CTwin – The Chattanooga Digital Twin

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Knoxville, TN

‘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

Goal: 20% energy savings in mobility for the region

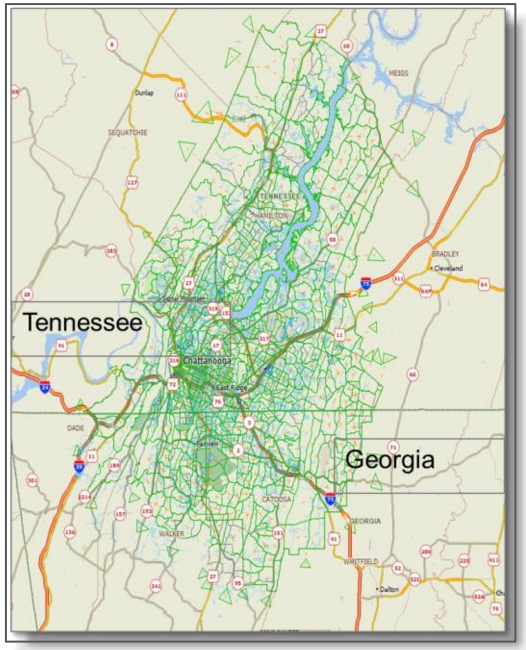
Significant opportunity as a live testbed for connected fleets, CAVs, V2I, and active control

Real-Time Data

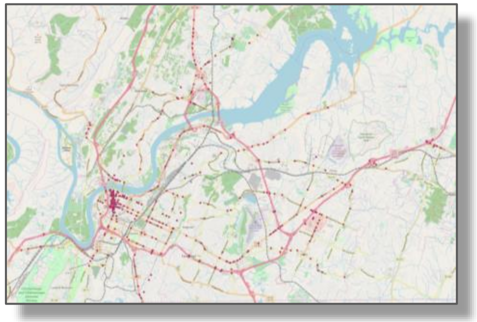
Chattanooga Department of Transportation,

Tennessee Department of Transportation,

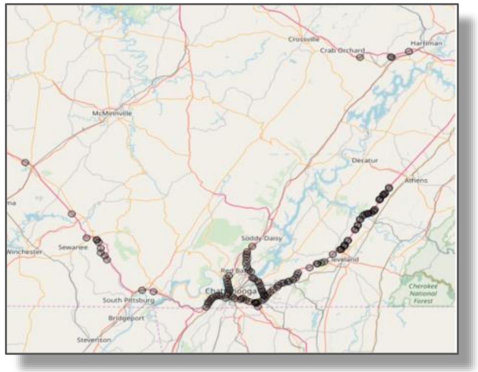
MPO, GA-DOT, Titan, INRIX, TomTom, HERE, ATRI, etc.



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, Video

500+ primary data streams from 7 proprietary vendor systems across 3 institutions
Additional 40+ distinct secondary data layers

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
- National Weather Service
- USGS hazards

- Probe data – ATRI, TomTom, INRIX
- Freight data
  - Data issues in automated classification from TDOT sensors
- Incident data
  - Some lag in availability
  - Multiple systems – 911 TITAN, GEARS, DPS, WAZE
- TNMap – TN GIS services
  - Police, Fire, Schools, Hospitals

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

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

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CTwin Real-Time Situational Awareness tool

- Providing observability

CTwin

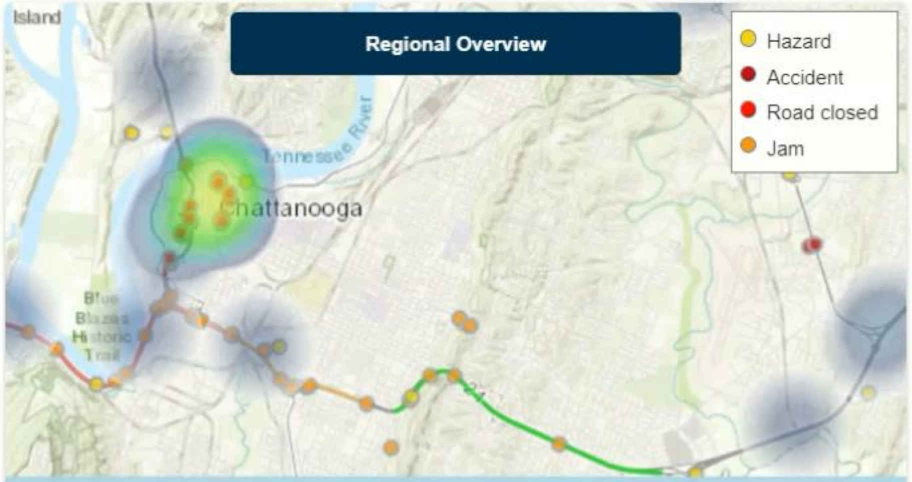
Home | Region | Corridors | Incidents | Metrics | Help | admin

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

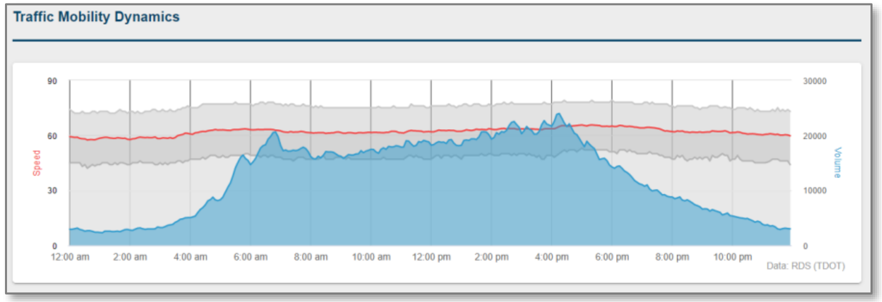
Go To System News

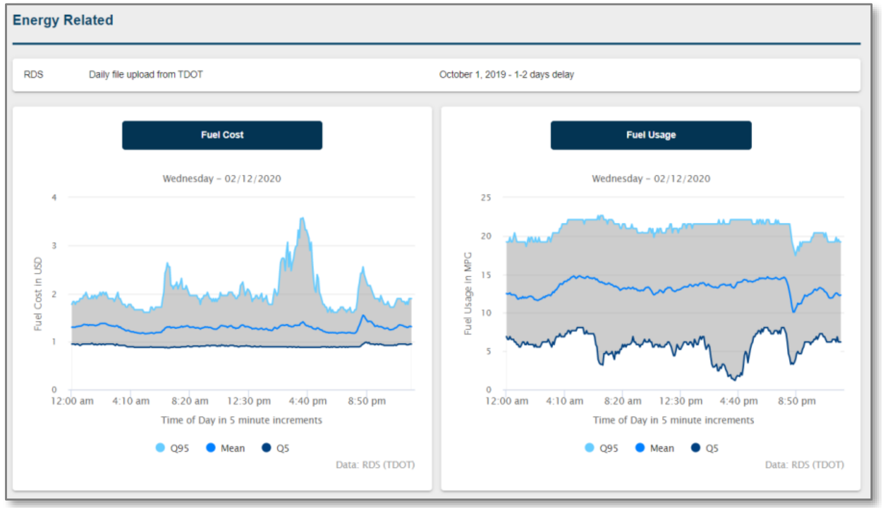
Metrics

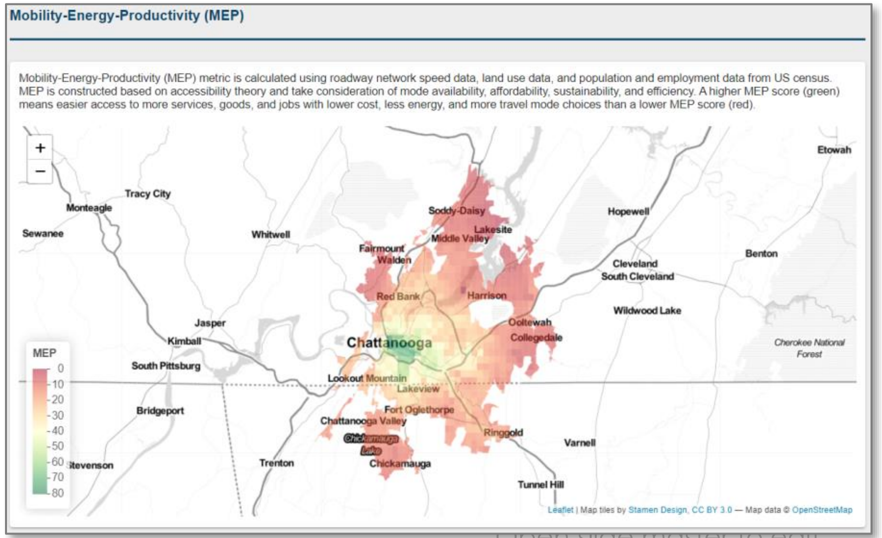
- Providing measurability

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])*







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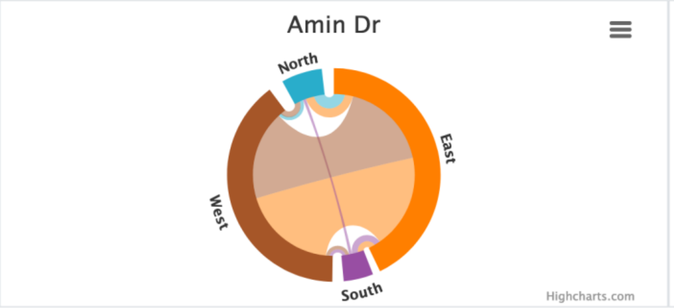
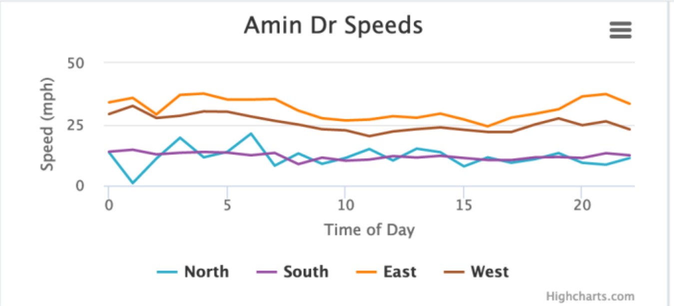
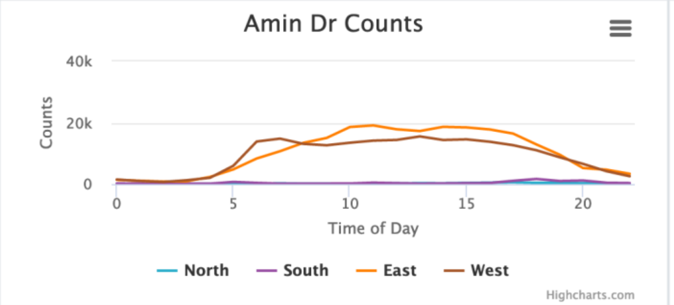
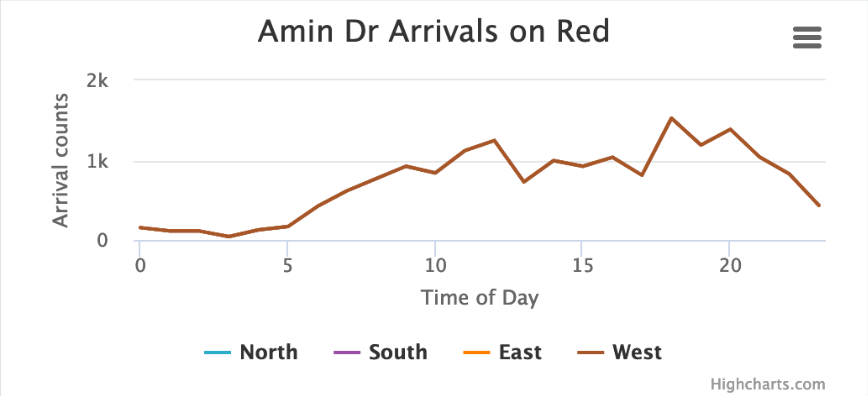
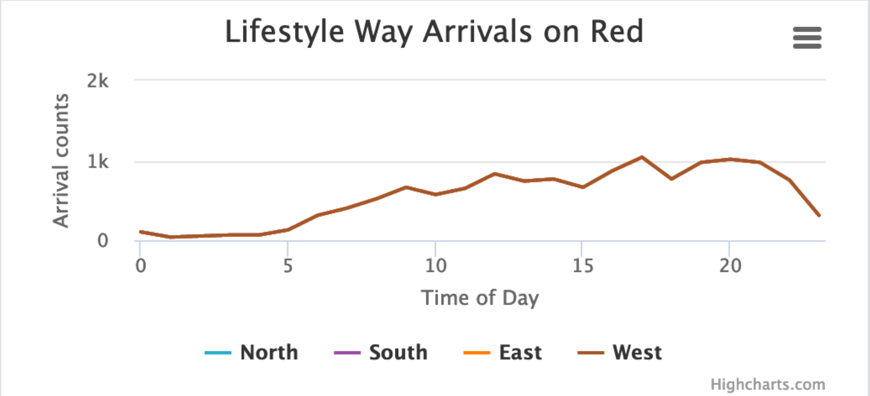
Automated Traffic Signal Performance Measures from Signal Phase and Timing (SPaT) Data

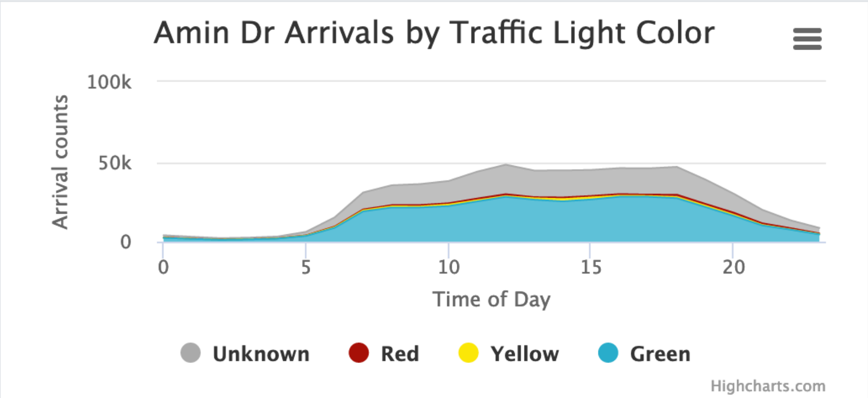


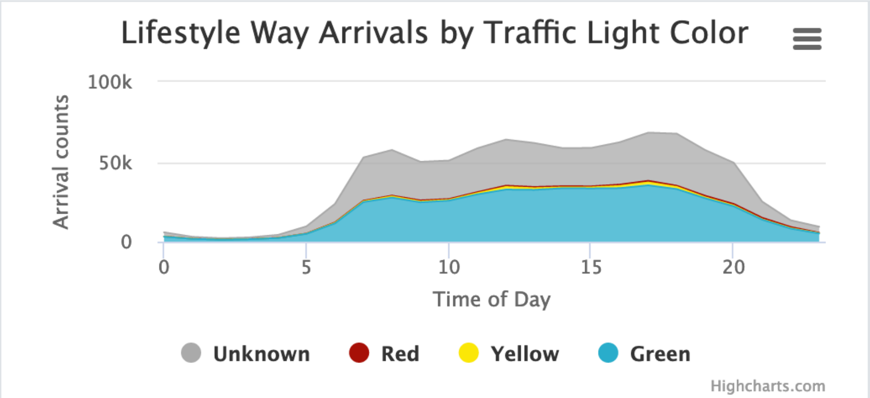








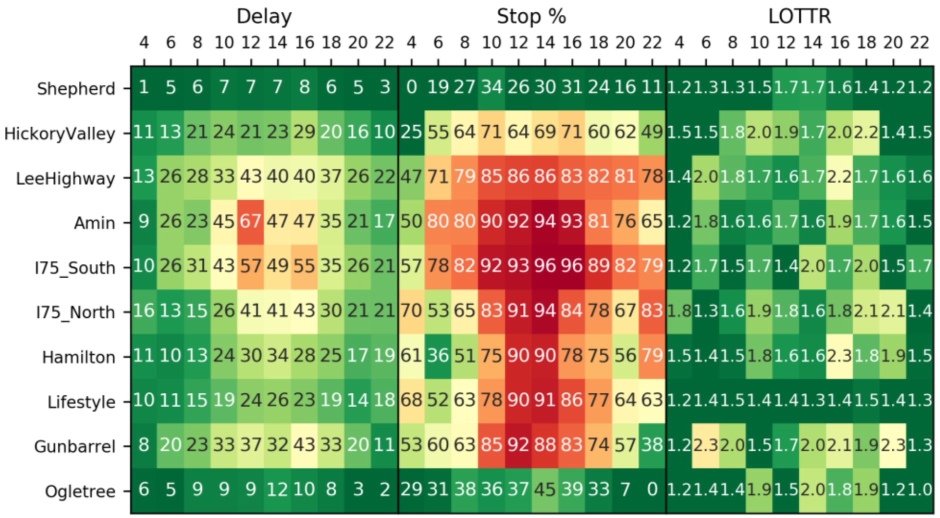




Data Science Highlights

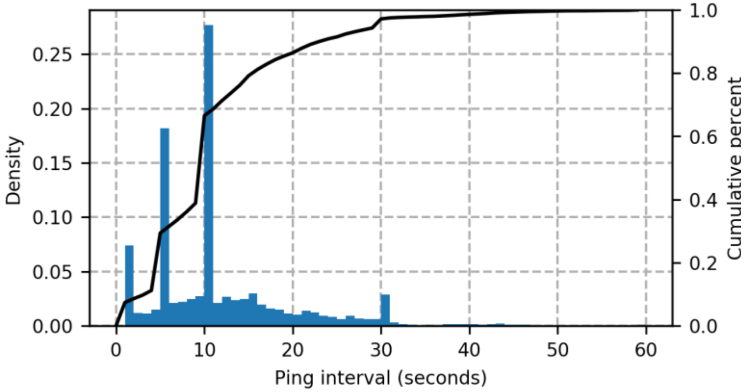
Shallowford Road Trajectory Data Analysis: High Arrival on Red around Noon

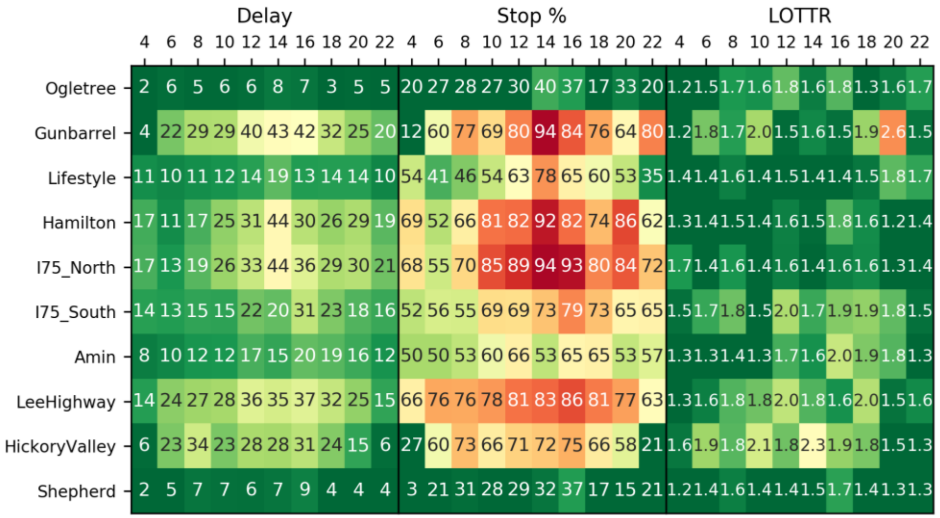
- Analysis performed using three months of multi-source trajectory data
- Scalable to other regions



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.





Real-time Regional Speed and Energy

TomTom Data

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

Volume Estimation

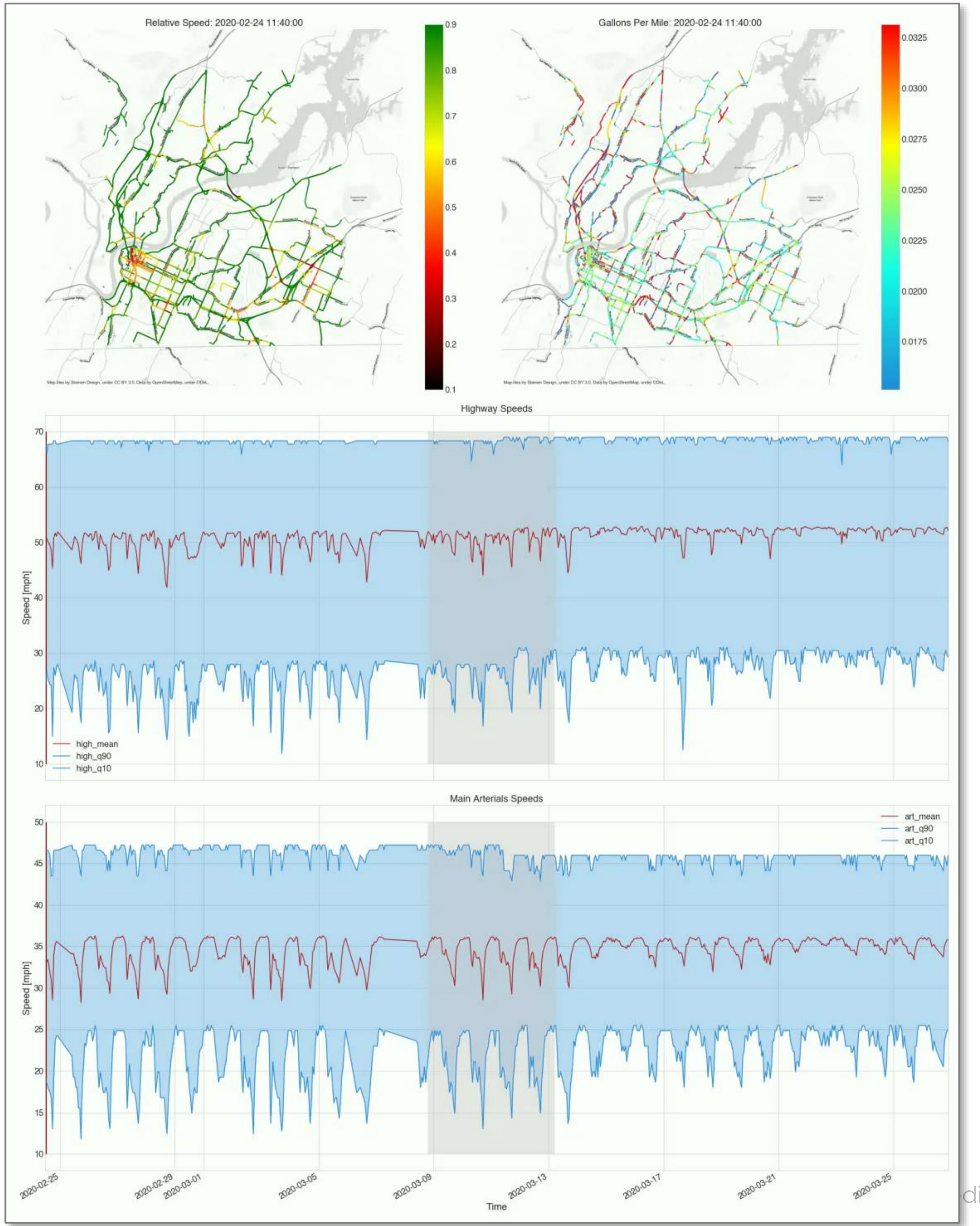
- Machine learning to estimate volume given weather, time of day, day of week, road type, speeds, probe counts

Map Matching

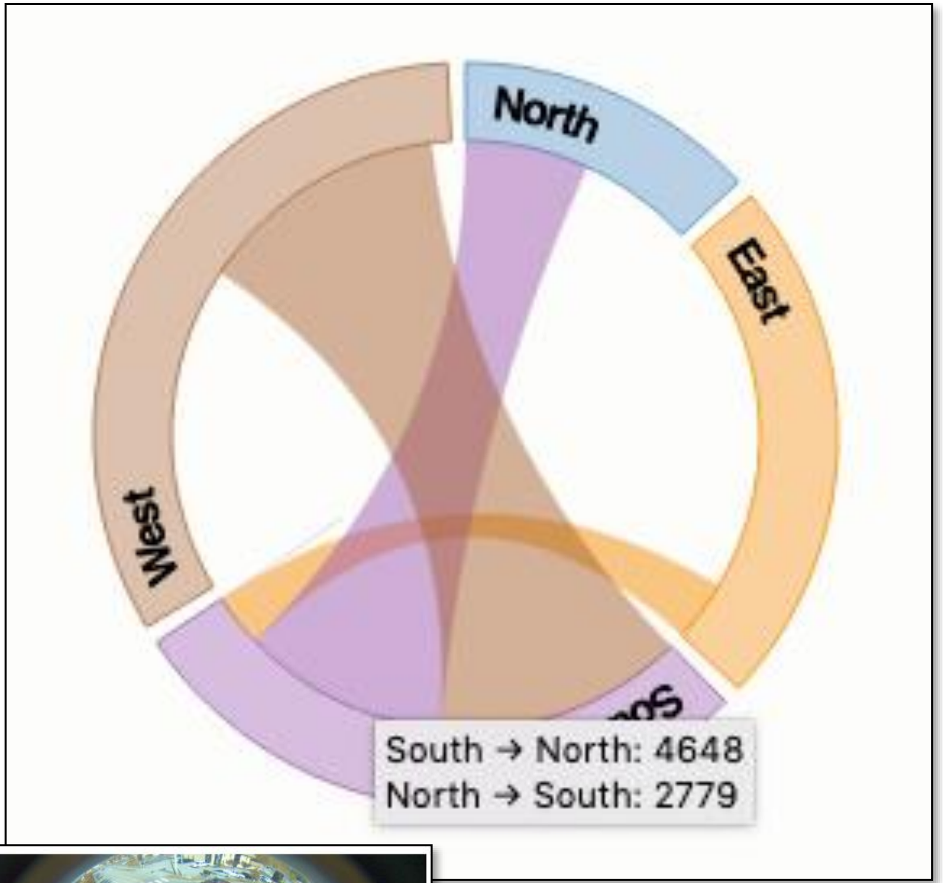
- Match TomTom road network to TPO network for network consistency
- Grid partitioning networks by grids decreased computation time from 2 weeks to 2 hours

Energy Estimate

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

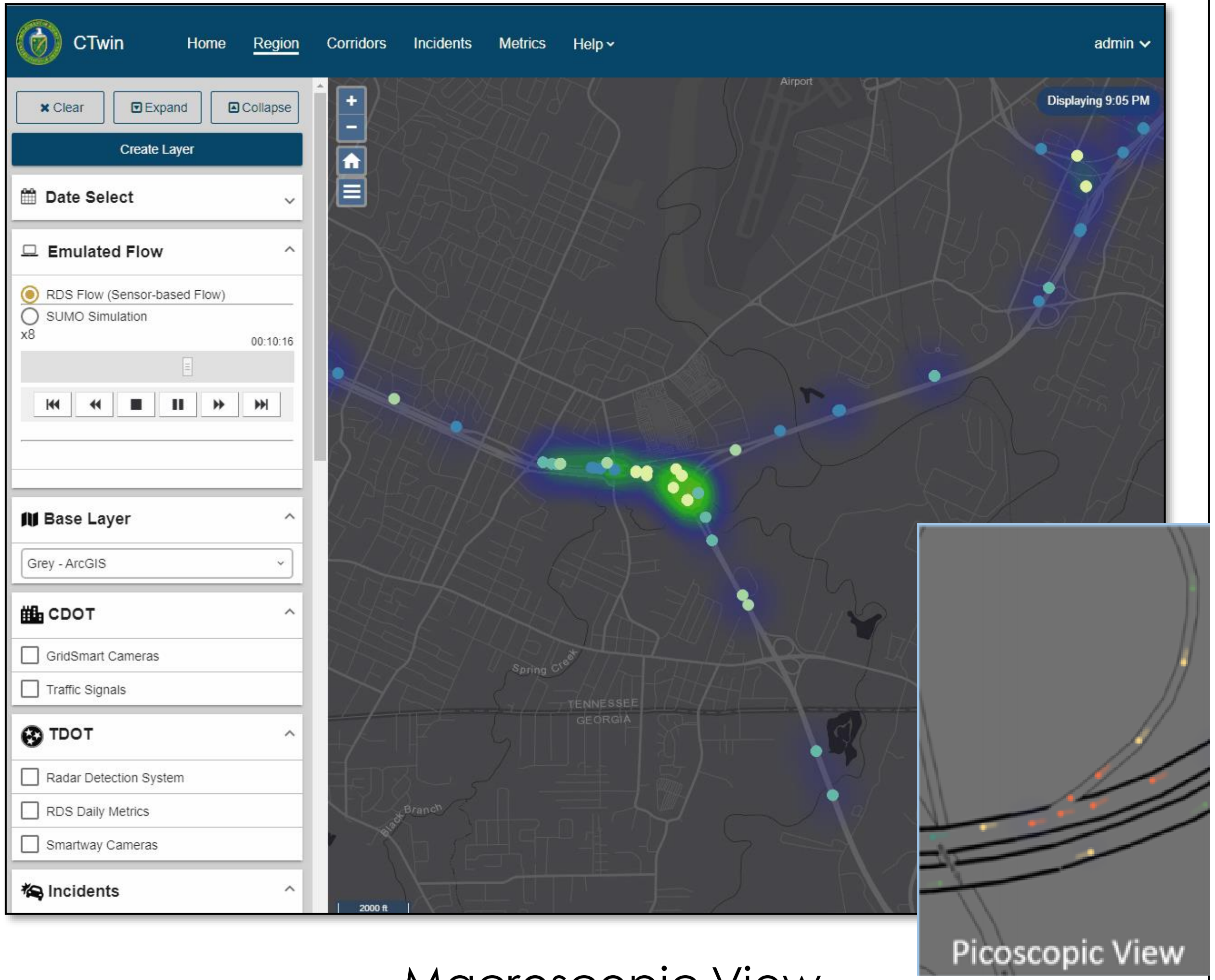


GridSmart data – Novel Turn Movement Visualization

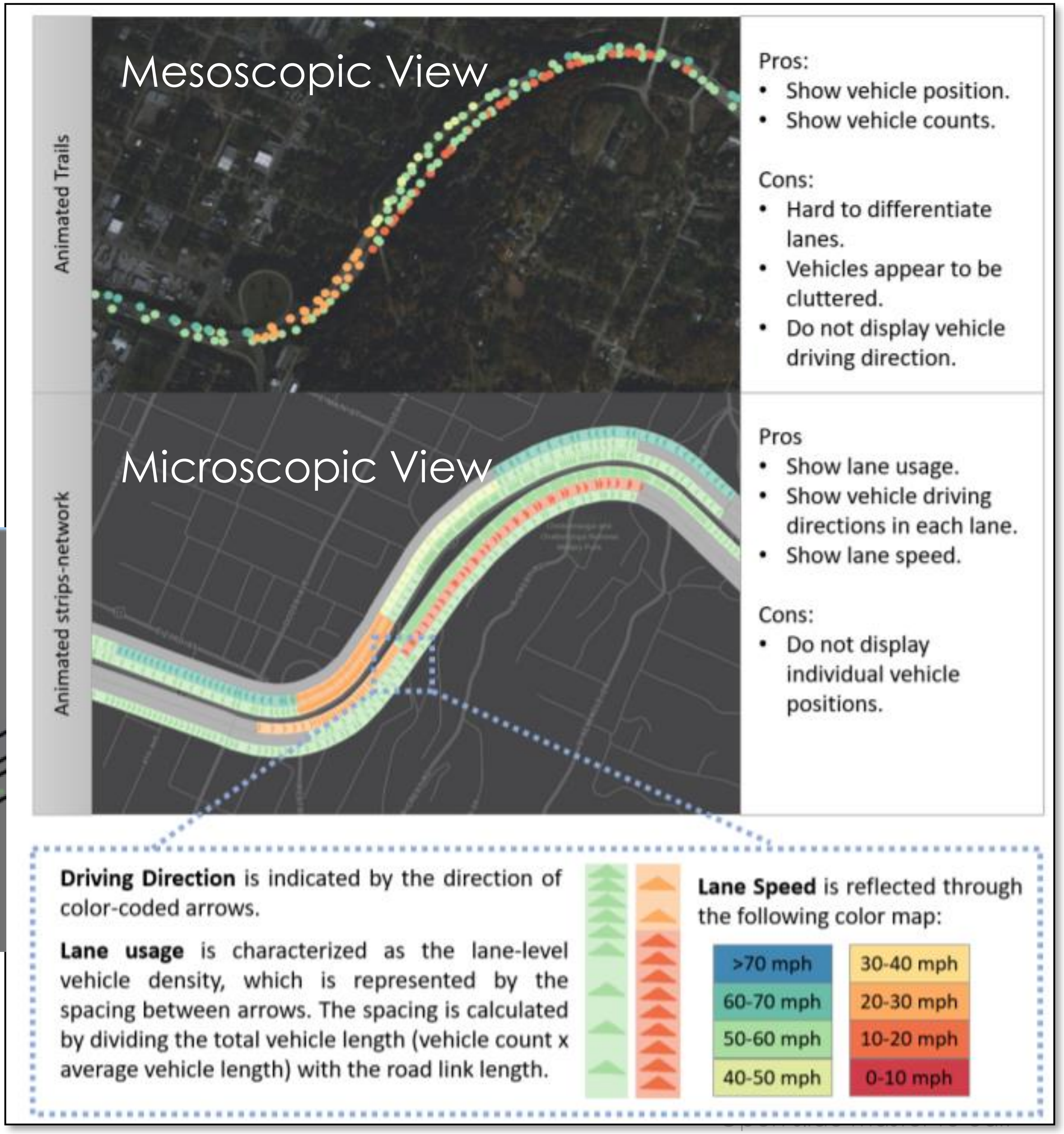


- New visualization of flow
- Automated Site Configuration Analysis
  - Do not use consistent phase numbering
  - Configurations have changed over time
- Implemented site history for any given date
- Easy-to-digest output that lists all phases and turns example : {'approach': 'Eastbound', 'turn': 'Straight'}

Emulated Flow from RDS Data



Macroscopic View



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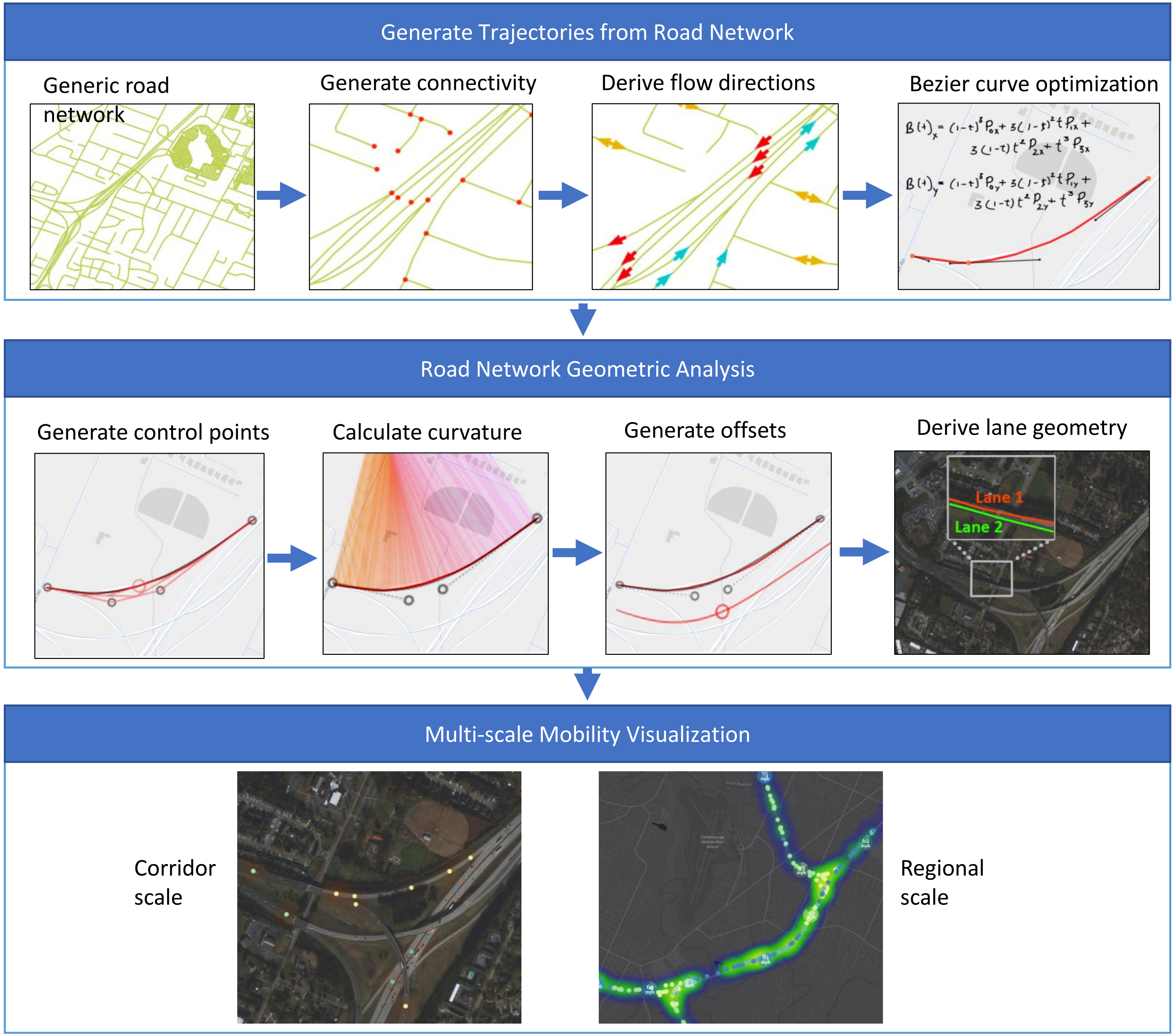


Generate Trajectories from Road Network
Generic road network
Generate connectivity
Derive flow directions
Bezier curve optimization
$B(t)_x = (1-t)^3 P_{0x} + 3(1-t)^2 t P_{1x} + 3(1-t) t^2 P_{2x} + t^3 P_{3x}$
$B(t)_y = (1-t)^3 P_{0y} + 3(1-t)^2 t P_{1y} + 3(1-t) t^2 P_{2y} + t^3 P_{3y}$
Road Network Geometric Analysis
Generate control points
Calculate curvature
Generate offsets
Derive lane geometry
Lane 1
Lane 2
Multi-scale Mobility Visualization
Corridor scale
Regional scale

Identify Freight with Video Feed Analysis

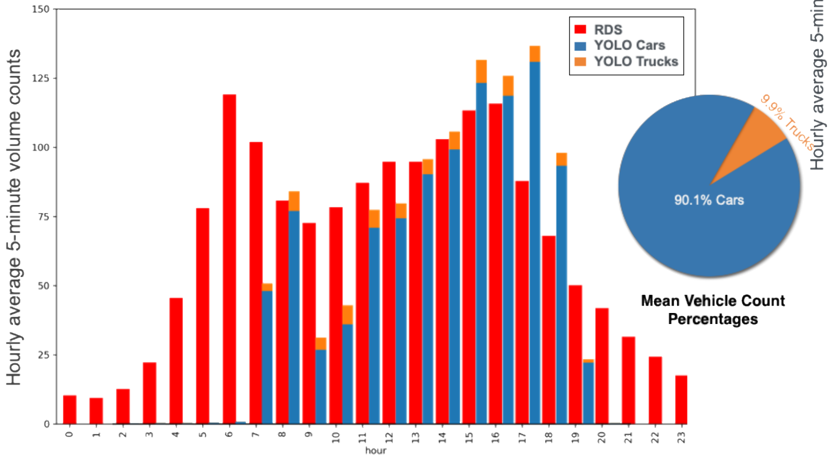
You-Only-Look-Once (YOLO V3) deep image processing network to identify cars and trucks from low-resolution traffic cameras.

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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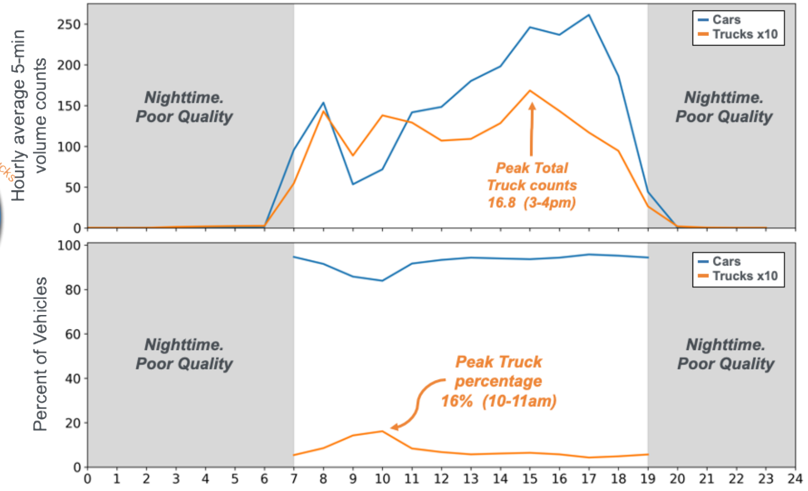


Modeling & Simulation

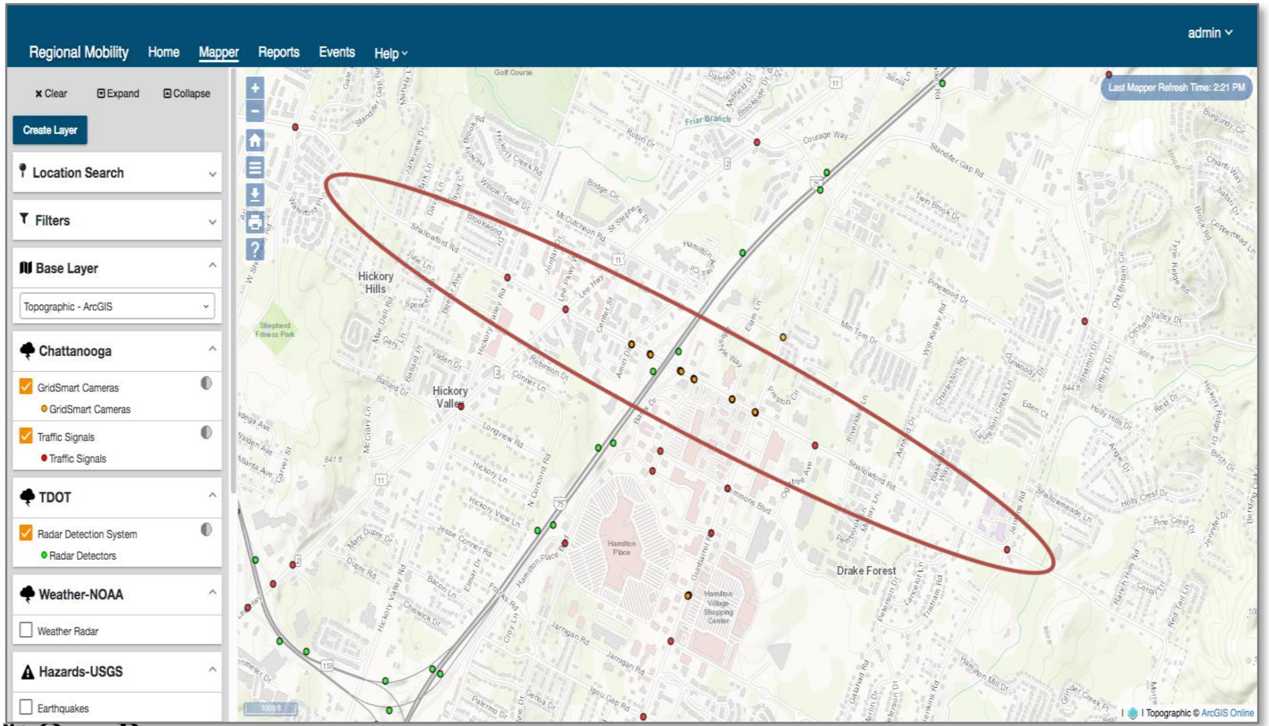
- In preparation for control

Candidate Corridor for Enacting Signal Control

<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

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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

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
  - Anticipatory routing
  - Collective control across diverse implementers

Cyber-Physical Control

Enacting control in the city infrastructure


SIEMENS m60
RING TIMERS AS:00 B:1:1:1
RING 1 RING 2 PHS..12345678 90123456
O/N ...0...0
VEH CRCCCRCC
PED
H/O 00000000
PASS 4 PASS 4
MAX1 20 MAX1 20
COMM STATUS
..PORT 2.. ..PORT 3..
SETTINGS....: 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
USB
3 AMP
A
B
C
D OPT
AC
3 FSK

Logical flow of cyber-physical interface with controllers

Hardware in the loop testing

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

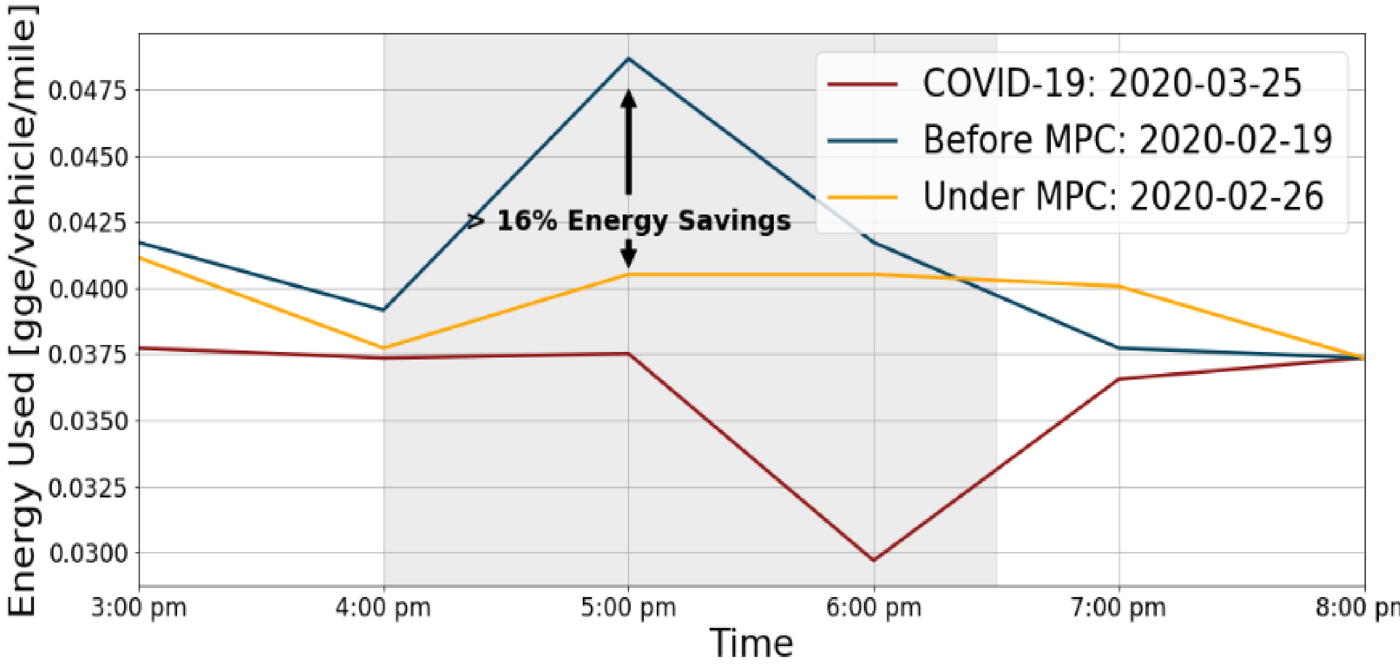
Vetting, deployment, and measurement

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

Phased strategy for signal control along Shallowford Rd

Soft-control phase: Using existing vendor interface

- Results from M&S available - Optimized timings showed:
  - **18% energy reduction in simulation**
  - Formulated the optimal signal timing problems for NEMA controllers as a nonlinear programming problem that can be solved by IPOPT
  - **16% observed in the field**
- 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



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Phased strategy for signal control along Shallowford Rd

Programmatic control phase: Software interface with controllers

- Working with Siemens as a partner
- 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
- Connectivity and boundary condition testing in progress with Chattanooga
  - Ability to change settings in ‘coordinated’ vs ‘free’ modes
  - Resolving synchronization lags, pedestrian calls, other factors
- Planning in progress for a controlled experiment in summer
  - Group 1: Pre COVID-19 Normalized Conditions
  - Group 2: Soft Control Experimental Work
  - Group 3: COVID-19 Conditions (soft control signal timings in place)
  - Group 4: Normalized COVID-19 Conditions (revert back to pre-covid signal timings)
  - Group 5: Hardware Actuation (new signal timings to be tested)

Experimental setup and testing

Metrics

- Corridor-level:
  travel time, speed and traffic volume (can be obtained from Waze, TomTom and GridSmart).
- Intersection level:
  Arrivals on green, cumulative intersection delay or average delay per vehicle (ratio of total delay by volume) and percent throughput on green along the Shallowford Road.

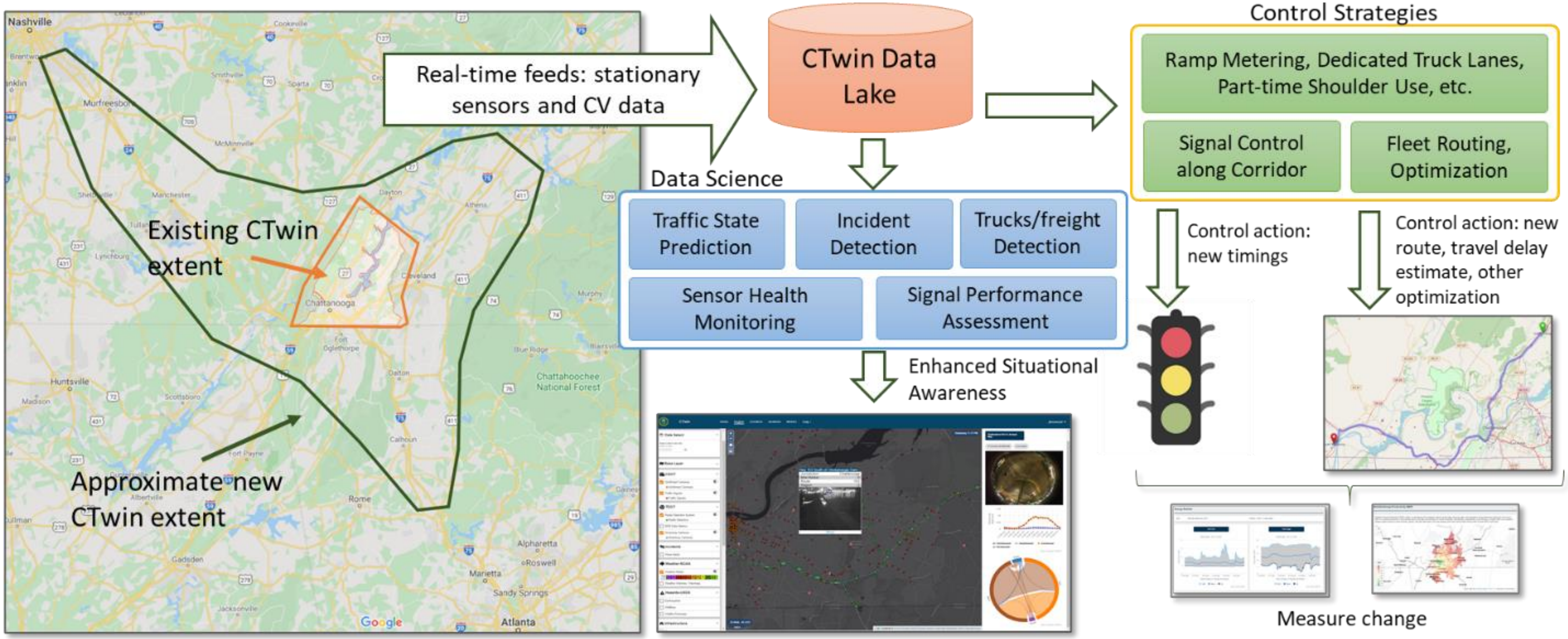
Statistical analysis

- Parametric Multivariate Sample T-test that determines the mean of the sample is different across the groups.
- Nonparametric Kolmogrov-Smirnov will determine if the density distributions of the performance measures (continuous variables only) different across the various groups.
- Freeman-Tuckey Chisquare test to determine the distributional differences across the groups. Primarily applicable to discrete variables only.
- Difference-in-Differences method can be used across the entire experimental setup to effectively determine the changes across the groups. This is similar to time-series based tests in observing how the group behavior changes.

Summary

- **Key target:** Achieve 20% energy savings at the regional level.
- **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
  - Massive data processing at scale
  - Large scalable computing
- **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 algorithmic decisions
  - Orchestration of field experiments
  - Pipelining for robust future deployments

Future work – Scaling it up!



GDOT, TDOT, CDOT, Chattanooga Public Works, Covenant Transport, FreightWaves, CARTA, Vanderbilt, UTK - Traffic Signal Academy, UTC - CIUP

Thank you!

- sanyalj@ornl.gov

Publications

- Joseph Severino et. al., “Development of automated pipeline for time-resolved link-wise vehicular energy consumption in the Chattanooga, TN road network, CoDA 2020 - Conference on Data Analysis 2020”
- Anne Berres, Srinath Ravulaparthy, Jibonananda Sanyal: Transportation Systems Analysis and Visualization: A Multiscale and Multivariate Approach to Shopping Districts. 9th International Visualization in Transportation Symposium: A Better View (Presented 11/2019)
- Haowen Xu, Anne Berres, Srinath Ravulaparthy, Jibonananda Sanyal: A Client-side Web Application for Visualizing Massive Regional Mobility Data Collected from Real-Time Traffic Sensors. Submitted AGU Fall Meeting. 2019
- Srinath Ravulaparthy, Steven Peterson, Anne Berres, Austin Todd, Ambarish Nag, Jibonananda Sanyal: Alternative Frameworks for Spatiotemporal Data Imputation Methodologies: Case-Study Analysis for Traffic Volume Forecasting. Submitted to Innovations in Transportation Modeling.
- Haowen Xu, Jibonananda Sanyal, Anne Berres, Sarah Tennille, Optimization of Network Datasets for Web-based System using Composite Bezier Curves, submitted to AAG Annual Meetings, 2019
- Juliette Ugirumurera, Wesley Jones, Jibonananda Sanyal, High Performance Computing Traffic Simulations for Real-time Traffic Control of Mobility in Chattanooga Region, Tennessee Sustainable Transportation Forum & Expo, 2019.
- Juliette Ugirumurera, Real-time answers for traffic jams, https://sciencenode.org/feature/Real-time%20answers%20for%20traffic%20jams.php, 2019

Talks

- Keynote talk: Jibonananda Sanyal, Regional Mobility in Chattanooga, TDEC Sustainable Transportation Forum and Expo, 1 Oct 2019
- Invited talks:
  - 2020 National Association of State Energy Officials Energy Policy Outlook Conference, Washington DC, 6 Feb 2020
  - Smart Citites and Communities, 2020 Annual ORAU Meeting, Knoxville, TN, 11 March 2020
  - SOS24 Workshop - Swiss National Supercomputing Centre, St. Mortiz, Switzerland (cancelled – covid)
  - Smart Cities Council annual meeting (cancelled – covid)