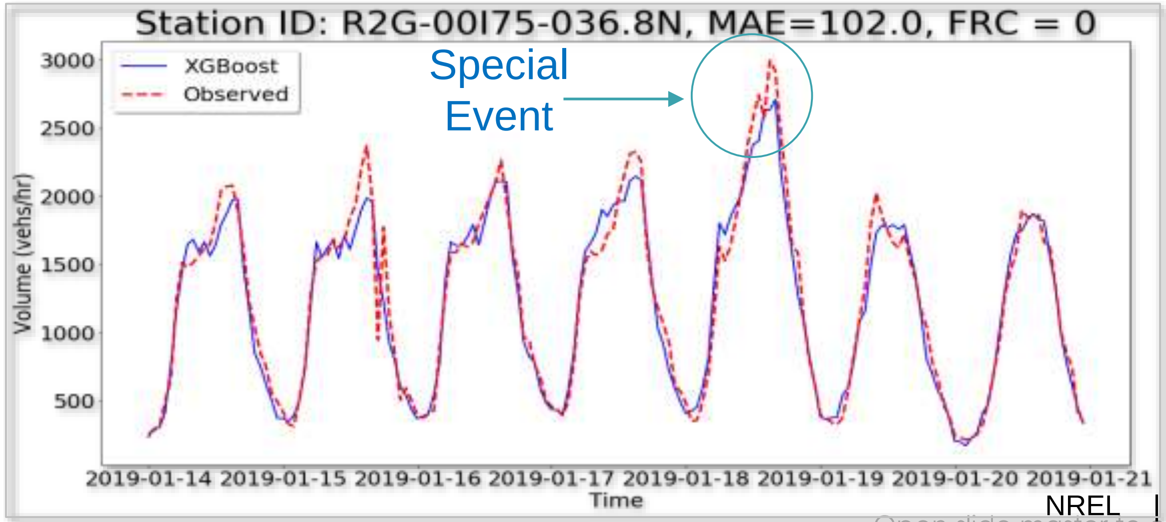


Non-interstates



Interstates





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Identify Freight with Video Feed Analysis

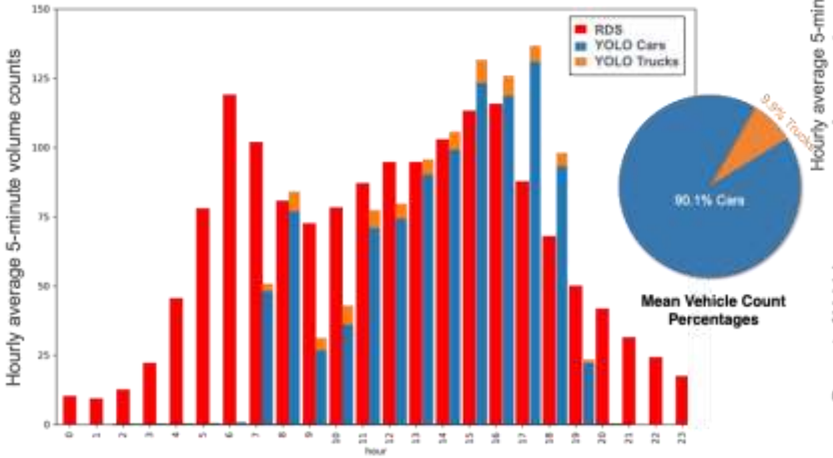
You-Only-Look-Once (YOLO V3) deep image processing network to identify cars and trucks from low-resolution traffic cameras.

Identifying trucks vs passenger vehicles is important for traffic mitigation strategies and energy calculations

Results

- Study performed over 2-week period in late October 2019
  - I-75 and Shallowford Road
- 10% Trucks and 90% Cars on average
- Performance degrades during rain events and with rotating camera angles
- Higher resolution video feed obtained; detection performance to be evaluated

Average hourly counts over study period (10/16/2019-11/02/2019)



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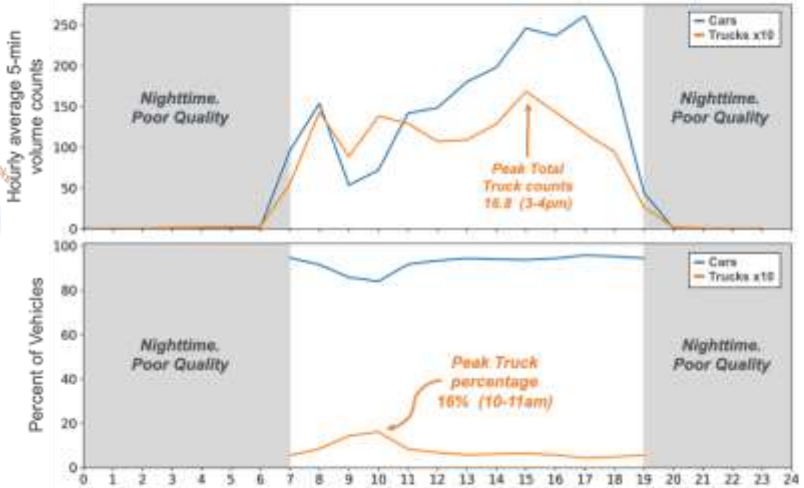

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Ac
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SIEMENS m60
RING TIMERS AS:00 B:1:1:1
RING 1 RING 2
PHS..12345678 90123456
PASS 4 PASS 4
MAXI 20 MAXI 20
COMM STATUS
SETTINGS....: ..PORT 2.. ..PORT 3..
19200,8N1 1200,8N1
STATUS.....: ON LINE OnLn NoSys
CARRIER.....: INACTIVE INACTIVE
TRANSMITTING:
RECEIVING...: DATA VALID
F1 F2 F3 F4 F5 HELP
A D 1 2 3
B E 4 5 6
C F 7 8 9
ESC 0 ENTER
PREV NEXT
NO YES
ON
AUX
OFF
FSK
USB
3 AMP
A
B
C
D OPT
AC 24 VDC

Logical flow of cyber-physical interface with controllers

Hardware in the loop testing

- **Ingest Traffic data** — Configure mapping of IP addresses between CDOT and ORNL to receive SPaT data
- **Derive Metrics** — Setup computing of ATPSM from data streams for each intersection
- **M&/Data Sc provides new values** — New values should be available from M&S and other control studies
- **Test setting values in lab env** — Develop software to send new values to controller

Vetting, deployment, and measurement

- **Vet approach with experts** — Evaluate the impact of new timings with Airton Kohls
- **Vet approach with CDOT** — Evaluate the strategy with Tommy and Cindy
- **Test on one intersection** — Test program-based control to change one intersection; observe and measure
- **Test along corridor** — Test program-based control to change signals along the whole corridor; observe and measure

Phased strategy for signal control along Shallowford Rd

Using existing vendor interface

- Results from M&S available - Optimized timings tested in simulations **showed 18% energy reduction**
  - Formulated the optimal signal timing problems for NEMA controllers as a nonlinear programming problem that can be solved by IPOPT
- Set new values using existing vendor software abstraction
  - Control ran for 3.5 hours one afternoon in February
- Some changes in CDOT deployment
- Positive feedback from CDOT

Programmatic interface with controllers

- Connect with the signal controllers using code
- Set new values using output from M&S and data science
- m60 controllers can be in 'free' or 'coordinated' modes
- After Hardware-in-loop testing, ran initial test in Chattanooga:
  - **Successfully changed minimum green time on all signals along Shallowford Rd**
- Can change phases and splits while keeping cycle length constant
  - Additional testing and vetting in progress

Prior AMR Comments/Questions

Main comments

- Reviewer 1: collaboration between ORNL/NREL not clear; are payments needed to get the real-time data
  - Individual lab milestones listed separately
  - Data obtained through collaborations; only ATRI data purchased
- Reviewer 2: 20% energy savings optimistic; team has not met with computational people yet; research plan needed to overcome barriers
  - About 18% energy savings showed in simulation; measurement in field to be conducted
  - Team is comprised of researchers with HPC experience
- Reviewer 3: Team has not put all pieces together; real-time feeds may be challenging; HPC needed to solve the simulation challenges
  - Hopefully, in this presentation, the individual efforts and the scale up is showing
  - HPC and data science strategies are employed in a significant way. The accomplishments are sectioned accordingly

Thank you for the feedback!

Collaboration and Coordination

- City of Chattanooga
- Tennessee Department of Transportation
- University of Tennessee at Chattanooga *(M. Sartipi)*
- University of Tennessee, Knoxville *(S. Chakraborty, A. Kohls)*
- Wayne State University *(Steve Remias)*
- TomTom *(Industry collaborator)*

Remaining Challenges and Barriers

- Data access and ingestion continues to be challenging
  - Primarily because of proprietary systems
  - Data partners extremely forthcoming
- Freight data availability is an issue
  - Data science techniques employed
- For cyber physical control
  - Measurement using GridSmart, SPaT, and TomTom have discrepancies
  - Graceful degradation on faults is needed
  - Spillover effects of optimization on neighboring roads calls for expanding across larger region

Proposed Future Research

FY2020

- Real-time RDS ingestion and data analysis
- Work though the controller to implement a full cyber-physical experiment on Shallowford Rd
- Develop real-time traffic volume estimation
- Energy estimates model refinement using random forest (ML) models, including freight model
- HPC-enabled calibration and validation of mesoscopic simulations
- Investigate utilization of wejo connected vehicle waypoint data
- Automate current manual ATSPM process for regional evaluation

FY2021

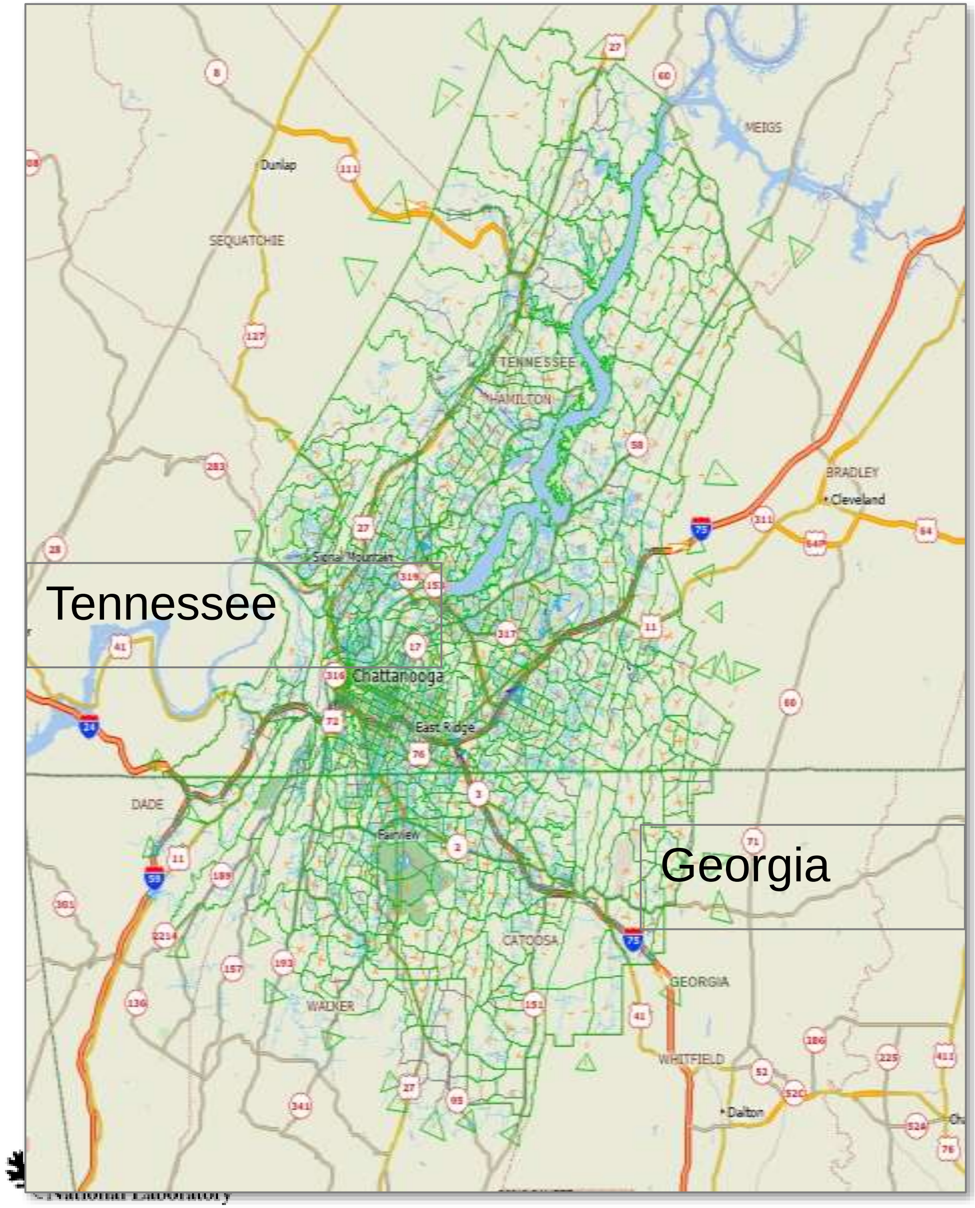
- Extend into Georgia and integrate new data sources in CTwin and demonstrate portability to other regions
- Improve upon and scale up the control algorithms, mechanisms and strategy within the city
- Data science for freight insights and control
- Advance volume estimation to real-time, use real-time connected vehicle data
- Streamline and scale vehicle classification from video analysis
- Data science for energy, sensor health, safety and TMC operations

Summary

- **Key target:** Achieve 20% energy savings at the regional level.
  - Highways, linked arterials and freight present an opportunity at the systems level.
  - Framework to be transferable and applicable to other regions.
- **Near real-time situational awareness:** Create a 'Digital Twin' of an entire metropolitan region providing real-time situational awareness for analysis of the entire region
  - Requires data processing at scale across a variety of data sources
  - Demands large scalable computing approaches
- **Near real-time control of traffic infrastructure and vehicles:** Digital Twin forms the basis of a cyber physical control system for control of the highway/road infrastructure and connected vehicles in the ecosystem
  - Fast simulation and algorithmic decisions
  - Orchestration of computational resources on High-Performance Computing resources
  - Data science and artificial intelligence/ machine learning approaches

Back-Up Slides

Chattanooga-Hamilton County



- Study region boundary defined
- Only TN side
- 1,037 TAZs for TPO region
- Complete street network with centroid connector notional links to represent within TAZ flows
- Origin-destination TAZ vehicle flow averages (at AM peak, PM peak, and off-peak times) for 2014 and projected for 2045 (passenger, single-unit, and multi-unit trucks)

Data	Acquired	Source
Road network	Yes	TPO, Navteq
Historic traffic flows	Yes	TDOT, GDOT
Historic radar data	Yes	TDOT, GDOT
Incident Data	Yes	TITAN, GDOT
Origin-Destination Data	Yes	TPO

Emulated Flow from RDS Data