Creating a Digital Twin for Chattanooga - Regional mobility solutions for the United States

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Climate/Microclimate
Transportation
Buildings
HPC
Big-Data
Sensor Data
Simulation
Visualization
Situational Awareness
Machine Learning
DOE Opportunity – Chattanooga Digital Twin

Regional mobility solutions for the United States

ORNL + NREL joint effort
Chattanooga ‘Digital Twin’ – Project Goals

• **Situational Awareness**: HPC to create a ‘Digital Twin’ of an entire metropolitan region providing real-time situational awareness for analysis of the entire region.

• **Near real-time control of traffic infrastructure and vehicles**: Orchestration of computational resources for cyber-physical control of the highway infrastructure and connected vehicles in the ecosystem to achieve a 20% energy savings in the region.
‘Digital Twin’ for Chattanooga

- 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 and Simulation for Optimizing Regional Mobility using HPC

Phase 1
Situational Awareness
- Visualize real-time data
- Quantify baseline energy consumption
- Estimate energy savings for identified corridors

With TDOT and CDOT partners
- Identify how to bridge to operations
- Run the paperwork
- Identify/address security risks

Phase 2
Simulation-based signal control
- Develop signal control optimization
- Simulation/Al driven control

Demonstrate feasibility

Phase 3
Scale-up to other areas
Operationalize
Connected freight

Phase 4
Light duty commercial;
Partnership;
Transport "App"

Phase 5
Autonomous Vehicles;
Advanced powertrain

Out years

Partnership with CDOT, TDOT, County

Data: 112 CCTV cameras
25 existing, 34 planned GridEye;
RDS data every ½ mile, On-street controllers, incident data, etc.

Provides Vehicle counts, types, lane occupancy, air quality, etc.

Geodatabase

Control Optimization

Control Actuation

Situational Awareness

Demonstrate on city infrastructure
- Understand infrastructure needs
- Understand control logic
- Be able to degrade gracefully
Data feeds for Situational Awareness
Data for Situational Awareness

• **Data from partner stakeholders is key**

• **Partners:**
  - City of Chattanooga
  - Tennessee Department of Transportation
  - Multiple other agencies: MPO, GA-DOT, Titan, INRICS, HERE, ATRI, etc.

• **Reference data:** this is data that provides information on location and characteristics of infrastructure

• **Dynamic data:** this is data that is collected by the deployed sensors

• **Significant complexity in variety and nuances of the data and in systems that serve the data**
Data from City of Chattanooga

- NDA executed
- VPN access setup
- Reference infrastructure received
- Signal timing info received
- Real-time access to GridSmart cameras working (38 +100 planned)
- Working on real-time data access
  - Traffic signals – signal performance measures
  - Sensys pucks – TACTICS ITS system
  - BlueToad devices

Map of Chattanooga illustrating the locations of the traffic signals.

Map of Chattanooga illustrating the locations of the traffic signals.
Data from TDOT

• NDA not needed
• Radar Detector Sensors
  – Located every ½ mile on average
  – Receiving daily 2GB file once a day
  – 30s data from RDS sensors
  – Lane occupancy, speed, classification
• Weather sensors – offline
• Real-time access needs and approach
  – TDOT development effort needed
Data from other sources

• Probe data – WAZE access granted
• Discussions with Tom-Tom and INRICS
• Incident data
  – Lag in availability
  – Multiple systems – TITAN, GEARS, DPS, WAZE – duplication and consistency issues
• NPMRDS data access available
  – Not real-time; only bulk downloads possible
• Freight data
  – Data issues observed in automated classification from TDOT sensors
  – ATRI is offering data for a price
Visual Summary of data sources

**Road Network**
- Chattanooga Streets
- Interstates
- State Highways
- TPO Roads
- TN Streets by County
- OSM
- TN only
- GA only

**Traffic Analysis Zones**
- TDOT

**Traffic Signals**
- Locations
- Synchro Schedule
- Tactics
- OSM

**Traffic Data**
- Origin/Destination Matrices
- Traffic Analysis Zones
- Tennessee Traffic History
- Radar Detection System
- Dynamic Messaging System
- GridSmart
- Incidental Management Data
- Sensys
- SUMO
- NPMRDS
- BlueToad

**Legend**

- **Primary Data**
  - Not Available
  - Partially Available
  - Available

- **Secondary Data**
  - Not Available
  - Partially Available
  - Available
Metrics to measure impact made
Metrics

• Metrics are measures of performance of the transportation system
  - Mobility – macroscopic and microscopic traffic flow dynamics
  - Safety – damages and fatalities form traffic incidents
  - Energy – system and vehicular level energy usage and consumption patterns
  - Mobility & Energy Productivity (MEP) – holistic measure of quality of mobility and energy

• Macroscopic Mobility
  - Demand flow – vehicle miles traveled by passenger and freight
  - Congestion – level of service (volume/capacity ratio), vehicle hours of delay, average speed
  - Variation & Reliability – average travel time, planning time index, buffer index and travel time reliability index
Metrics

• Microscopic Mobility
  – Vehicle queues occur at segments/intersections
    • 95th Percentile queue length is the typical measure
  – Controlled delays from signalized intersections
    • LOS (A,B,C,D,E,F) as defined by HCM 2017

• Safety
  – Crash rates commonly used for performance evaluation
    • Segment level - Fatalities per VMT, Serious injuries per VMT
    • Intersection level – crashes per 100,000 vehicles

• Energy
  – RouteE – Route Energy estimation over a particular link or series of links (route) in the network
  – On-road vehicle fuel consumption = VMT*1/MPG

• Mobility-Energy-Productivity
  – MEP Metric = F (mobility weighted by [energy, cost, trip purpose])

Source: Heatmap of Speed by time-of-day on I-5 corridor in Portland ODOT 2018
Modeling and Simulation
Chattanooga-Hamilton County-North Georgia TPO

- Study region boundary defined
- 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)

<table>
<thead>
<tr>
<th>Data</th>
<th>Acquired</th>
<th>Requested</th>
<th>Source</th>
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<tbody>
<tr>
<td>Road network</td>
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<td>No</td>
<td>TPO, Navteq</td>
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<tr>
<td>Historic traffic flows</td>
<td>No</td>
<td>Yes (GDOT)</td>
<td>TDOT, GDOT</td>
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<tr>
<td>Historic radar data</td>
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<td>Yes (GDOT)</td>
<td>TDOT, GDOT</td>
</tr>
<tr>
<td>Incident Data</td>
<td>Yes</td>
<td>Yes (GDOT)</td>
<td>TITAN, GDOT</td>
</tr>
<tr>
<td>Origin-Destination Data</td>
<td>Yes</td>
<td>No</td>
<td>TPO</td>
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</tbody>
</table>
Candidate Corridor for Simulation

Shallowford Road Arterial 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 for year 2018

Spatial scope: Signalized Arterial

Temporal scope: frequency of adjusting signal settings

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Signal settings optimization-standard techniques</th>
<th>Performance-based optimization</th>
<th>Near real-time optimization</th>
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<tbody>
<tr>
<td>5-15 minutes</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Hourly</td>
<td>Yes</td>
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<tr>
<td>Time-of-day</td>
<td>Yes</td>
<td>Flexible</td>
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<tr>
<td>Daily</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Weekly</td>
<td>Yes</td>
<td>Yes</td>
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</table>
Corridor-level Simulation Setup

• Build a calibrated traffic microsimulator
  – Simulation for Urban Mobility (SUMO)

• Develop, validate and calibrate for Shallowford Road Arterial
  – Real-world traffic count data
  – Speeds and travel time profiles
  – Signal control settings

• Baseline metrics for current conditions
  – Control delay
  – Fuel consumption
  – Queue length
  – Multi-class vehicular flow (passenger & freight)
Scaling up to Regional Mobility

- Demand and supply side modeling
- More corridors – sensor deployment expansion
- Ramp metering
- Dynamic rerouting

Disruptions may lead to more arterial traffic
- Temporal and spatial distribution of the spill-over
- Duration of incident occurrence and recovery

Change in land use at local or regional level
- Building a shopping mall or a new Amazon HQ

Change in network capacity/infrastructure
- Tolls, road maintenance, lane-closure, weather effects
HPC: Simulation and ML: Patterns for Regional Mobility

HPC unlocks the power of Simulation and Machine Learning through parallel processing, distributed computing and accelerators.

Data Science:

Faster interactions with larger datasets.

Greater application of complex analysis pipelines.

Advanced algorithms that learn quantities of interest from integrating ground truth data and sparse but extensive data.

HPC Simulation and Optimization:

Large scale simulation of regional mobility for Chattanooga

Faster turn around on ensembles of simulations:
• Larger simulations
• Exploration,
• Calibration,
• Validation,
• Optimization
• Learning
• Scenarios.
HPC as an enabler for Regional Mobility

• Principle: exploit task or data parallelism for faster time-to-solution
RDS Highway Data: Shallowford Road

- RDS sensors (November 2018 to March 2019)
- Gridsmart cameras
- Interstate on/off ramps
- TDOT SmartWay Traffic cameras

Analyze long-term RDS data to identify patterns in the traffic flow near Shallowford Road and the shopping center.

Northbound:
Noticeable speed-up and reduction of congestion north of Shallowford Road (detector 1419)

Southbound:
Significant influence of vehicles entering the interstate from shopping mall during evening peak
- Increases congestion and slows traffic

Using the You-Only-Look-Once (YOLO) deep image processing network to identify cars and trucks from low-resolution traffic cameras
Focused HPC Simulation of Chattanooga

Pipeline to ingest data from partners.
- Network and demand data
- Energy estimates
- Optimization of signaling

Network processing challenges
- Mapping from MPO data to simulation data
- Preserving network Integrity
- Translating signal control information to simulation
- Missing/Incomplete data
  - E.g. lanes

Demand modeling challenges
- Old data
- Mapping low resolution to high resolution simulation,
  - TAX to mid-link
  - morning peak, afternoon peak, and off peak.
- Validation
Cyber-Physical Control
Cyber-Physical Control – Load control example

Gym with 4 HVAC units
Objective: Can we reduce the load by using only 2 HVACs at a time without compromising comfort?
Cyber-Physical Control of Chattanooga Signals

• CDOT open to considering pilot control
• Vetting of control decisions will be needed
  – Key is to assure partners that the control actions will not harm their system or compromise public safety
• Mechanisms to manually adjust controls is understood
• Mechanisms for software control is not understood yet
Towards smarter mobility solutions

• Holistic urban modeling
• Transactive energy – electric grid integration
• Integration with how buildings operate
Exascale Computing Project: Holistic Urban Modeling

• Coupled multi-scale models

• Three focus areas
  – Urban weather/micro-climate
  – Socio-economics and transportation
  – Building and district-scale energy

• Characterization and optimization of district performance over decades

5 Lab effort: ANL, ORNL, LBNL, NREL, PNNL
Interaction of Urban Systems

- Impacts of greenhouse gases (GHG) on local climate
- Resulting impacts on city function
- Incorporation of renewables into city energy portfolio
- Resilience of physical infrastructure
- Economic protection, resilience, and enhancement
- …
Chicago North Branch

Block
- 1 sq. block
  - 10 buildings

District
- 16 sq. blocks
  - 100 buildings

Large City
- 500 km²
  - 500k buildings

Mixed building sizes
- 20km

Large buildings
- 3-50 km²
  - 20000 buildings

Medium City or Large District
- 3 km³
  - 760 acres

- 2,000 buildings

- 16 km riverfront

- 20 km³

- 20k buildings

- 20-50 km³
  - (20000 buildings)
Socio-Economic Modeling and Data Flow

- How will competing district-scale designs, zoning, and transportation changes impact energy use? Water supply requirements? Storm and sewer networks? Microclimate? Traffic congestion? Job growth?
- How will distributed energy storage impact generation and distribution requirements?
- How will green infrastructure (roofs, new parks, etc.) or district-scale building configurations impact urban airflow?
- What is the impact of adding dedicated transit lanes?
- How would energy use change if human behavior with regards to decisions about commute options and commute times are altered?
Transportation Simulation for Chicago North Branch

- Microscopic approach using socioeconomic input to show high-resolution traffic activity
- Chicago North Branch scenario
- Init data from IL DOT
- Titan runs:
  - Commute and evacuation scenarios
  - Evacuation scenario, runs in 4m 50s
    ~300,000 vehicle agents, 2.3 GB, 1 sec resolution output
  - Daily commute scenario for 3 years in, 1hr 50m
    ~300,000 vehicle agents, 40GB, hourly output
- Creating representative scenarios: Incorporating the effect of weather
Mapping Vehicles/Humans Arriving at Buildings

- Determine arrival time and location for all agents (vehicles) in the system
  - 364,000 vehicle agents
  - 120,000 buildings

- Recursively find buildings that are closest to agent locations using quadtree representation
  - Split criterion: number of agents and buildings
  - Trade-off:
    - **Speed**: smaller split number is faster
    - **Accuracy**: Cell sizes need to be large enough to accommodate buildings.
  - Processed full dataset:
    - > 43 billion comparisons: ~4min 20s
Building Energy Modeling at Scale

- Automatic calibration of building energy models
- 45TB/hr building simulations
- 270TB of annual building energy
Neighborhood, Settlement, and Building Mapping

Settlement patterns as socioeconomic indicators

Damascus, Syria

- Unstructured Settlements
- Lowest to lower middle income
- Rural migrants

- Very loosely structured
- Historically ethnic neighborhoods
- Poor residents; displaced in some areas with urban development/tourism

- Formal urban planning
- Typical urban services
- Middle to upper income
Accelerated Global Human Settlement Discovery:

Using **deep learning** to detect buildings

25 million core-hours ALCC allocation on Titan

Processed Yemen **in under two hours** using and 4,758 nodes and as many GPUs. There were 4,758 images totaling to 45.5 TBs

Processed Zambia in **3 hours 45 mins.**

Detected all swimming pools in TX in **~10 minutes**
Graphic illustrates electric outages from 2019 with several active hurricanes.

US DOE’s operational real-time energy-sector situational awareness tool.

Outage monitoring for over 128 million customers; 87%+ coverage of US.

Users are from DOE, White House, DHS, NGA, DOD, FEMA, USDA, state emergency responders, among others.
Integrated Simulation of Travel Behavior

**Traveler Behavioral/Decision Modeling**
- Activity Planning
- Activity Generation
- Activity Scheduling
- Vehicle Choice
- Route Choice
- Housing Choice

**Performance**
- Congestion
- Safety/Incidents
- Energy Use
- Emissions

**Transportation Network**
- Activity Engagement
- ITS Infrastructure
- Traveler Movements
- Intersections
- Links

**Communication Infrastructure**
- Sensor Networks
- Traffic Management
Thank you!

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