Applications of Integrated Energy and Emissions Modeling Tools

Randall Guensler, Michael O. Rodgers,
Michael Hunter, Angshuman Guin
Haobing Liu, Xiaodan Xu, Hanyan Li,
Daejin Kim, Yingping Zhao, Hongyu Lu

Georgia Institute of Technology
School of Civil and Environmental Engineering

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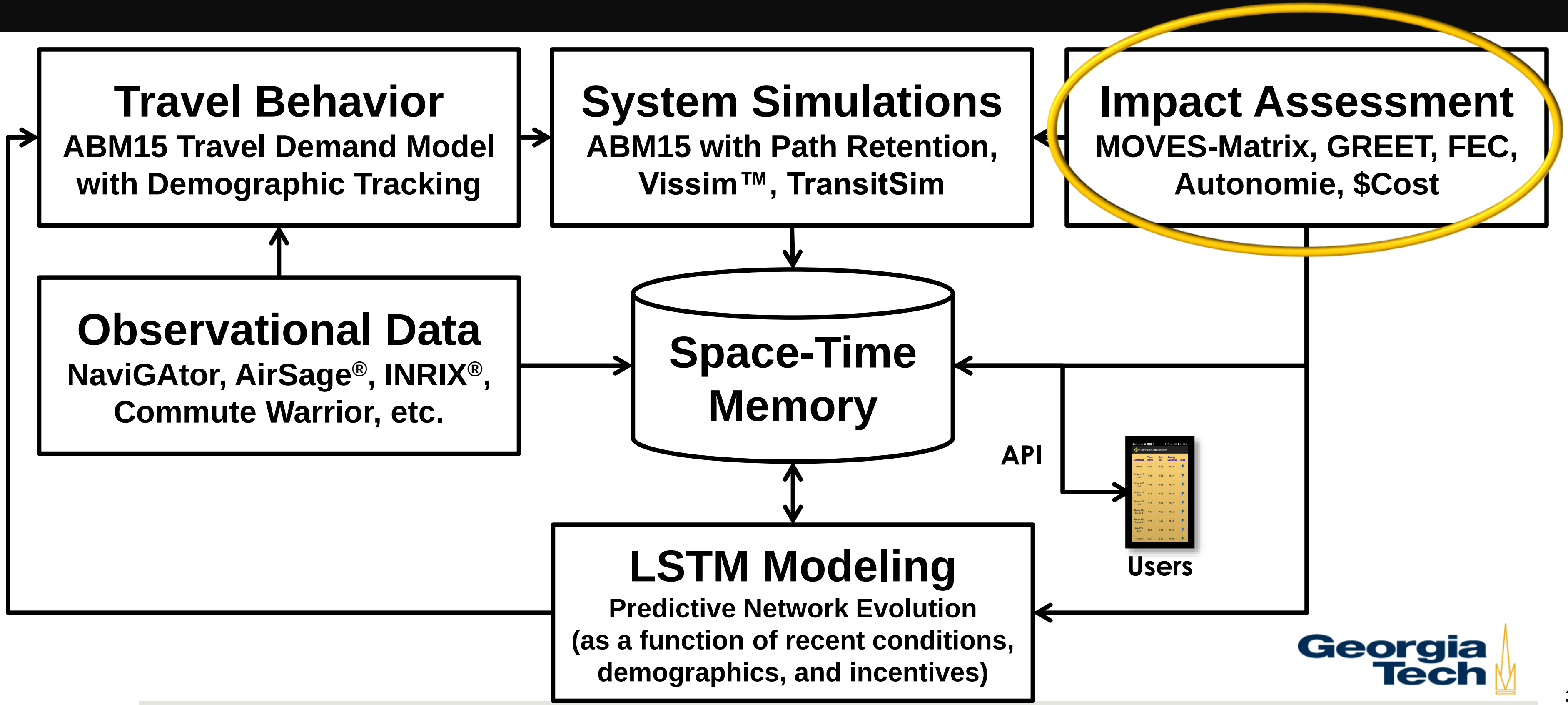
Overview

- Systems Model
- MOVES-Matrix
- GT Fuel and Emissions Calculator
- Personal Vehicle Operating Cost Calculator
- Grade Integration
- Applications:
  - Travel Demand and Activity-based Models (ABM)
  - DTA, Vissim™, etc.
  - TransitSim/RoadwaySim
  - Monitored vehicle activity
- AERMOD-Grid and Screening Tools

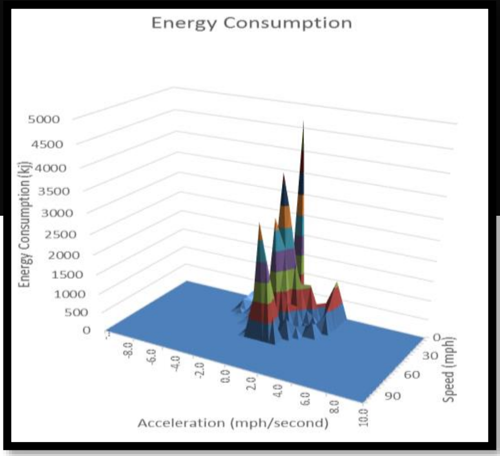
Integrated Modeling Systems



MOVES

- Difficult to analyze complicated dynamic with MOVES
- Users often generate lookup tables to support modeling
- Why not pre-run MOVES for all combinations of input data?
  - Configure MOVES for distributed computing
  - Iterate runs across all inputs
  - Compile emission rates into a multi-dimensional matrix
- Fleet and individual vehicle emission rates can then be quickly derived and applied at any modeling scale

MOVES-Matrix Modeling



- EPA's MOVES emission rate model
- Iterate across all input variables
  - 146,853 model runs
  - Energy/emission rates by calendar year, temperature, humidity, vehicle type, model year, on-road operating conditions, regional fuel parameters, I/M program, etc.
  - 90 billion energy and emission rates per region (2 Gb)
- Assemble fleet emission rates at any scale for any application from the multi-dimensional array

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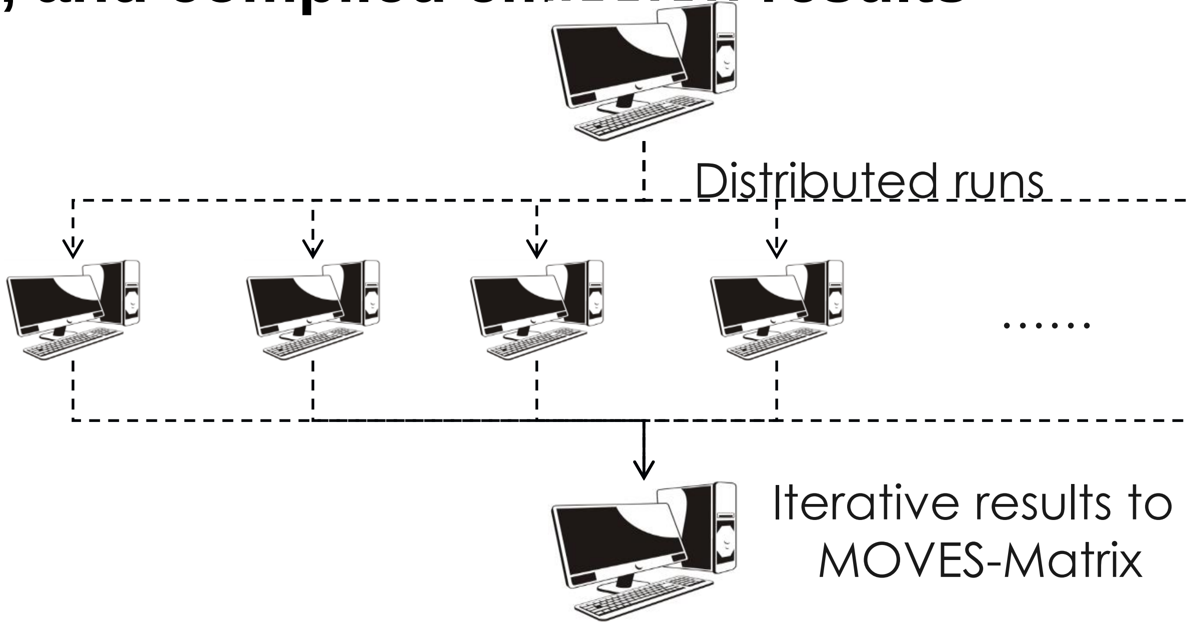
MOVES-Matrix Background

- Iterate MOVES runs across all variables that affect output emission rates
- Iterations yield emission rate applicable to:
  - A uniform fleet (single source type and model year)
  - Specific temperature and humidity conditions
  - Specific onroad operating conditions, by speed and road type, or by VSP/STP operating mode bin
  - Set calendar year, regional fuel, I/M program, etc.
- Composite fleet emission rates are assembled from the Matrix of uniform fleet results

MOVES-Matrix Development Approach Employs Distributed Iteration Runs

- **Configured MOVES to run on a distributed computing cluster, and compiled emission results**

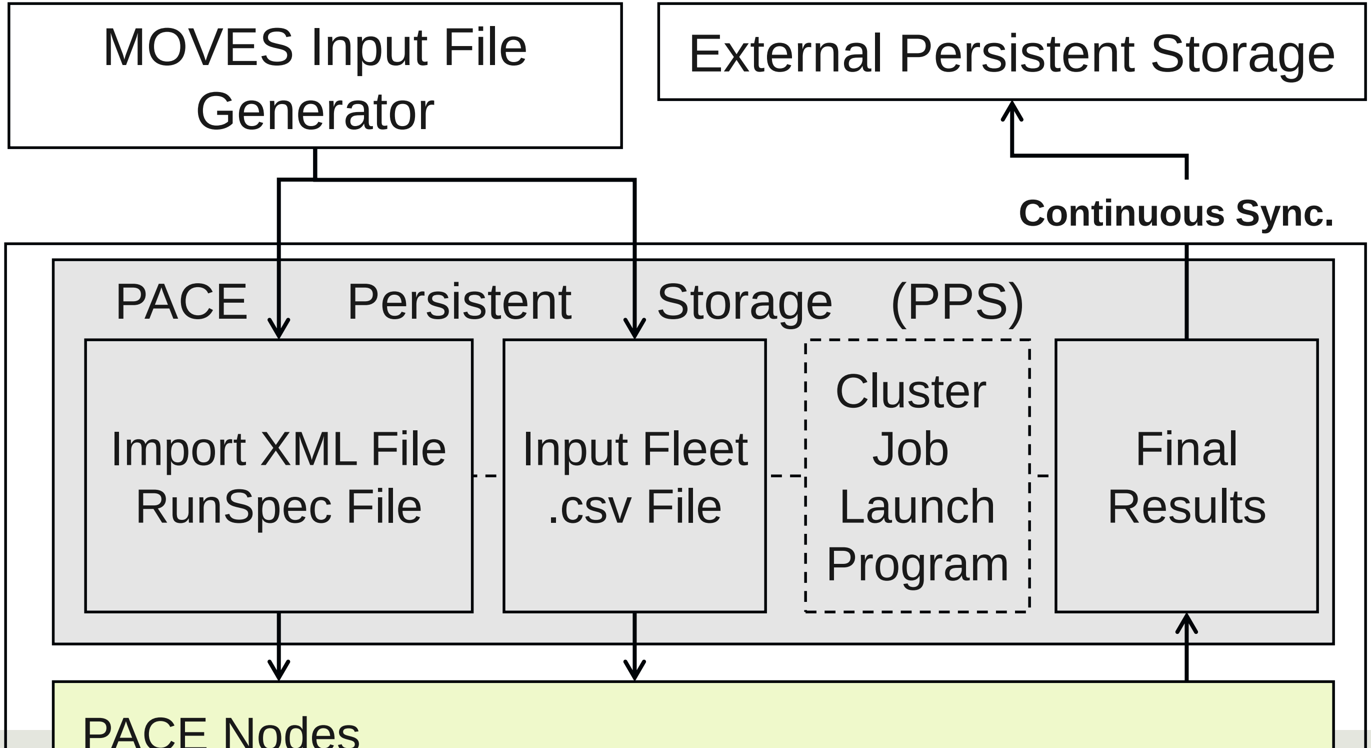


Partnership for an Advanced Computing Environment (PACE)

- Partnership between Georgia Tech faculty, researchers, and the Georgia Tech Office of Information Technology
- Distributed computing center
  - 35,000 cores
  - 90 terabytes memory
  - 2 petabytes of storage
- PACE applications:
  - MOVES-Matrix runs
  - AERMOD Runs
  - Bandwidth analysis
  - Simulation testbed

https://pace.gatech.edu/

Partnership for an Advanced Computing Environment (PACE) System Overview



Atlanta MOVES-Matrix Iterations (Atlanta IM and Fuel Program)

- Emission rates (energy, criteria pollutants, CO_2, etc.)
  - City: Atlanta (Fulton County)
  - Calendar years:
    - 2010-2024 (1-Year interval)
    - 2025-2050 (5-Year interval)
  - Fuel Type:
    - Winter (Nov - March),
    - Summer (May - September)
    - Transition (April, October)
  - Temperature: 0°F - 110°F (5°F bins)
  - Humidity: 0% - 100% (5% bins)
  - All source types
  - All age groups (0-30 years)
  - Road types (urban freeway, local)
  - Speed-bins (MOVES-cycles)
    (0-80 mph, 0.1 mph speed bins)
  - 23 OpMode Bins

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Atlanta MOVES Runs per Region

- On-road exhaust: 30,429 runs
  - 21 calendar years
  - 3 fuel months (summer, winter, transition)
  - 23 temperature bins (5°F bins)
  - 21 humidity bins (5% bins)
- 20 minutes/core/run
  - Five days in PACE (80+ sustained cores assigned)
- 5,348,983,500 running emission rates per region
- 121.2 Gb emission rate matrix per region

MOVES-Matrix 2.0

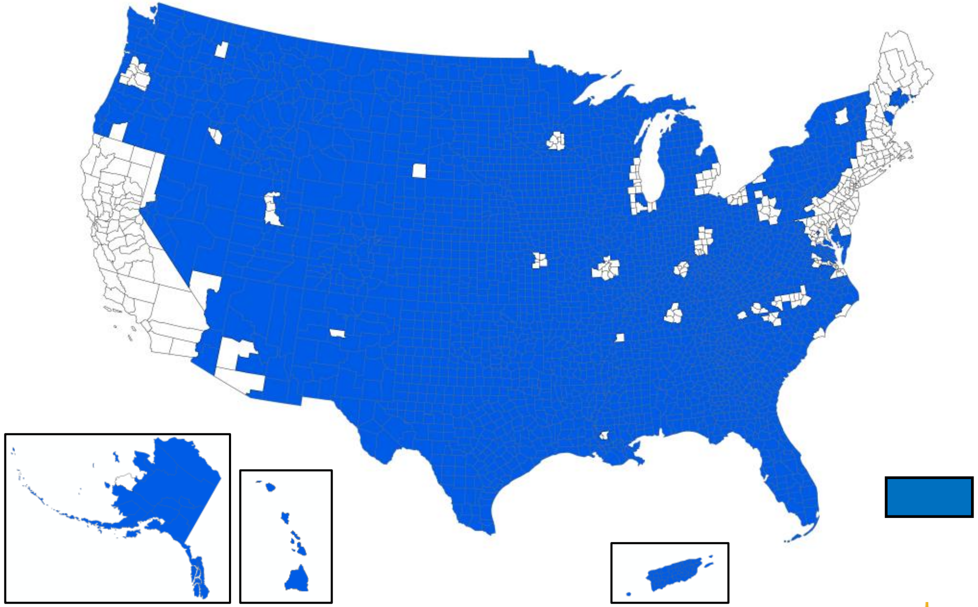
- Updated MOVES-Matrix to integrate:
  - Start exhaust, truck hoteling, and evaporative emissions
- MOVES-Matrix can now be used for regional emissions
  - Atlanta regional inventory case study
  - MOVES-Matrix generates exactly the same results

MOVES-Matrix 2.0 Modeling Runs

- 1,909,089 MOVES runs per region
  - Running exhaust, start exhaust, evaporative, hoteling
  - 21 calendar years, 3 fuel months, 111 temperatures (1°F), 21 humidity bins (5%)
- Generates 437,034,528,000 emission rates per region
  - 5.5Tb emission rate matrix per region
- Processing time
  - One region in PACE (actual): 25 days
  - One region in Titan (est.): 1.8 days (1% core allocation)

Current On-Road MOVES-Matrix Coverage

- 22 MOVES fuel regions
- 89 MOVES I/M scenari
- 117 unique fuel and I/M program combinations
- MOVES-Matrix covers 2,892 of 3,228 counties



Titan Supercomputer
Oak Ridge National Lab

- **Department of Energy Cray XK7™ Supercomputer**
  - **27,000 trillion calculations per second**
  - **299,000 cores**
  - **710 terabytes of memory**
- **With 1% core allocation, one region should run in <8 hours**

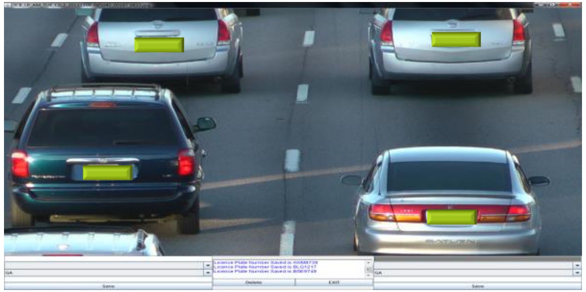
Source: https://www.olcf.ornl.gov/olcf-resources/compute-systems/titan/

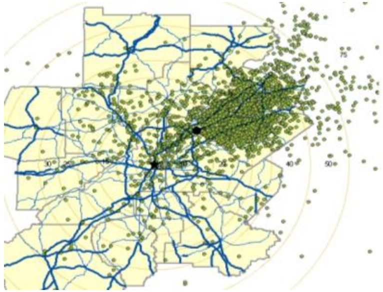
Applying MOVES-Matrix Rates

- Fleet composition (monitored or modeled)
  - Vehicle source types and model year distribution
- On-road operating conditions
  - Assumed drive cycles (by vehicle source type)
  - Assumed operating mode bin distributions
  - Observed speed-acceleration traces
- Can be specified for regions, sub-regions, road classes, individual road links (modeled or monitored), or by individual vehicle
- Works with VISSIM simulation and travel demand models

Fleet Composition

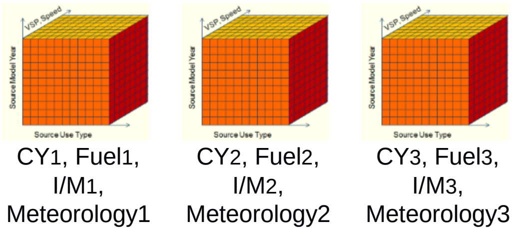
- License plate data collection and registration
  - Vehicle make, model, model year
- Travel demand model (synthetic households)
- Map make/model/model year to source type
  - 6000-row lookup table





MOVES-Matrix Run Module: Developing On-Road Fleet Emission Rates

Regional Matrix



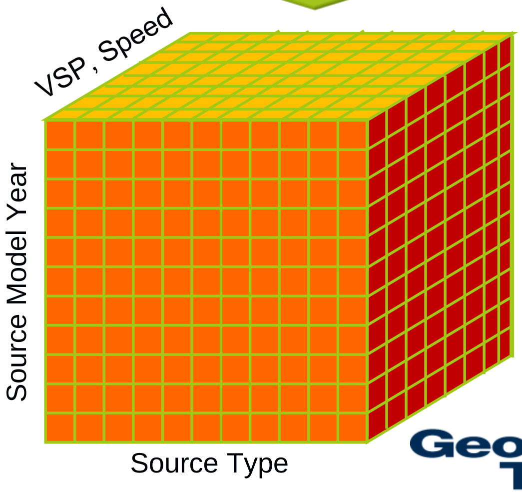
Select sub-matrices

Regional Inputs:
Calendar Year,
Fuel, I/M, Meteorology

Fleet Activity:
Link Data, Source Type Distribution, Model Year Distribution, VSP, Speed/OpMode Bin

Query sub-matrix

Return fleet emission rate
(weighted by onroad activity)



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MOVES-Matrix Run Module: On-Road Fleet Emission Rate Calculation

- **Each cell yields an applicable emission rate**
- **Weight emission rates by source type (ST), model year (MY), and operating mode (OM) activity (or average speed and facility type (SF) activity), to generate the fleet emission rate**

$$\mathrm{ER}_{\mathrm{Fleet}} = \sum_{\mathrm{ST}} \sum_{\mathrm{MY}} \sum_{\mathrm{OM(SF)}} \mathrm{ST}\% \times \mathrm{MY}\%_{\mathrm{ST}} \times \mathrm{OM(SF)}\%_{\mathrm{ST,MY}} \times \mathrm{ER}_{\mathrm{ST,MY,OM(SF)}}$$

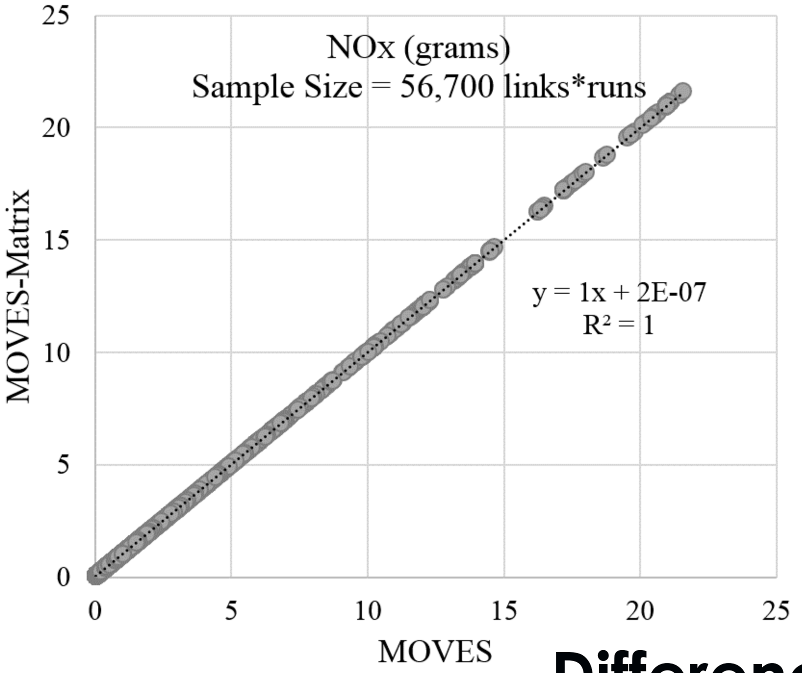
- **Output is fleet emission rate (g/sec, g/hour, g/mile)**

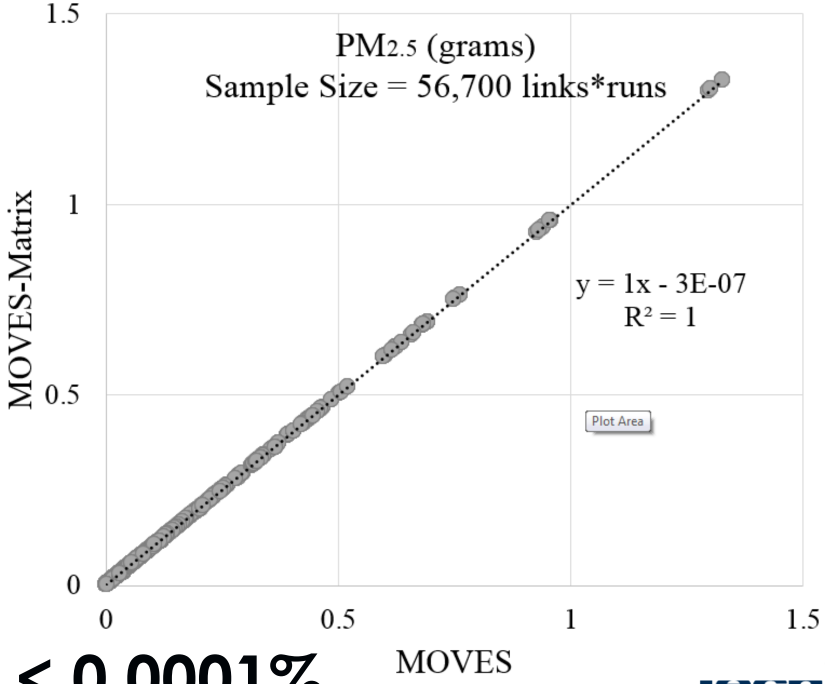
MOVES vs. MOVES-Matrix Iteration Scenarios for Test Runs

Variables	Iteration Increment	Number
Facility type	Freeway, Local	2
Fleet (MY & type)	Freeway fleet, Local fleet	
Calendar Year	2010-2050 in 5-year interval	9
Fuel month	January (winter), April (transition), July (summer)	3
Temperature	20-100 F in 20-F interval	5
Humidity	20-100% in 20% interval	5
Operation input	Average speed, OpMode distribution, Driving cycle	3
Total Scenarios (Number of Runs): 2×9×3×5×5×3		4,050
Number of links in each run	• Average speed method: 5-70 mph in 5-mph interval • OpMode distribution method: 5-70 mph in 5-mph interval with each applied with operating mode distribution • Driving cycle method: 14 links with each applied with customized second-by-second driving schedule	14
Total Number of Link Scenarios: 4,050×14		56,700
Emission type	THC, CO, NO_X, $PM_{2.5}$, CO_2	5
Total Number of Emission Results: 56,700×5		283,500

MOVES vs. MOVES-Matrix Results

➢ **Results are exactly the same as MOVES GUI results**





Difference < 0.0001%

MOVES-Matrix Performance Calculations Run 200x Faster

Model	Process	Method [Runs = 4,050]					
		Average Speed Method (1,350 runs)		OpMode Distribution Method (1,350 runs)		Driving Cycle Method (1,350 runs)	
		Time (hours)	Speed (sec/link)	Time (hours)	Speed (sec/link)	Time (hours)	Speed (sec/link)
MOVES	Load Input	3.66	0.69	4	0.76	4	0.76
	Calculation	206.3	39.29	152	28.95	191	36.4
	Total	210	40	156	29.71	195	37.1
MOVES-Matrix	Load Input	0.77	0.14	0.15	0.029	0.54	0.10
	Calculation	0.06	0.01	0.02	0.004	0.16	0.03
	Total	0.83	0.15	0.17	0.032	0.70	0.13
Run Time Ratio (MOVES Batch Mode Run / MOVES-Matrix Run)		253		917		278	

Plus, there is no need to prepare MOVES input files

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MOVES-Matrix Benefits

- MOVES emission rates are employed directly
  - No code modifications, no correction factors, no approximations
- Allows users to assess impacts of changes in onroad operating conditions and onroad fleet composition
- Facilitates MOVES sensitivity analysis
- Python and Perl scripts can be used to link MOVES emission rates with travel demand models, traffic simulation, monitored data, and dispersion models
- Open source and collaborative

MOVES-Matrix Applications

- MOVES-Matrix can be applied at any spatial and temporal scale and can be linked with any model via Python scripts
  - Regional travel demand models
  - Corridor/scenario analysis
  - Vissim™ and other microscopic simulation
  - Microscale pollutant dispersion modeling
  - App-based vehicle energy and emissions modeling
- FEC and Cost Calculator can be applied in series

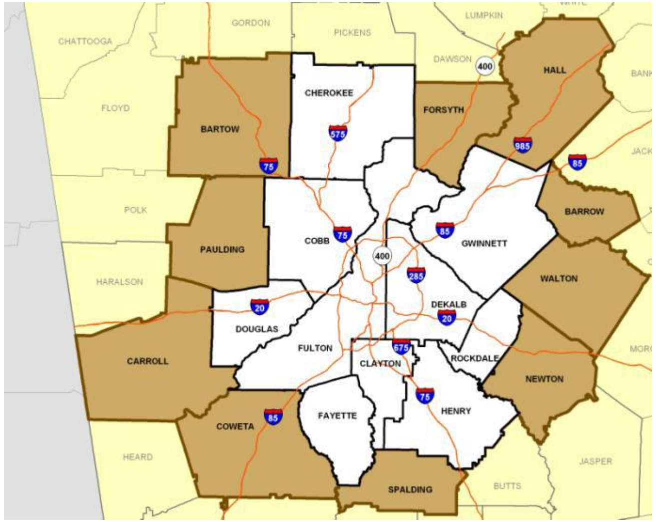
MOVES-Matrix Applications

- Regional travel demand model (average speeds)
- Corridor modeling (average speeds)
- Vissim® microscopic simulation (second-by-second)
- Individual vehicles (second-by-second)

- Microscale dispersion modeling

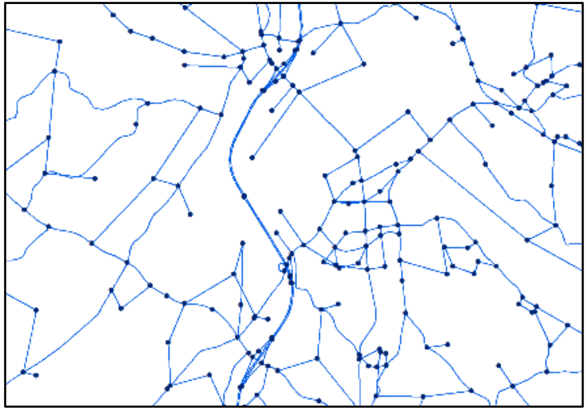
MOVES-Matrix 2.0
Connectivity with Travel Demand Models

- **MOVES-Matrix 2.0**
- **Atlanta Regional Commission's (ARC's) regional activity-based travel demand model ABM15**
- **Activity-based model (ABM) predicts trips (origin-destination) and link-level travel**
  - **5,981 zones**
  - **74,500 network links**

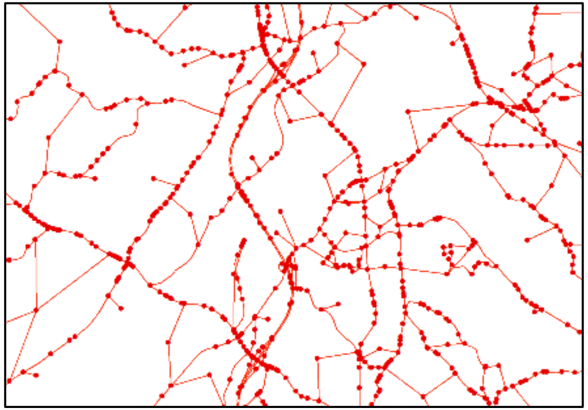


Source: Atlanta Regional Commission

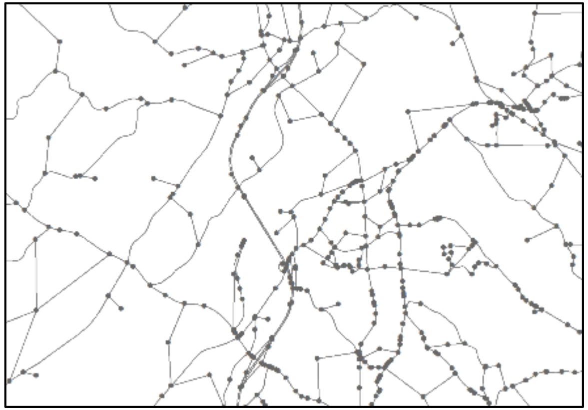
Modeling Spatial Structure



ARC Planning Network
74,469 Links
27,059 Nodes
5,873 TAZs



ABM15 Unconsolidated
202,994 Links
93,621 Nodes
5,873 TAZs



ABM15 Consolidated
131,864 Links
56,537 Nodes
5,873 TAZs

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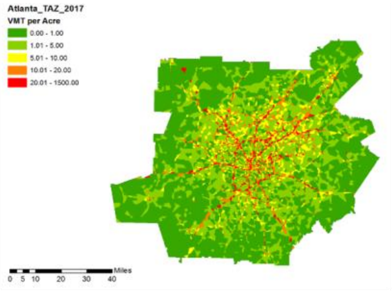
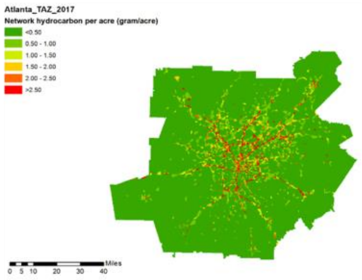
Atlanta's ABM15 Activity-based Model On-network and Off-network Emissions

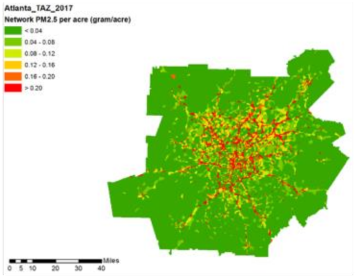
On-network



VMT

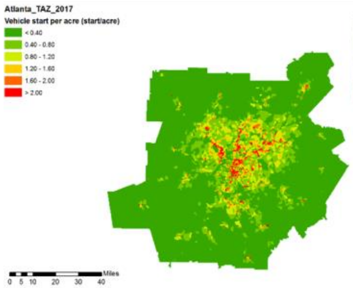


HC

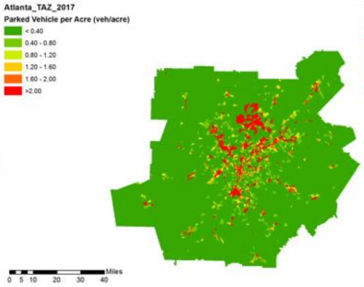


$PM_{2.5}$

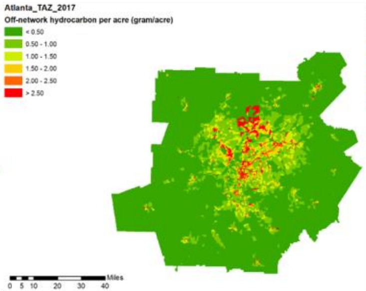
Off-network



Starts



Parked Vehicles



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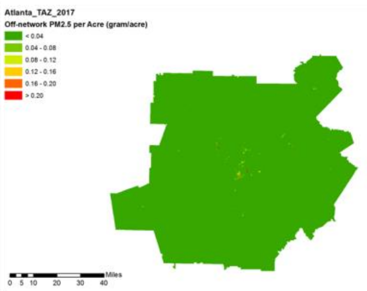

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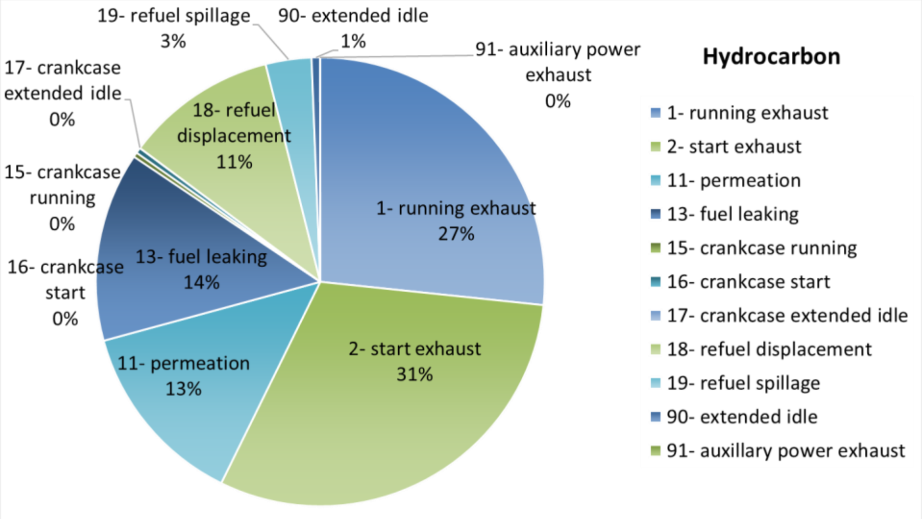
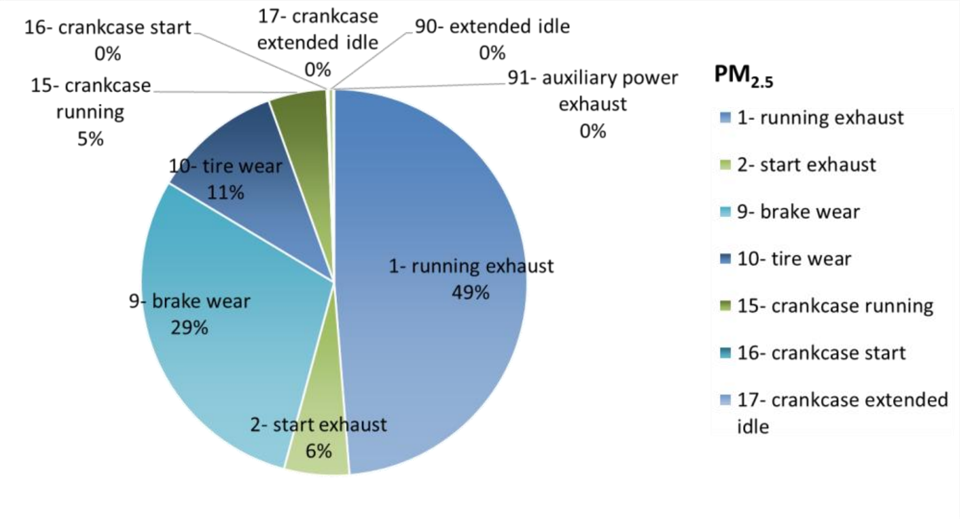
ABM15 Activity-based Model Emissions by Source





Xu, X., H. Liu, Y. Xu, M. Rodgers and R. Guensler (2018). Regional Emission Analysis with Travel Demand Models and MOVES-Matrix (18-05363). 97th Annual Meeting of the Transportation Research Board (presentation only, full paper review, extended abstract in proceedings). Washington, DC. January 2018.

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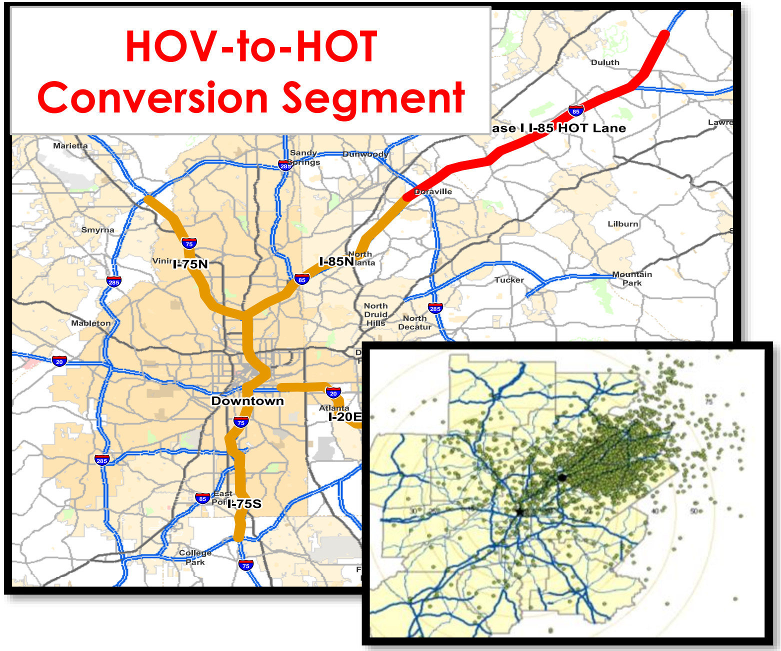
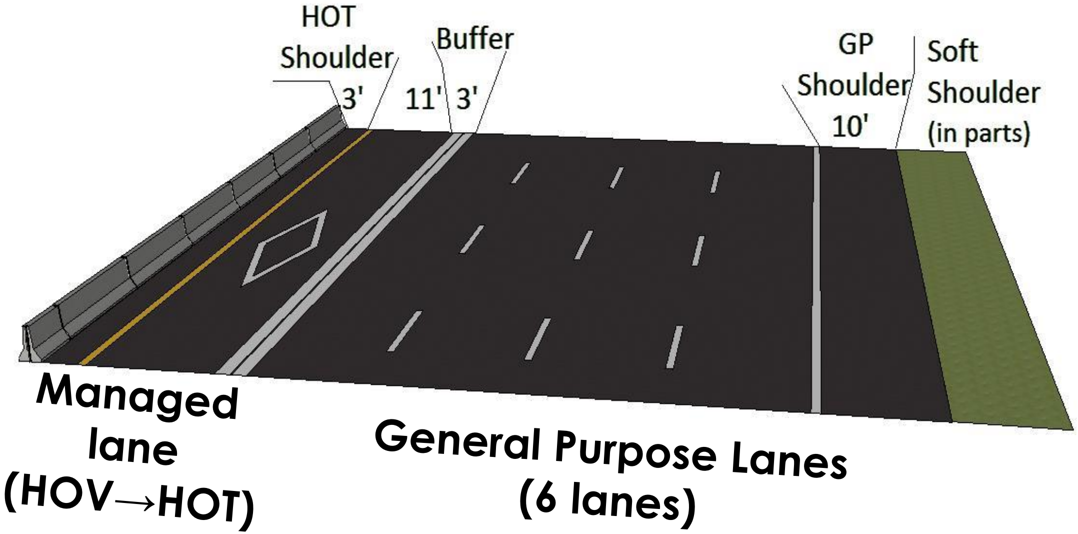
Corridor-level Case Studies
High-occupancy Toll (HOT) vs GP Lanes





Changes in traffic volumes, fleet composition, and operating conditions observed by lane

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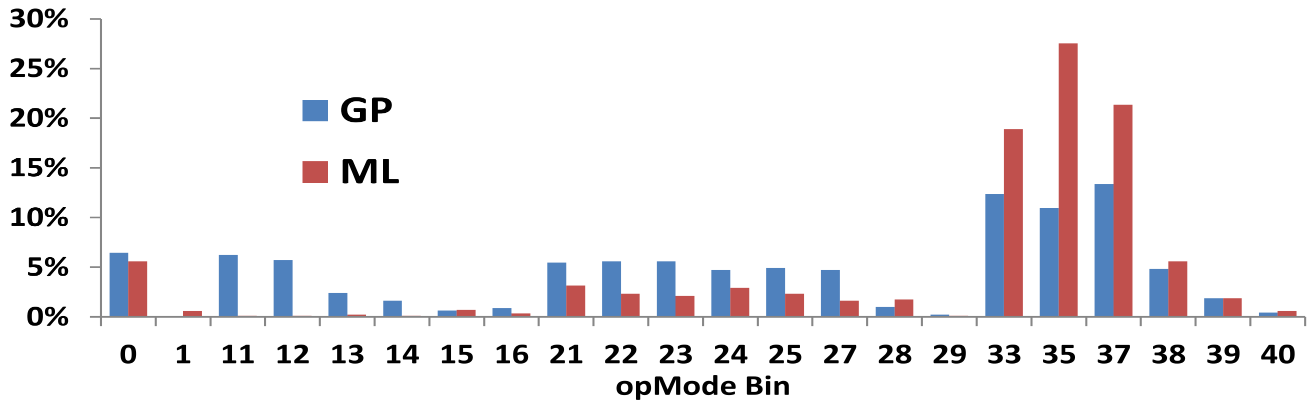
High-occupancy Toll (HOT) vs. GP Lanes On-road Operating Condition Differences

- General Purpose Lanes (GP)
  - Congested
- HOT Managed Lane (ML)
  - Uncongested



Xu, Y., Liu, H., Rodgers, M., Guin, A., Hunter, M., Sheikh, A., and Guensler (2017), R. Understanding the Emission Impacts of HOV to HOT Lane Conversions: Experience from Atlanta, GA. Journal of the Air & Waste Management Association. 67(8):910-922. doi: 10.1080/10962247.2017.1302518

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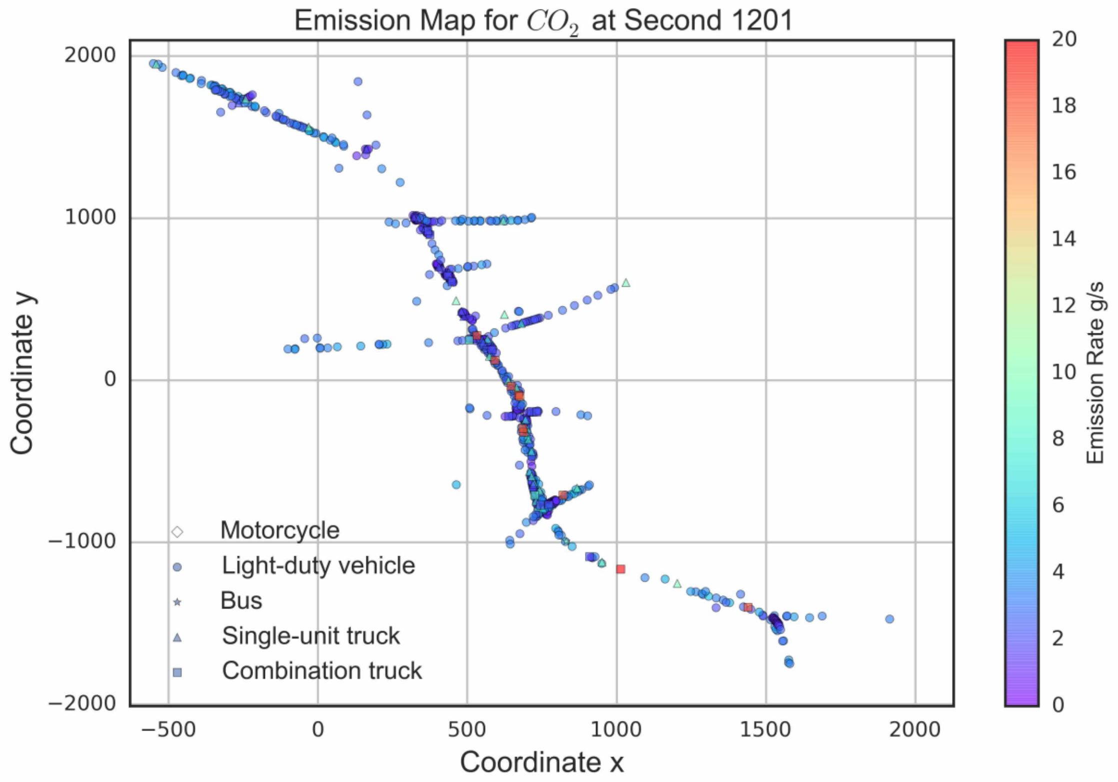
Vissim™ Microscopic Simulation

- Automated linkage between Vissim™ and MOVES-Matrix
- Python scripts
  - Run Vissim™ microscopic simulation (defined network)
  - Retrieve vehicle trace data via Vissim™ COM interface
  - Assign source types
  - Process sec-by-sec trace data to VSP
  - Match to MOVES-Matrix energy/emission rates
  - Append energy/emissions to trace data

Xu, X., H. Liu, Y. Xu, M. Hunter, and R. Guensler (2016). "Estimating Project-level Vehicle Emissions using Vissim™ and MOVES Matrix." DOI 10.3141/2570-12. Transportation Research Record. Number 2570. pp. 107-117. National Academy of Sciences. Washington, DC. 2016.

Vissim™ and MOVES-Matrix Jimmy Carter Boulevard, Gwinnett, GA



Includes 12 signalized intersections and freeway ramps

With links to microscale dispersion models

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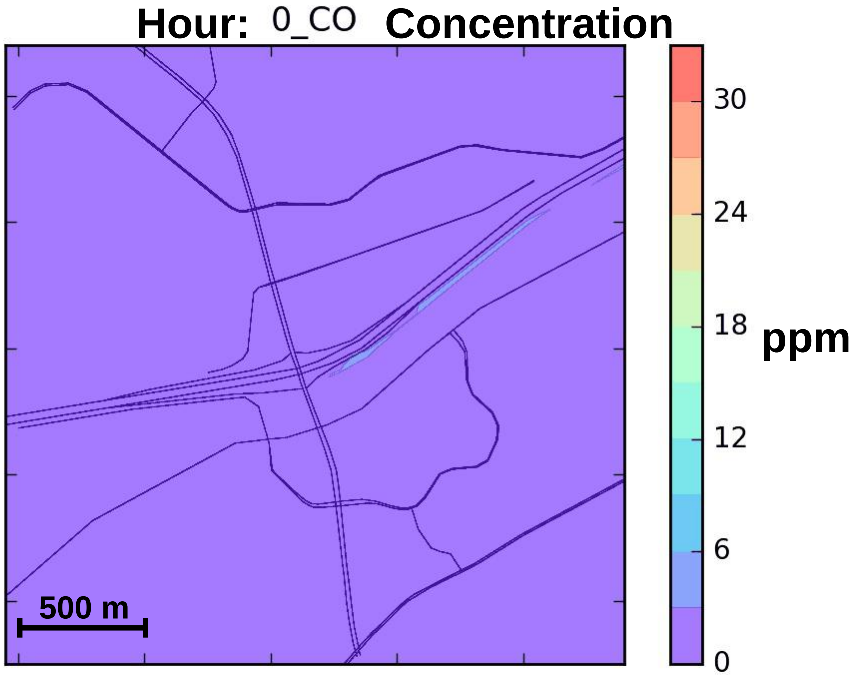
AERMOD-Grid Visualization
Jimmy Carter Boulevard, Gwinnett, GA

- **Hourly CO concentrations**
  I-85 and Jimmy Carter Blvd.
- **Winter weekday 2012**
- **Background excluded**



Liu, H., X. Xu, M.O. Rodgers, Y. Xu, and R. Guensler (2017) MOVES-Matrix and Distributed Computing for Microscale Line Source Dispersion Analysis. Journal of the Air & Waste Management Assoc. 67(7):763-775.

AERMOD Screening Analysis

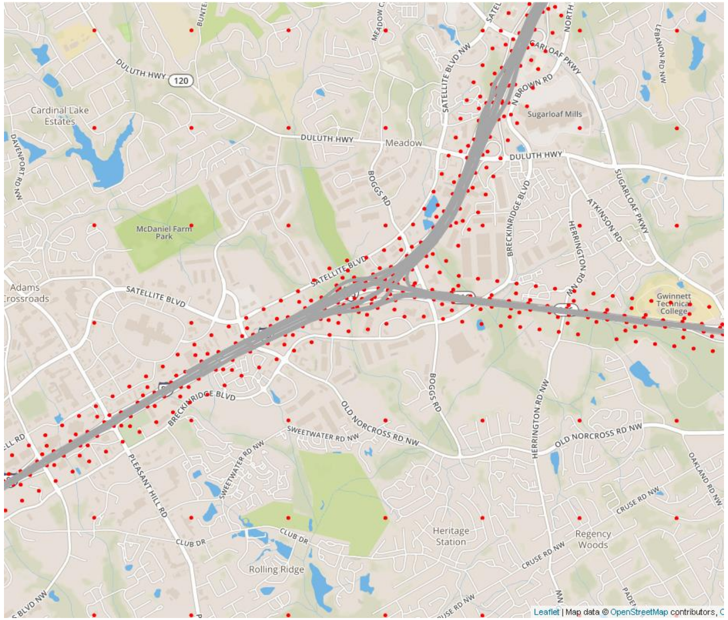
- Region-level air quality impact assessment screening methodology for microscale pollutant concentrations
  - MOVES-Matrix for emission rates
  - AERMOD for microscale dispersion
- Outputs "worst case" pollutant concentrations
  - Identify insignificant impacts
  - Identify potential hot-spots (for deeper investigation)

Liu, H., D. Kim, H. Lu, R. Wayson, M.O. Rodgers, and R. Guensler (2019). A Regional Air Quality Impact Assessment Screening Tool based upon MOVES-Matrix and AERMOD. Guidelines on Air Quality Models: Planning Ahead. AWMA 8th Specialty Conference on Air Quality Modeling. Durham, NC. March 19-21, 2019.

AERMOD Inputs

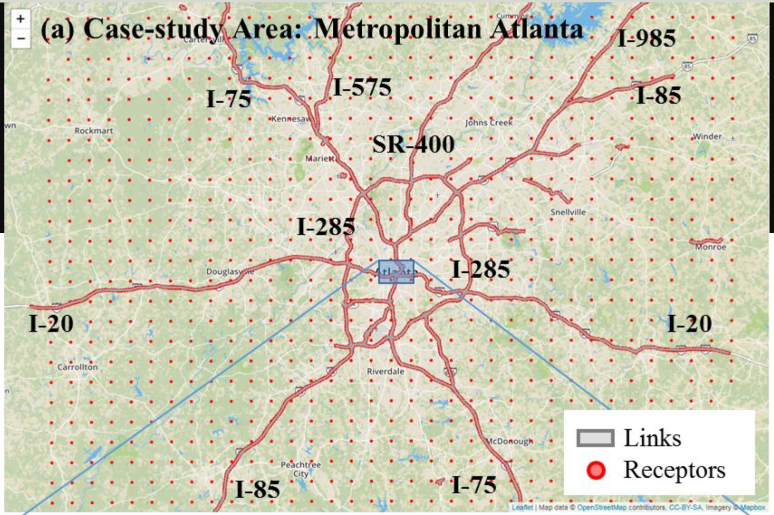
AERMOD Source Geometry Input Generation

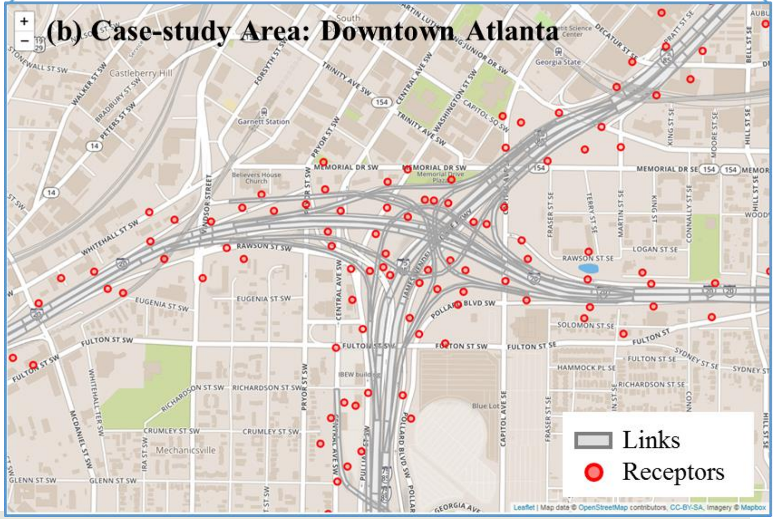
Siting Receptors



AERMOD-Grid Case Study for $PM_{2.5}$

- Atlanta Metropolitan Area
- All highways (I-85, I-75, I-20, etc.)
- 1,163 roadway miles
  - 976 highway miles
  - 189 ramp miles
- 5,642 polygon link segments
- 54,017 receptors
- 7-day PACE modeling run



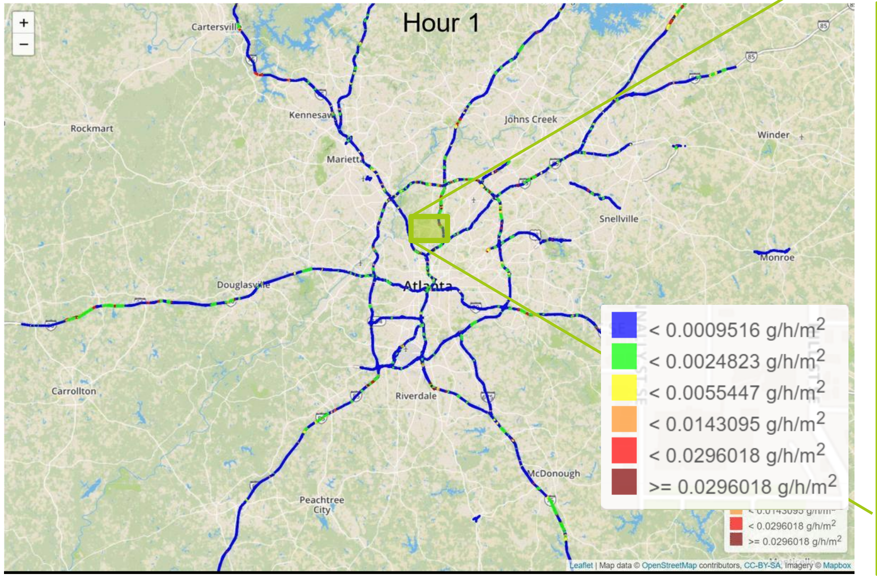


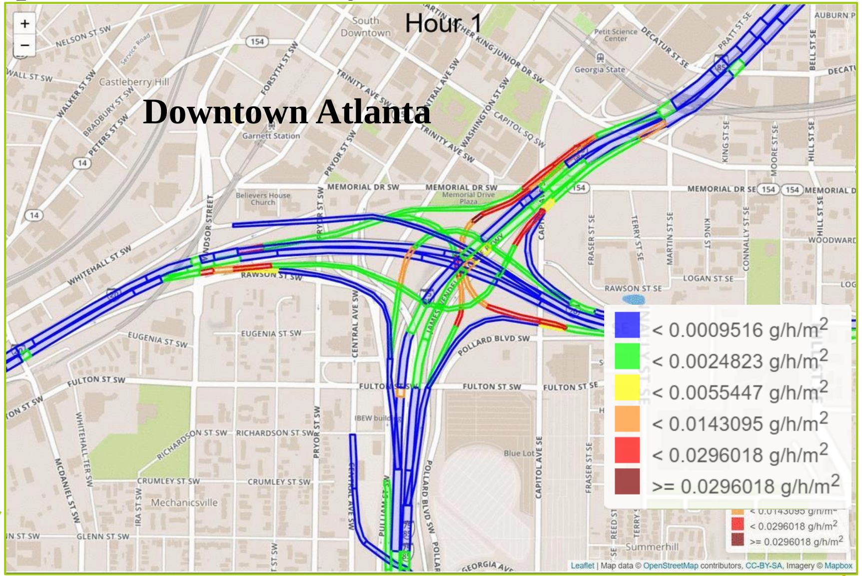
Results can be found at:
http://movessensitivity.ce.gatech.edu/osm_link_emissions/outputs.html

Emissions Calculation

- **Emission rates (grams/hour/m^2) per link**

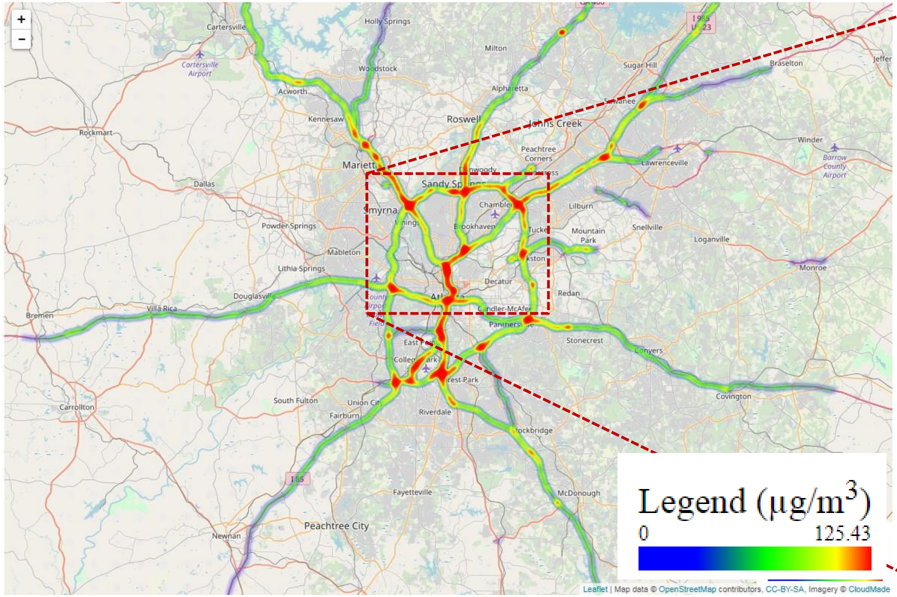
January weekday with the lowest temperature and humidity conditions)

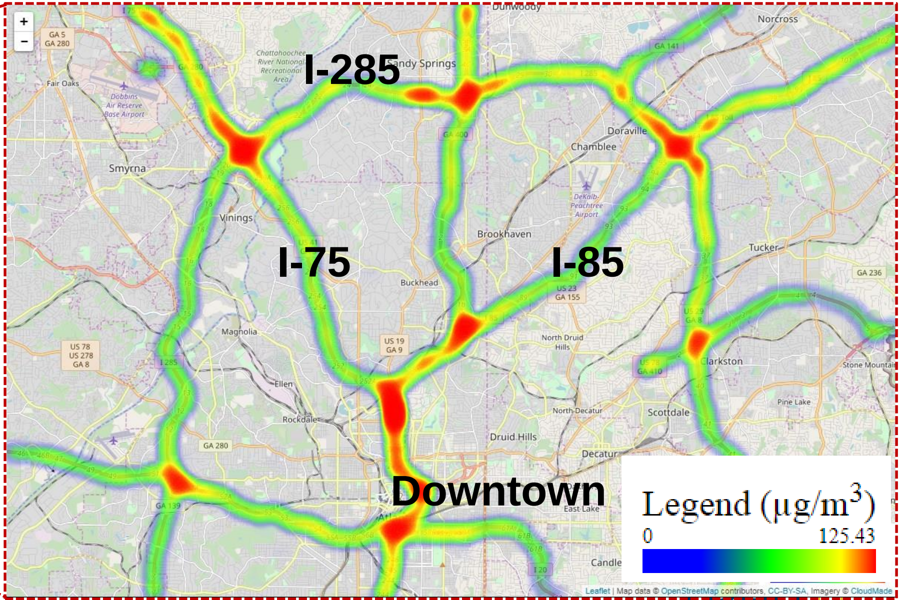




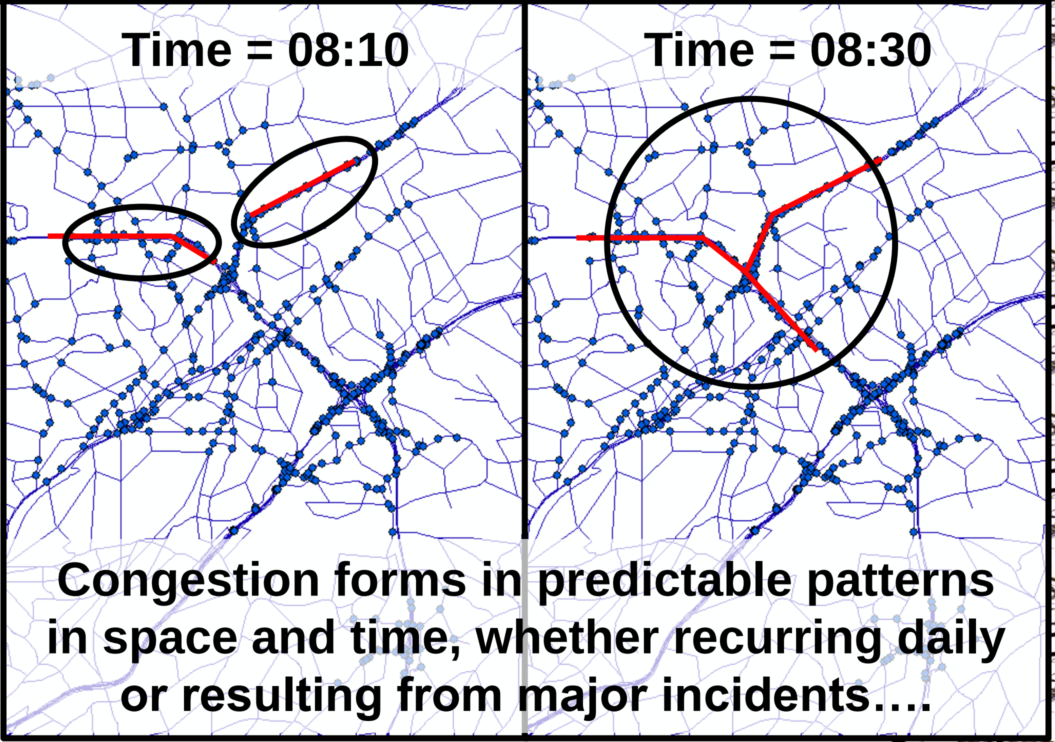
$PM_{2.5}$ Emissions and Dispersion Modeling (Atlanta Regional Case Study)

- Atlanta freeway worst case AERMOD assessment
- Identifies areas for more refined modeling

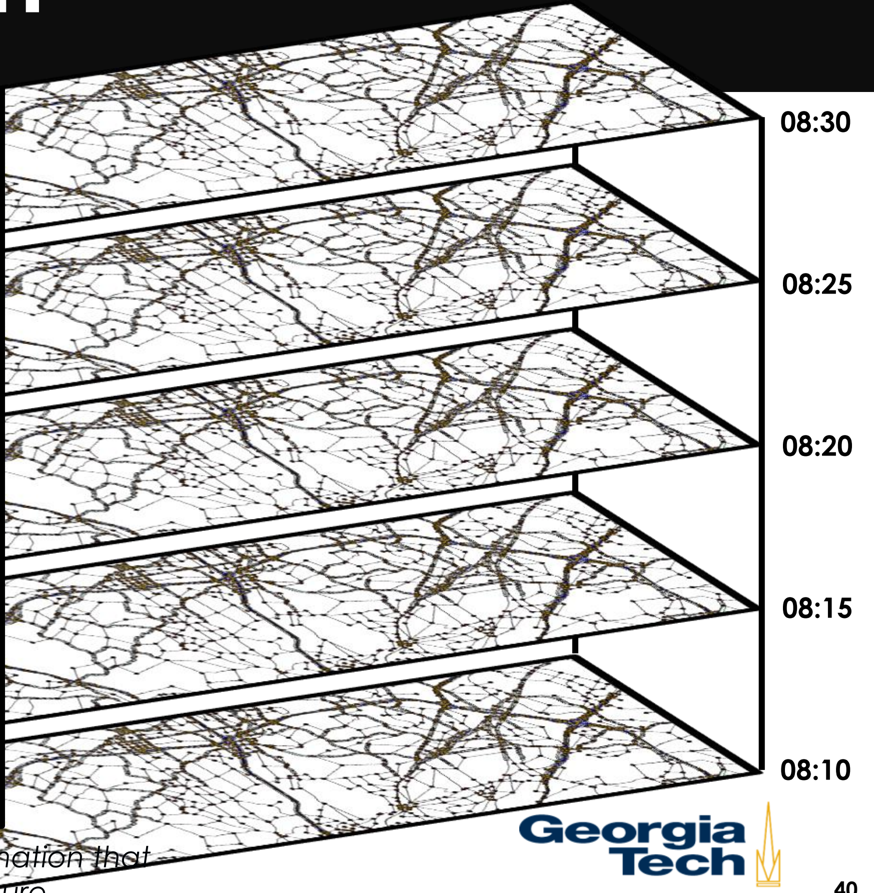




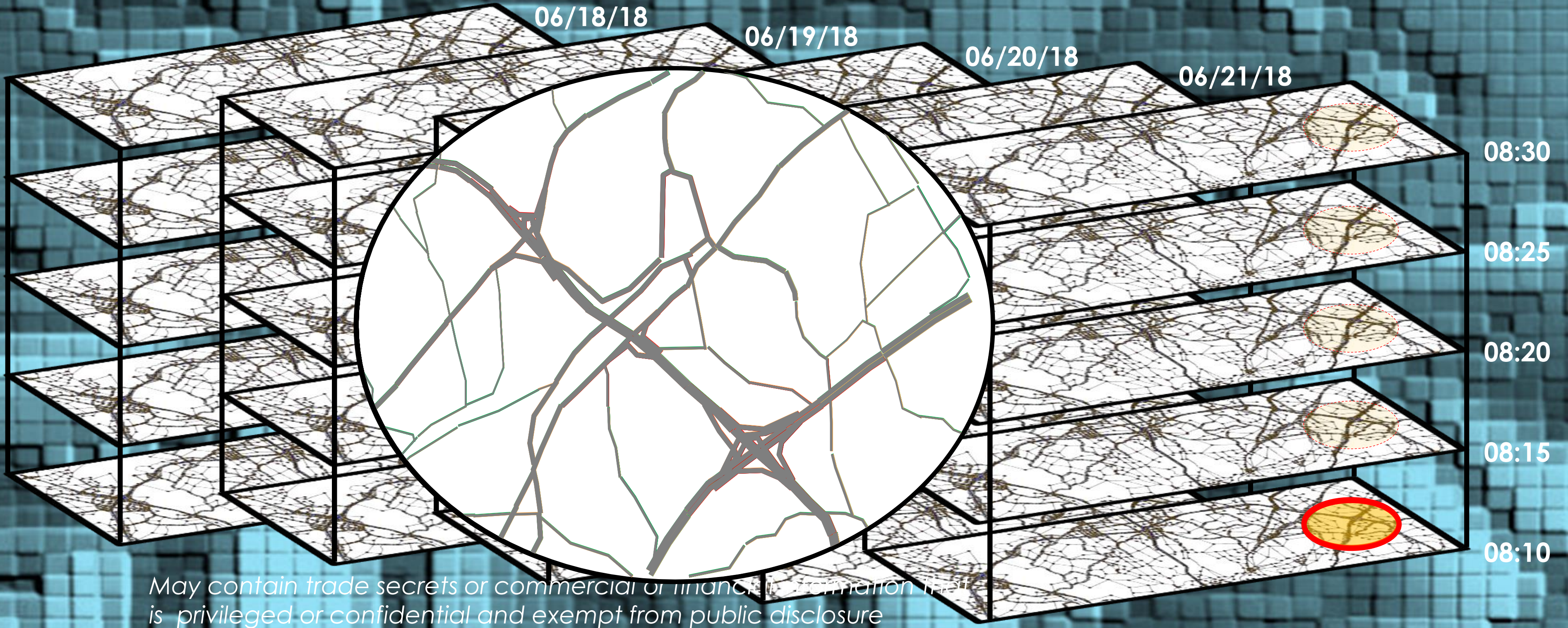
Congestion Formation



Congestion forms in predictable patterns in space and time, whether recurring daily or resulting from major incidents….

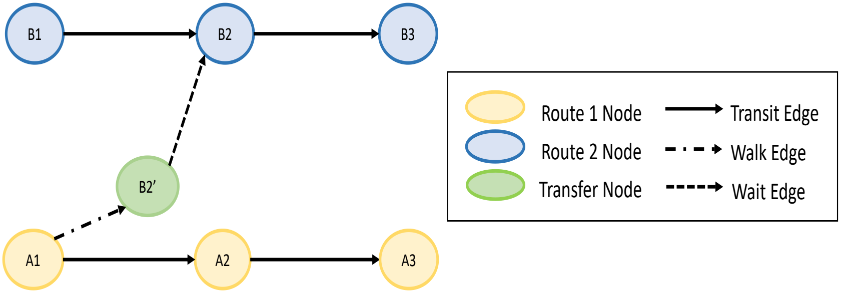


Space-Time Memory (STM)
100+ Elements for Deep Learning



Regional Roadway Simulator (RoadwaySim) and Transit Simulator (TransitSim)

- Python-based shortest-path models
  - 203,000-link road network
  - 90+ MARTA bus/rail routes
  - 23 GRTA express bus routes



- Users provide origin-destination pair and departure time
- Simulators find shortest path trajectories through the STM
  - Trajectories move through space <u>and</u> time
  - Can account for congestion formation and dissipation

Georgia Tech

RoadwaySim/TransitSim
Shortest Path Modeling Demonstration

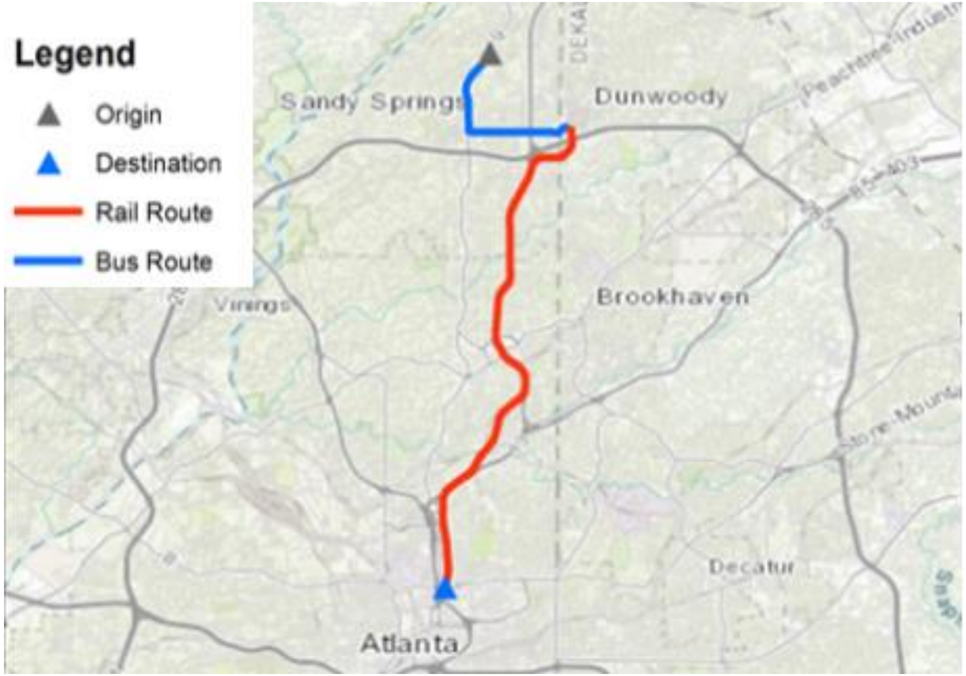
- Compare options for an origin-destination pair
  - Sandy Springs single-family home (origin)
  - Midtown Atlanta Bank of America (destination)
- Travel options:
  - Two driving routes
  - Transit route, with one transfer
  - Transit route, no transfers
  - Rail transit, park-and-ride access
  - Xpress bus, park-and-ride access

Driving (First Route)

- 26 minutes
  - Drive to work: 26

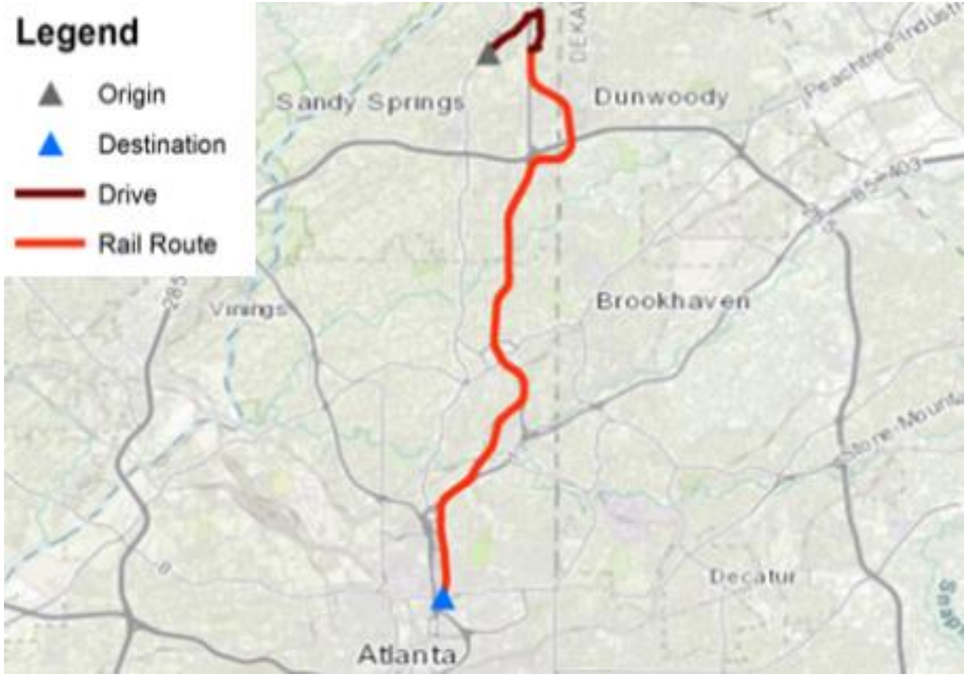
Transit Only (One Transfer)

- **44 minutes**
  - **Walk to bus: 4**
  - **Ride on bus: 18**
  - **Walk to rail: 1**
  - **Ride on rail: 18**
  - **Walk to work: 3**



Rail Transit, Park-and-Ride

- 35 minutes
  - Drive to rail: 10
  - Ride on rail: 22
  - Walk to work: 3

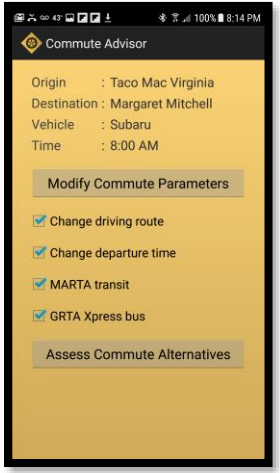


Xpress Bus, Park-and-Ride

- 94 minutes
  - Drive to Xpress: 23
  - Ride on Xpress: 68
  - Walk to work: 3

Commute Alternatives Analysis

- 12 alternatives options
  - Routes
  - Times
  - MARTA bus and rail
  - GRTA Xpress bus
- STM trajectories return to the app for each alternative
- App displays time, cost, and energy for each choice



Commute Advisor

Twelve Option Returns

MARTA Bus Route 36

May contain trade secrets or commercial or financial information that is privileged or confidential and exempt from public disclosure

Summary

- MOVES-Matrix (brute-force modeling with MOVES)
  - Obtains exactly the same energy and emissions rates
- Applicable at any spatial and temporal scale
  - Regional, corridor case studies, simulations, apps, etc.
  - Links to dispersion modeling (AERMOD-Grid)
- Matrices are very large (Python scripts required)
  - Python, distributed computing, GIS, visualization, traditional modeling (regional, simulation, dispersion)
- Big data and deep learning applications are evolving

Ongoing Work

- Dissertations:
  - Road grade integration into modeling tools (complete)
  - Hybrid/electric vehicles (Autonomie) into VSP framework
  - Transit fleet optimization modules
  - Distributive justice assessment models
  - Daily pollutant exposure assessment tools
- Theses:
  - Energy and emissions impacts of managed lanes