# Distributed computing for traffic-related air pollutant concentration modeling at regional scales

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# Bio

- (2023~) Assistant Professor in Asia Pacific School of Logistics at Inha University
- (2020~2023) Assistant Professor in Dept. of Urban Planning & Real Estate at Gangneung-Wonju National University
- (2020) Ph.D. in Transportation Engineering at Georgia Tech
- (2018) M.S. in Computational Sci. & Eng. at Georgia Tech
- (2013) Master of Urban Planning at Seoul National University
- (2011) B.S. in Transportation Engineering at University of Seoul

**General Research Interests**

1 Sustainable transportation/logistics – Energy use, emissions, air quality

2 Smart and shared mobility – Carsharing, electric vehicle, autonomous vehicles

3 Data analytics – Simulation, big data, machine learning, high-performance computing, statistics, data visualization

# Background

- Transportation has significant impacts on the Environment
  - Transportation/logistics contributes around 24% of global $CO_2$ emissions
  - 20~25% of consumed energy
  - Major sources of urban air pollutions (PM, ozone, CO, etc.)

*"4.2 million premature deaths globally are linked to ambient air pollution, mainly from heart disease, … acute respiratory infections in children."*

*"South Korea has the worst air pollution among the developed nations in the Organization for Economic Cooperation and Development (OECD)."*

*"… air pollution was the No. 1 source of concern for South Koreans. It scored 3.46 points out of 5, the highest in the survey, …"*


*Transportation pollutions are becoming threat to public health*

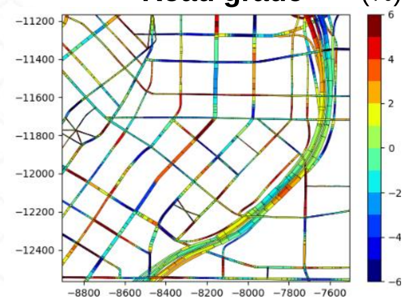
# Objective

- The research aims to predict emissions & energy consumption, and pollutant concentration from on-road transportation, and identify hot-spots where people are vulnerable to harmful pollutions

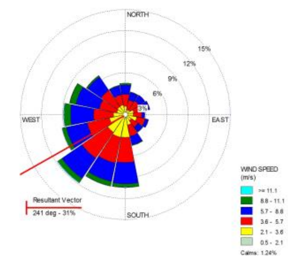
**Traffic volumes**

**Link speeds**

**Road grade** (%)




**Meteorology**




**On-road Emissions**

**Pollution Levels**

**Health Impacts**

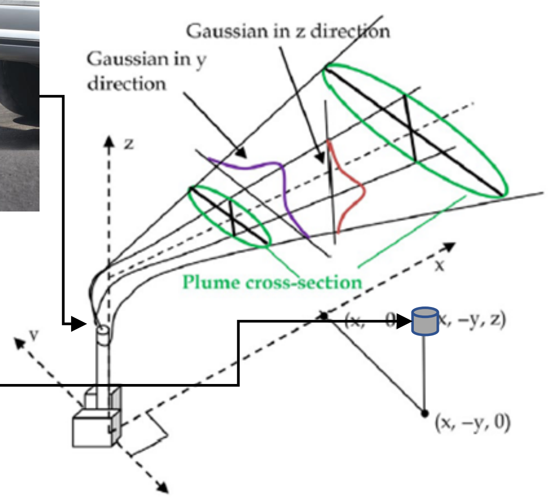

Source: Large-Scale, Dynamic, Microscopic Simulation for Region-Wide Line Source Dispersion Modeling. Georgia Institute of Technology.

# Objective

- Previous research efforts tried to develop models for predicting pollutant concentration from transportation sources using travel activity data and microscale dispersion models
- USEPA's recommended tools such as AERMOD, CALINE3/4, and R-LINE have generally been used for air quality assessments for traffic-related emissions
    - ➢ Generalized Gaussian plume equation

**Emission**

**Concentration site**




$$C(x,y,z;H) = \frac{Q}{2\pi u \sigma_y \sigma_z} \cdot exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{exp\left[-\frac{(H-z)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2\sigma_z^2}\right]\right\}$$

Where, $C$ = air pollutant concentration in mass per volume, in g/m$^3$,

$Q$ = source pollutant emission rate, in g/s,

$u$ = wind speed at the point of release, in m/s,

$\sigma_y$ = horizontal standard deviation of the emission distribution (in m)

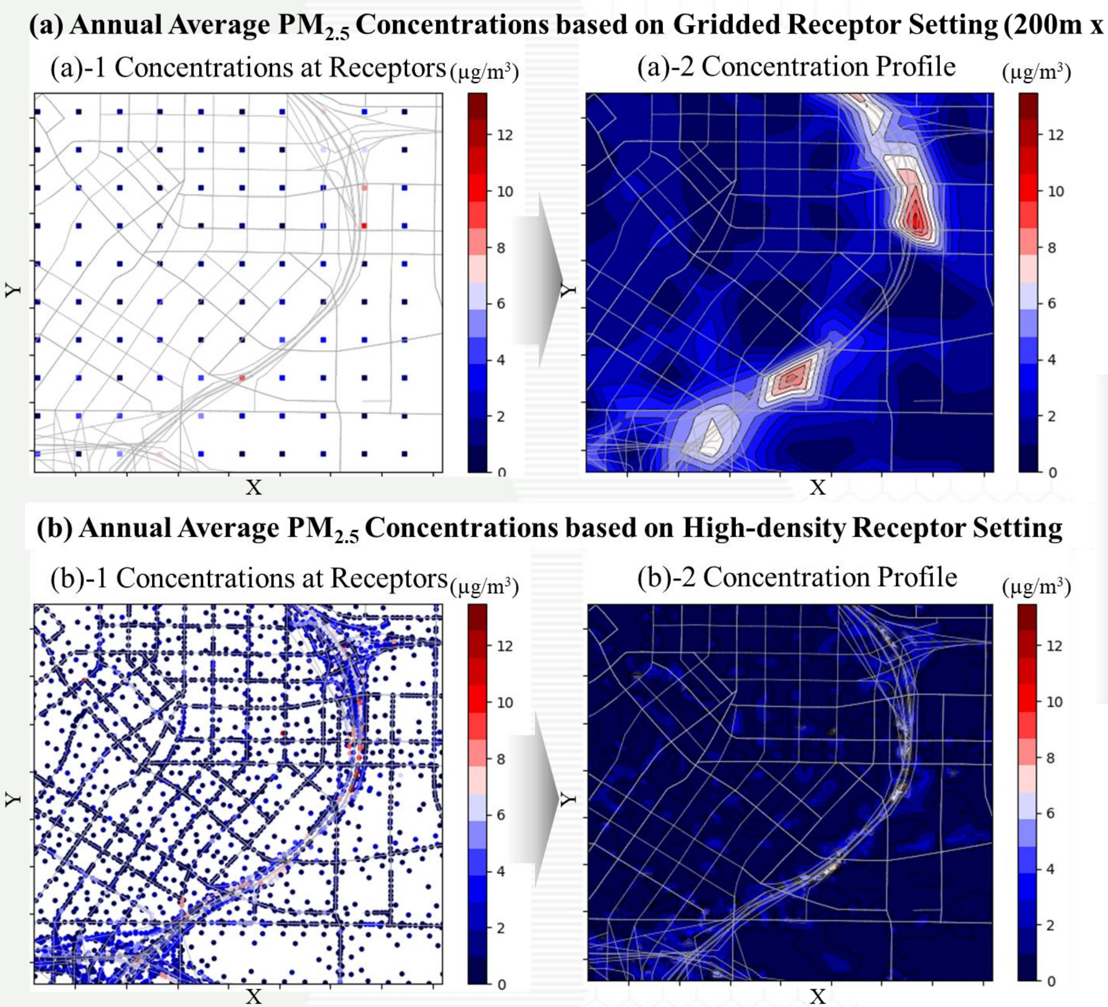
$\sigma_z$ = vertical standard deviation of the emission distribution (in m)

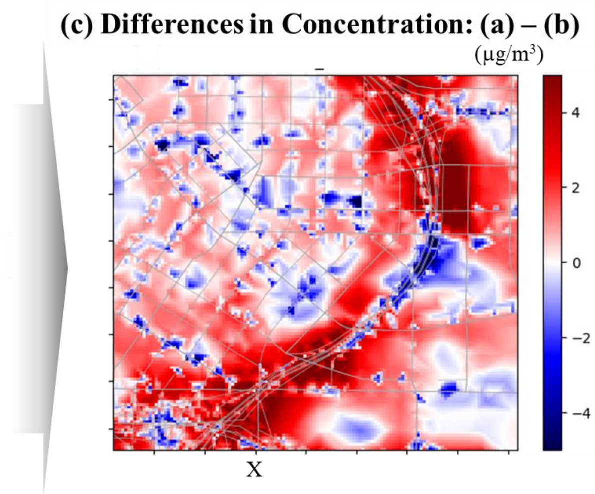
$H$ = height of emission plume centreline above ground level, in m.

# Objective

- Limitations in previous region-level dispersion modeling efforts:
  - ➢ Low-resolution receptor (site of interest to estimate pollutant concentration) grids make it difficult to identify potential hotspots
    - ✓ Most models apply uniform grids of receptors at low-spatial-resolution
    - ✓ Concentration predictions are necessarily biased, because receptor concentrations are sensitive to the distance between receptor and pollutant source link
  - ➢ Computing requirements are high for large areas and dense receptor grids
  - ➢ Analyses do not currently consider dynamic traffic operations (e.g., variations in fleet composition, traffic conditions, meteorology, and road grade)
  - ➢ Tools are not publicly available

# Objective



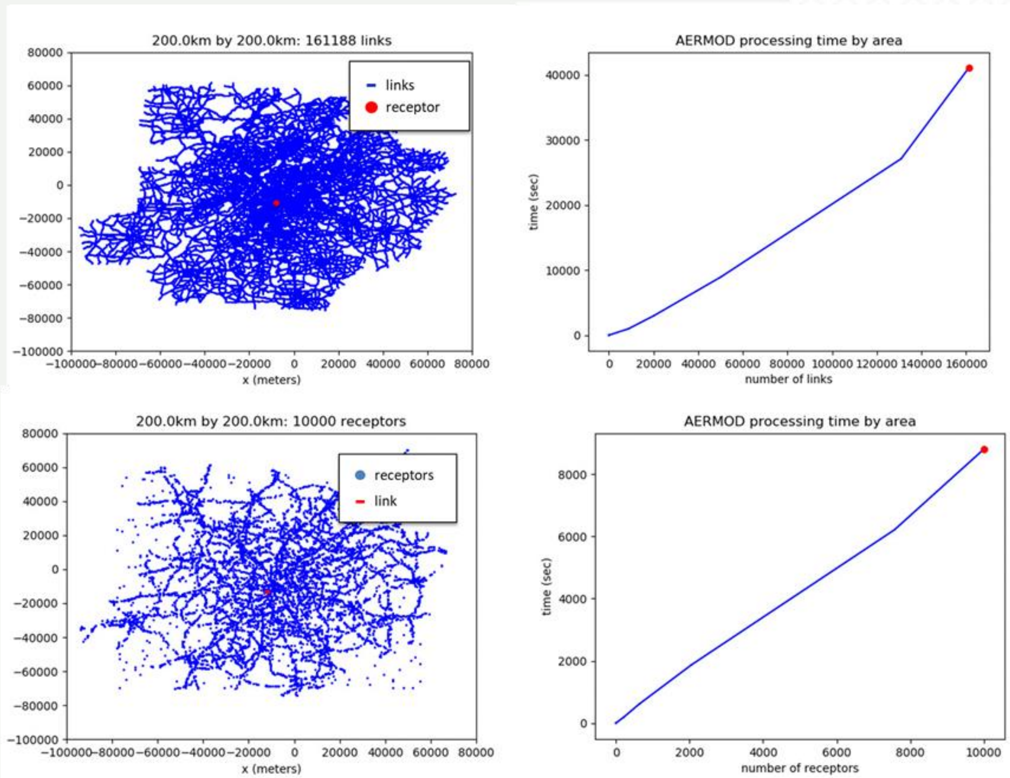




Note: Graph (a)-2 and (b)-2 display contour plots representing the $PM_{2.5}$ concentrations at all available receptors ((a)-1, (b)-1) on a 200 by 200 grid space

Source: Kim, D., H. Liu, X. Xu, H. Lu., R. Wayson, M.O. Rodgers, R. Guensler. (2020) Streamlined Data Processing for Regional Scale Applications of Line Source Dispersion Modeling via Distributed Computing. Presentation at the 99th Transportation Research Board (TRB) Annual Meeting, 2020.

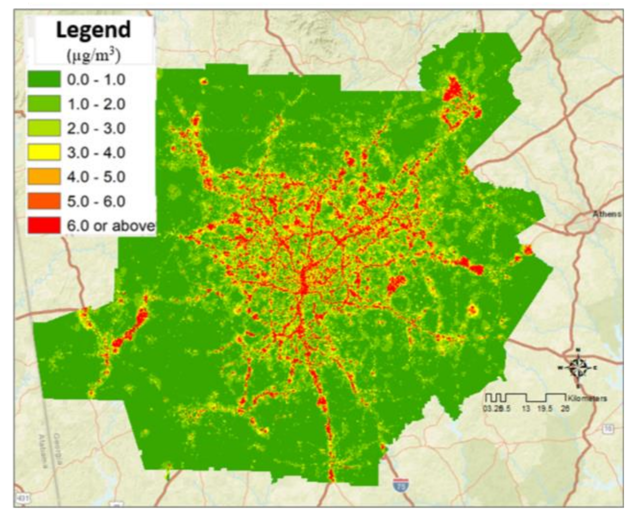
# Objective

- **Pollution dispersion modeling for large-scale transportation network requires a huge simulation time**
  - ➢ **Combination of the number of roadway links and point of interests exponentially increases the total dispersion simulation time**




Total runtime would take many years with traditional modeling methods

**Estimated PM2.5 Concentration Profile (Metro Atlanta)**



# Goals

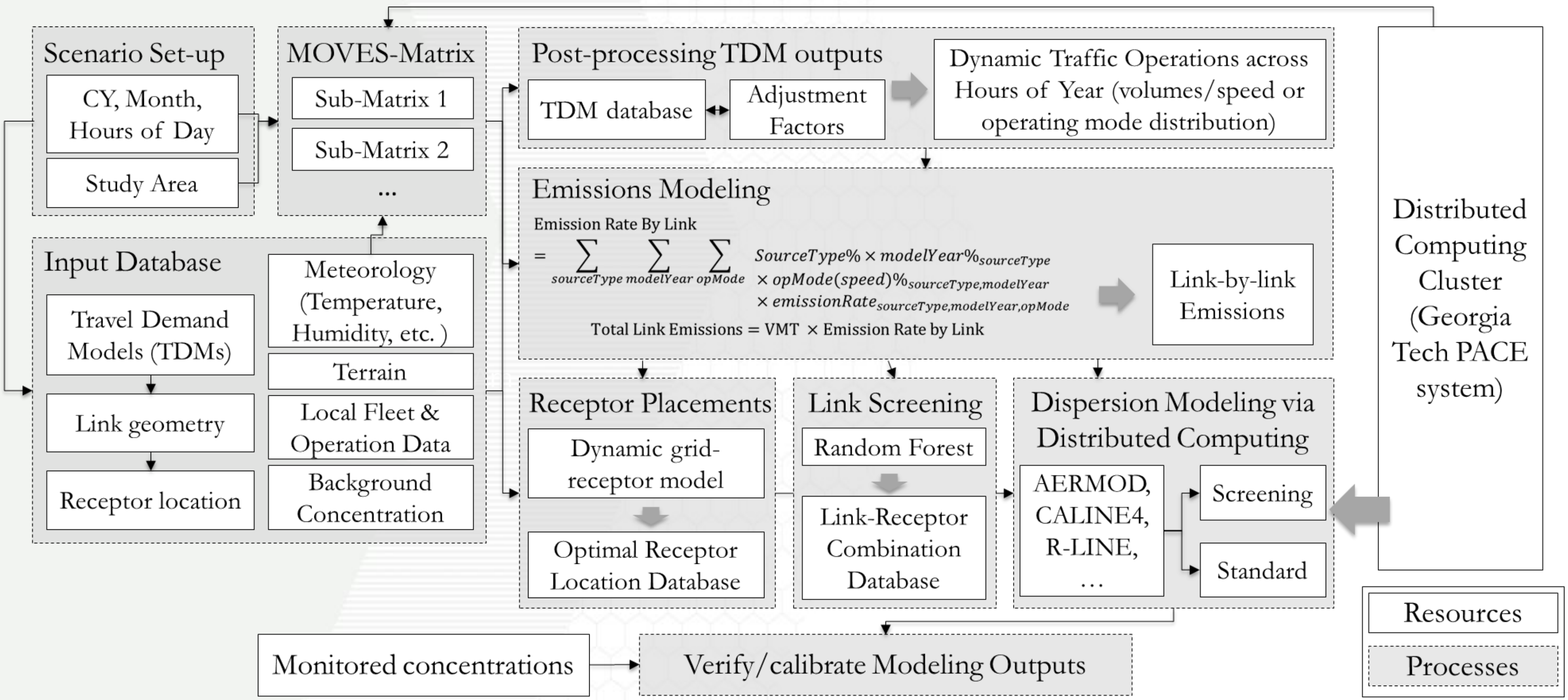
- Computationally efficient modeling at high spatiotemporal resolution
  - Reduce spatial bias
  - Reasonable runtimes
- User-friendly
  - Minimize data input preparation
  - Minimize manual labor
  - Streamline and integrate emissions and dispersion modeling processes

**Large-scale, Dynamic, Microscopic Simulation for Region-wide Line Source Dispersion Modeling**

- Dynamic Grid-Receptor Model
- Supervised Link Screening
- Streamlined Data Processing for Dispersion Modeling
- Case Study for Metro Atlanta

# Modeling Framework

- **Streamlined modeling system that combines input data preparation, travel demand modeling, emissions modeling, and dispersion modeling via distributed computing**



# Advanced Emissions Modeling

- **MOVES is a recommended vehicle emission simulator in the U.S.**
  - **Time consuming and not user-friendly**
- **MOVES-Matrix is high-performance emission modeling system developed by Georgia Tech**
  - **Analyze energy consumption and pollution emissions efficiently**
  - **Super-faster (x 200) than USEPA's MOVES and user friendly**
- **Emissions calculations for each link based on MOVES-Matrix**

$$\text{Emission Rate by Link} = Activity_{fleet} \sum_{ST} \sum_{MY} \sum_{FTS} (ST\% \times MY\%_{ST} \times FTS\%_{ST,MY}) \times ER_{ST,MY,FTS}$$

Where,

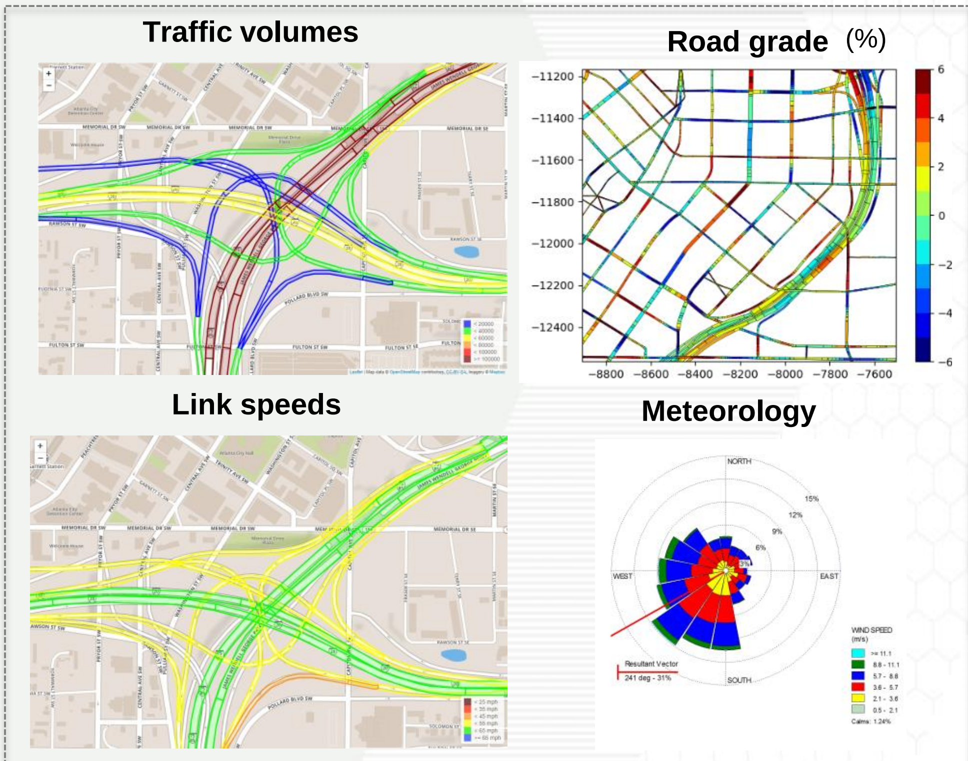
$Activity_{fleet}$ is on-road vehicle activity on a link (in vehicle-miles or vehicle-seconds)

$ST\%$, $MY\%$ and $FTS\%$ are distributions of vehicle source type, model year by source type, and on-road activity (facility type and average speed) by model year and source type

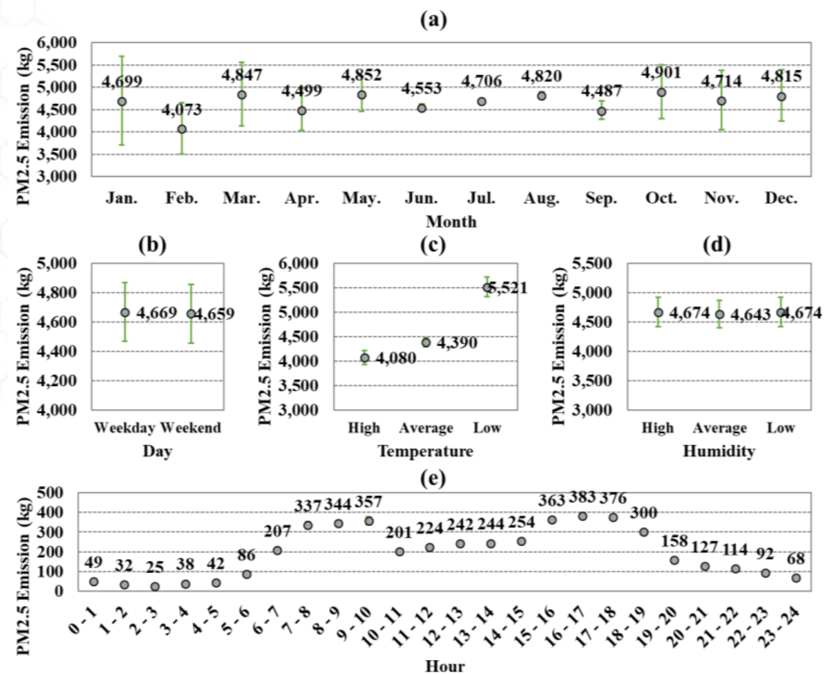
$ER$ is the corresponding MOVES emission rate (grams/mile, or grams/second) contained in MOVES-Matrix for each facility type, operating speed, source type, and model year

# Advanced Emissions Modeling

- Traditional modeling considered static traffic condition (e.g., annual average traffic volumes and speeds)
- The modeling system is able to estimate spatiotemporal variation in on-road emissions considering dynamic traffic condition




Temporal variation in $PM_{2.5}$ Emissions in Metro Atlanta

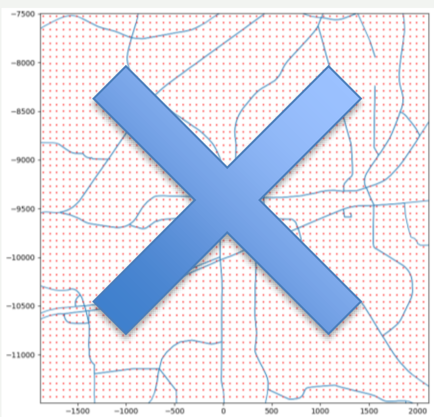



Note: The gray circle represents the sample mean. The green error bar represents a 99% confidence limit on the mean.

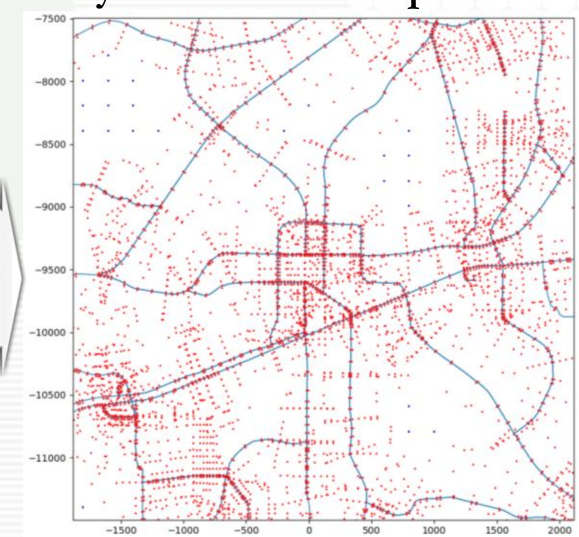
# Advanced Dispersion Modeling

- Chapter 1: Dynamic Grid-Receptor Model
  - Most previous studies for region-wide dispersion modeling have utilized gridded receptors with relatively low resolution (e.g., 200 m x 200 m)
  - However, increasing number of receptors results in longer total processing times
  - The research aims to estimate unbiased concentration profile while minimizing the total computational time

Static Grid-receptor Model

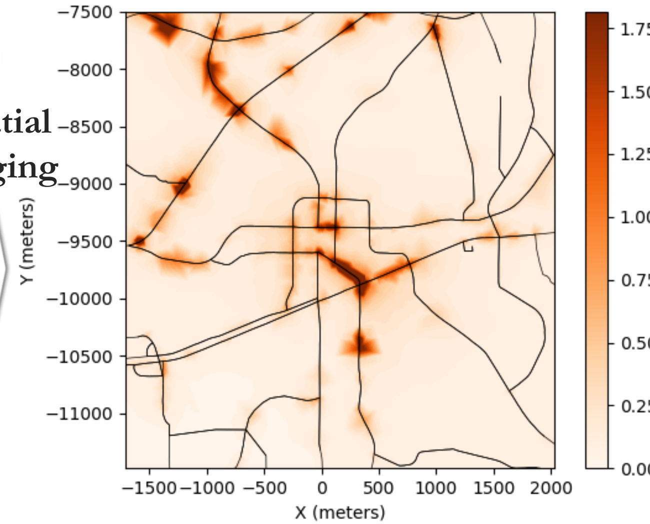


Dynamic Grid-receptor Model



Spatial kriging

Unbiased concentration profiles

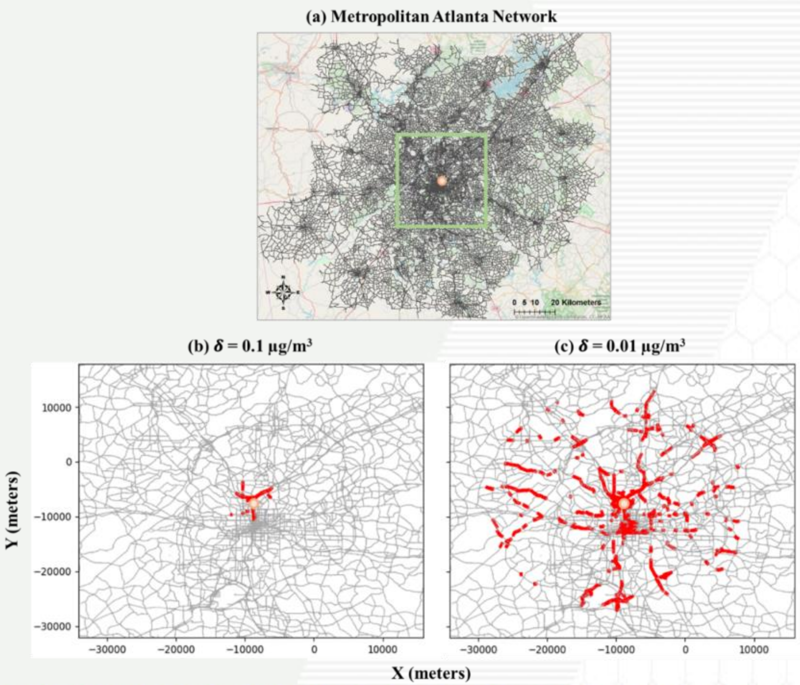


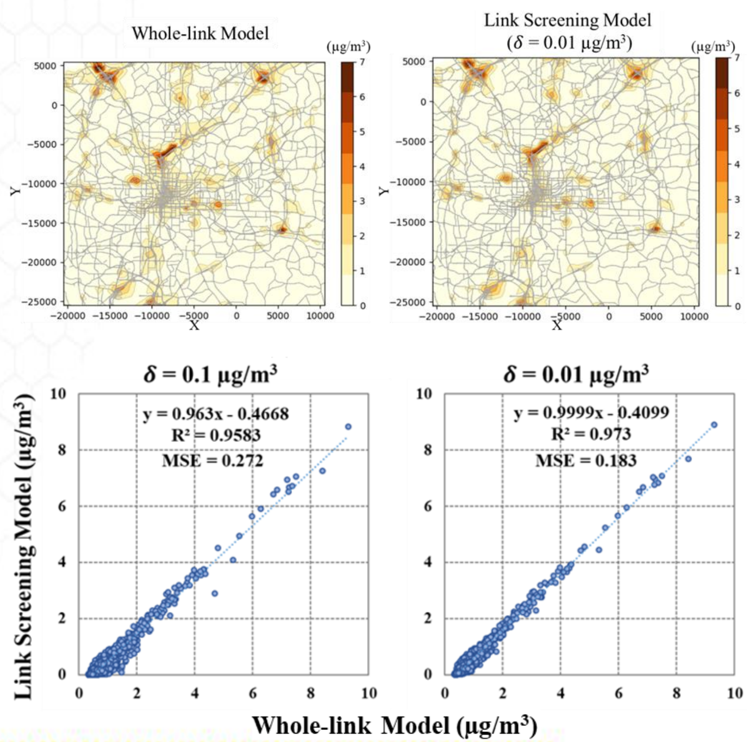

Kim, D., Liu, H., Rodgers, M. O., & Guensler, R. (2022). Dynamic grid-receptor method for regional-level near-road air quality analysis. *Transportation Research Part D: Transport and Environment*, 105, 103232.

# Advanced Dispersion Modeling

- Chapter 2: Supervised Link Screening (SLS)
  - The purpose of link screening is to identify and remove roadway links with negligible concentration contributions for each receptor to minimize computation cost, without undermining estimation precision
  - Machine learning (random forest) identifies roadway links that significant affect pollutant concentration at site of interest

**Supervised Link Screening**



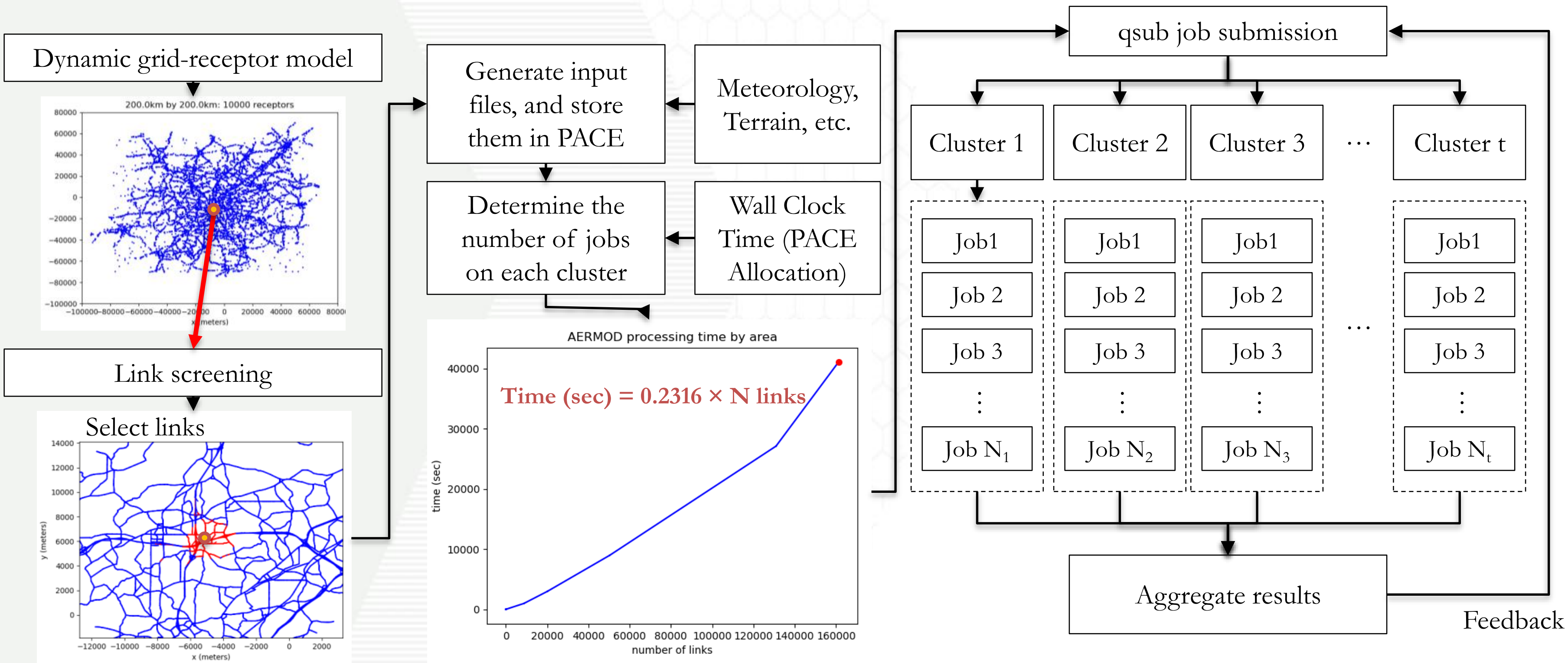





Kim, D., Liu, H., Rodgers, M. O., & Guensler, R. (2020). Development of roadway link screening model for regional-level near-road air quality analysis: A case study for particulate matter. *Atmospheric environment*, 237, 117677.

# Distributed Computing

- Chapter 3: High-performance distributed computing
  - Allocate dispersion modeling jobs into distributed computing resources (e.g., Georgia Tech's PACE super-computing cluster)

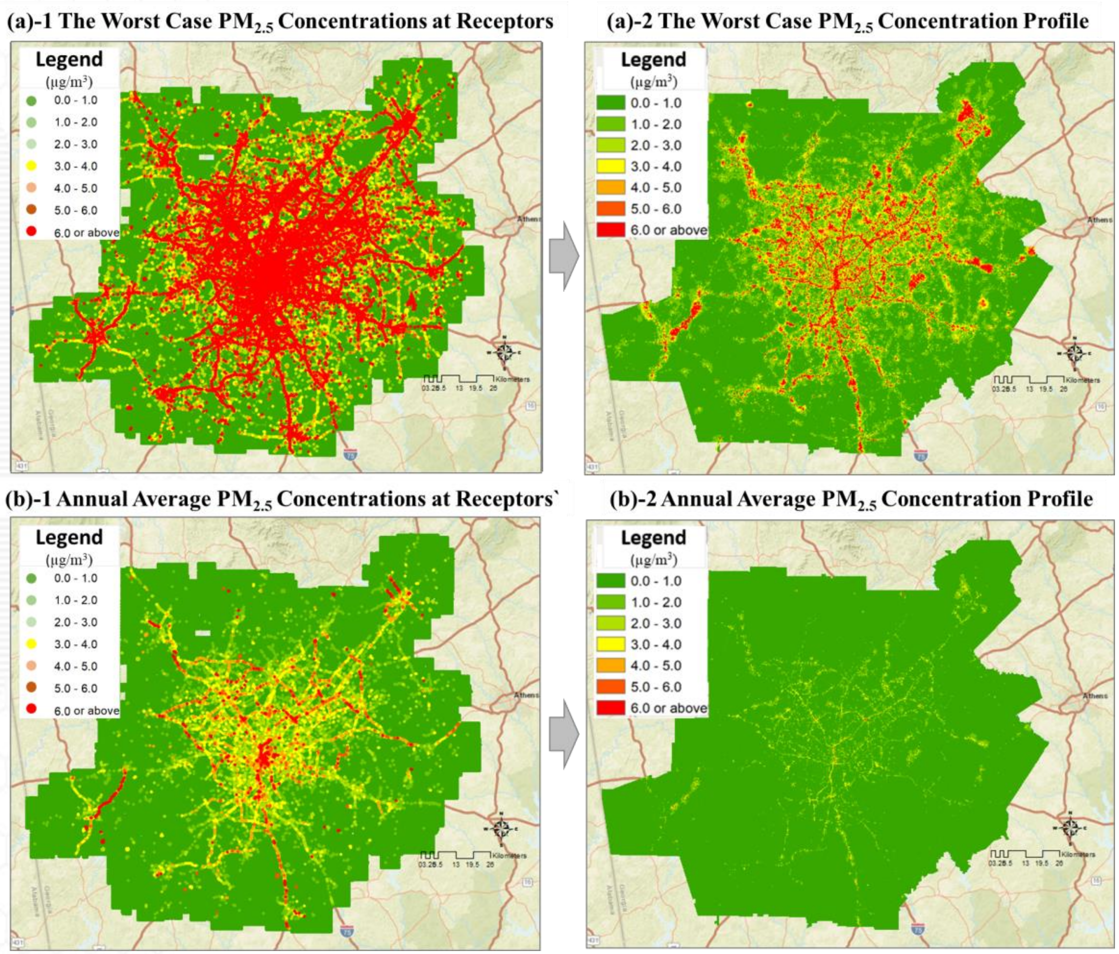



Kim, D., Liu, H., Xu, X., Lu, H., Wayson, R., Rodgers, M. O., & Guensler, R. (2021). Distributed computing for region-wide line source dispersion modeling. *Computer-Aided Civil and Infrastructure Engineering*, 36(3), 331-345.

# Case Study: Metro-Atlanta

- The case study demonstrated the performance of the modeling system, compared to existing approaches, in terms of total processing time
- Screening model run (worst-case): about three days
- Standard model run (annual average): about ten days
- Traditional methods: years to perform the same analyses on a single machine

**Estimated $PM_{2.5}$ Concentration Results:**
**(a) Screening Model (b) Standard Model**



# Case Study: Metro-Atlanta

- **The dramatic reduction in computational time is mainly due to applying the dynamic grid-receptor model, supervised link screening model and employing the PACE distributed computing platform**

**Expected and Actual AERMOD Runtimes for Metro Atlanta (Standard Modeling)**

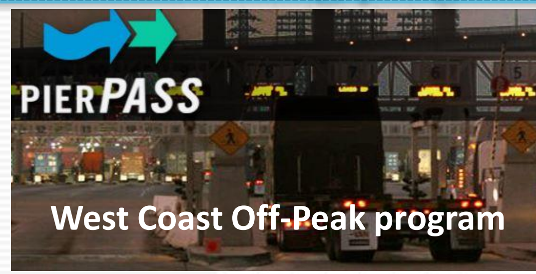
| Classification | Average number of links | Receptors | Total runtime |
|---|---|---|---|
| Traditional modeling | 161,188 | 10,626,677 [1] | many years [2,3] |
| After applying dynamic grid-receptor model | 161,188 | 878,731 | many years [2,3] |
| After applying link screening | 23 | 878,731 | 1,220 days [2,3] |
| Dispersion modeling through PACE | 23 | 878,731 | 10 days [3] |

[1] The number of receptors is determined based on USEPA's hot-spot guidance (25-m resolution near roads and 100-m resolution for other areas)
[2] Expected runtime
[3] The runtime does not include ARC-ABM model runtime. The ARC-ABM traffic assignment runs around 1.5 days (or 4 days with path retention)

# Applications: Freight truck shifting programs

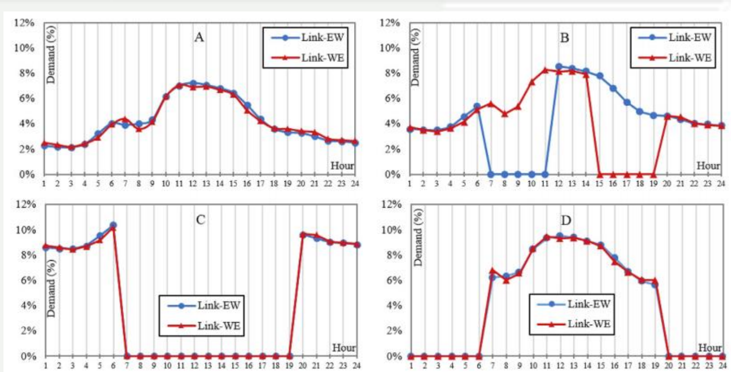
- Environmental assessment of freight truck shifting programs
  - ✓ Freight transport is mainly operated by diesel engine-driven heavy-duty vehicles causing negative externalities on the environment and livability
  - ✓ Truck shifting programs can mitigate energy consumption and pollution

## Truck shifting programs

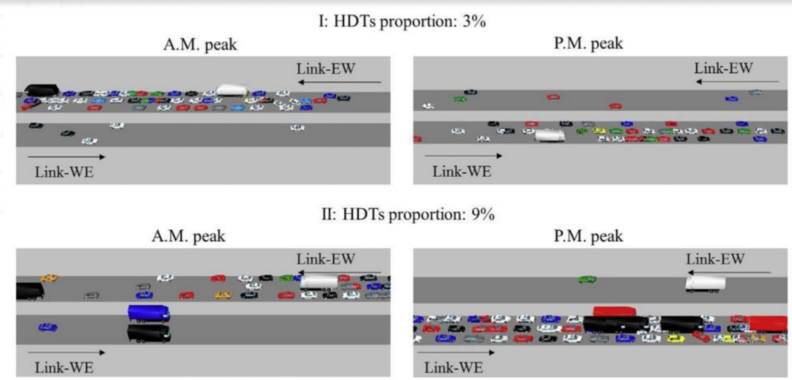





## Scenario set-up




## Traffic simulation using VISSIM

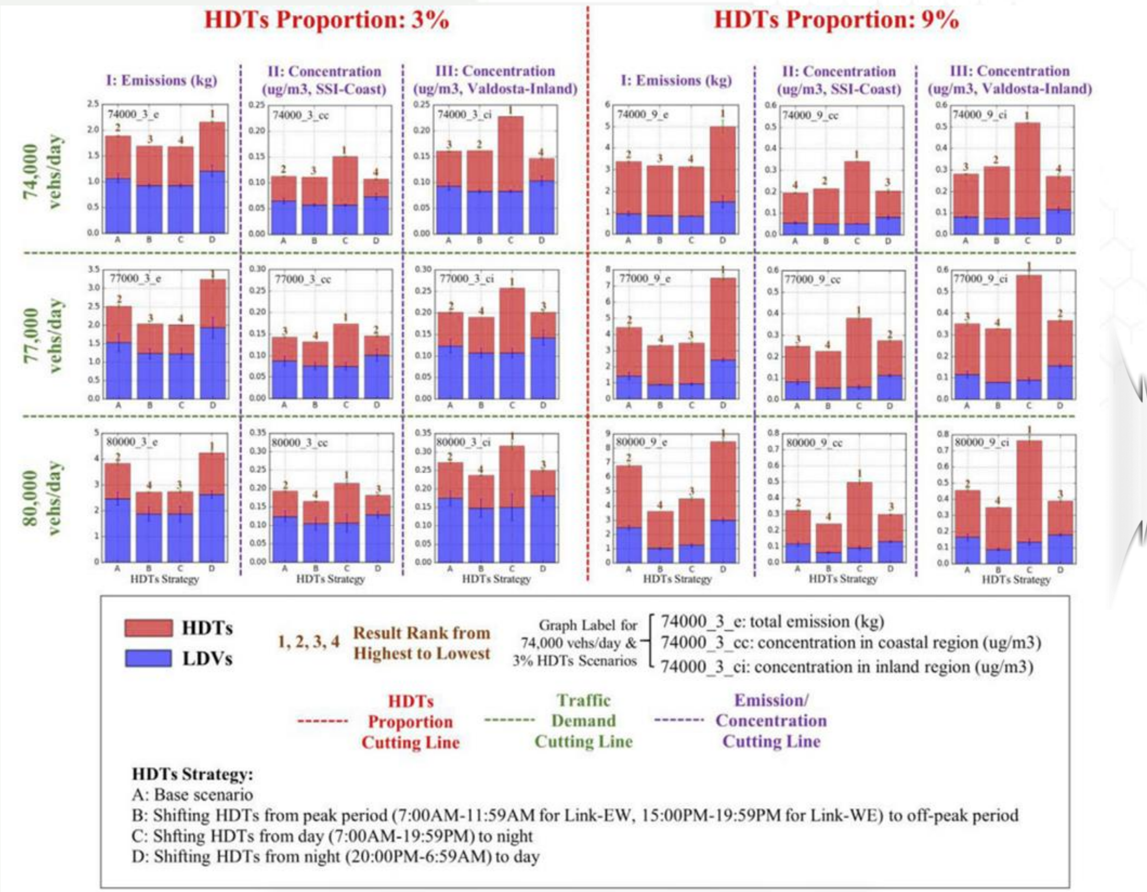





Source: Simulating the uncertain environmental impact of freight truck shifting programs. *Atmospheric Environment*, 214, 116847. 2019.

# Applications: Freight truck shifting programs

- Impact of truck shifting programs on near-road pollutant concentration
  - ✓ Truck shifting programs influence particulate matter (PM) emission and concentration depending on meteorology and traffic conditions




## Policy implications

**Peak-period to off-peak program** is effective to reduce emissions and PM concentration under high traffic volume and high truck proportions

**Night to day program** increases total emissions, but decreases average PM concentrations under low traffic conditions

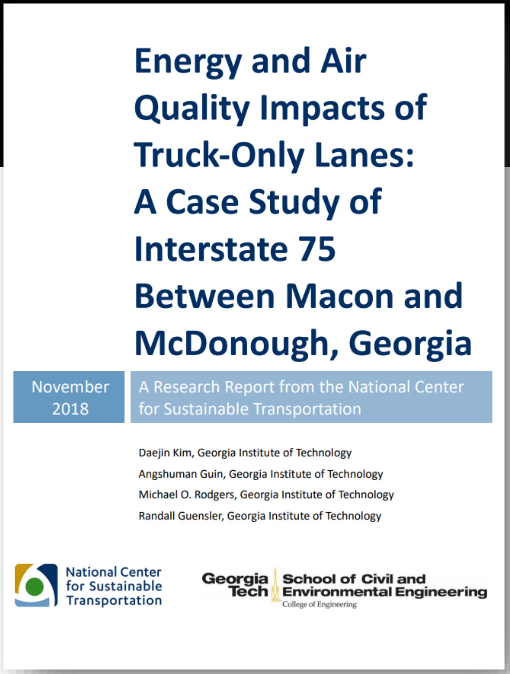
**Day to night program** can minimize total emission, but contributes to higher average PM concentrations



Source: Simulating the uncertain environmental impact of freight truck shifting programs. *Atmospheric Environment*, 214, 116847. 2019.

# Applications: Truck-only lanes

- Environmental assessment of [truck-only lanes]
  - ✓ Truck-only lanes enhance safety and traffic flow by separating trucks from mixed-flow traffic, and also potentially reduce emissions and concentrations
  - ✓ Individual research funding ($60,000 USD/year) from National Center for Sustainable Transportation (NCST)



Energy and Air Quality Impacts of Truck-Only Lanes: A Case Study of Interstate 75 Between Macon and McDonough, Georgia

November 2018

A Research Report from the National Center for Sustainable Transportation

Daejin Kim, Georgia Institute of Technology
Angshuman Guin, Georgia Institute of Technology
Michael O. Rodgers, Georgia Institute of Technology
Randall Guensler, Georgia Institute of Technology

National Center for Sustainable Transportation

Georgia Tech School of Civil and Environmental Engineering College of Engineering

## Georgia Plans $2 Billion Truck-Only Roadway to Fight Traffic Bottleneck

May 02, 2016 by Clarissa Hawes


# Applications: Truck-only lanes

- Effectiveness of [truck-only lanes]

## Design Layouts of I-75 Truck-only Lanes from GDOT

## Traffic Simulation

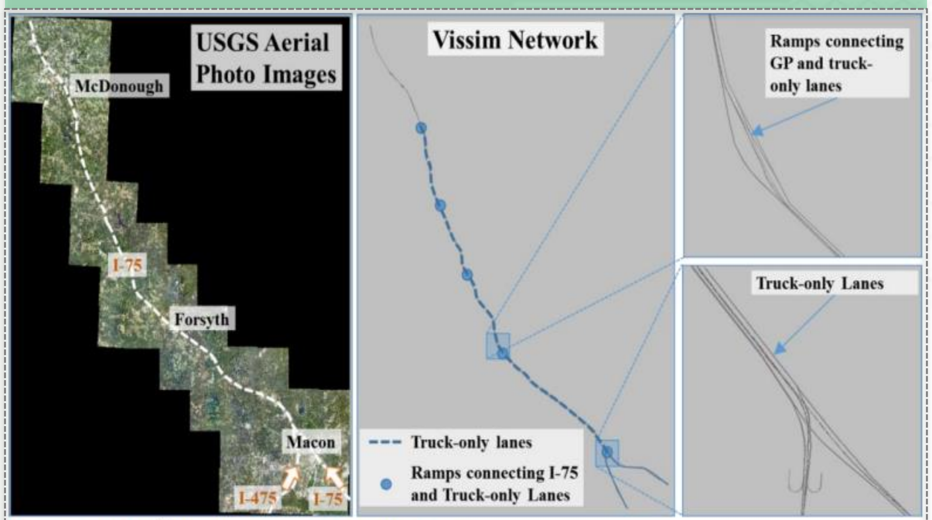



Figure 3. Vissim® Network Generation Process

## Findings

**Separation effects**
- Average travel speeds increase from 68.3 mph to 71.9 mph (+5.3%)

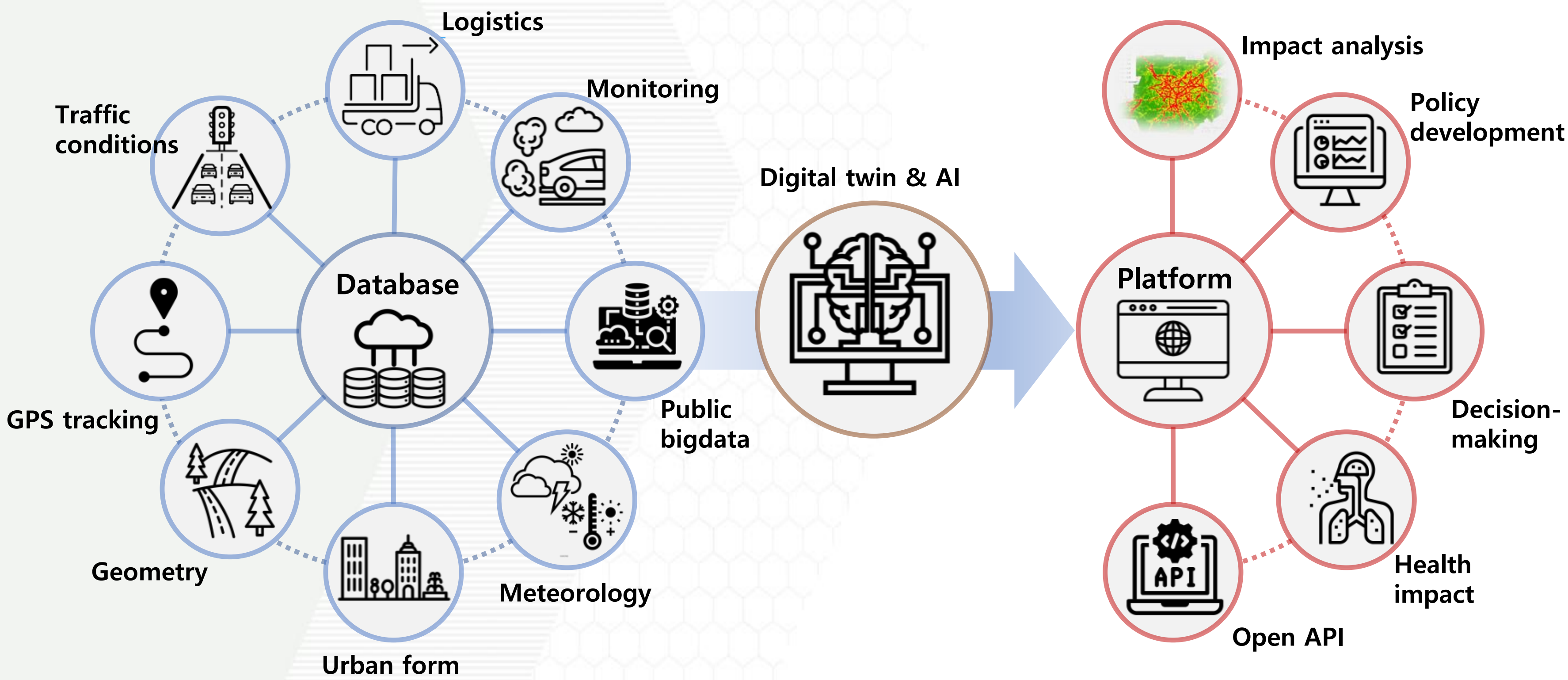
**Reduction in energy use and emissions**
- Fuel: 797 GJ to 776 GJ (-2.6%)
- $CO_2$: 57,663 kg to 56,085 kg (-2.7%)
- $PM_{10}$: 2,055 g to 1,947 g (-5.3%)

**Pollutant concentration reduction**
- CO: 122.6 $\mu g/m^3$ to 110.9 $\mu g/m^3$ (-9.5%)
- $PM_{10}$: 0.29 $\mu g/m^3$ to 0.27 $\mu g/m^3$ (-7.7%)
- NOx: 8.2 $\mu g/m^3$ to 7.8 $\mu g/m^3$ (-5.3%)

# On-going Research

## Big Data Based Policy Making System

- Effective policy development tool for evaluating the impacts of prospective sustainable transportation/logistics operation and infrastructure



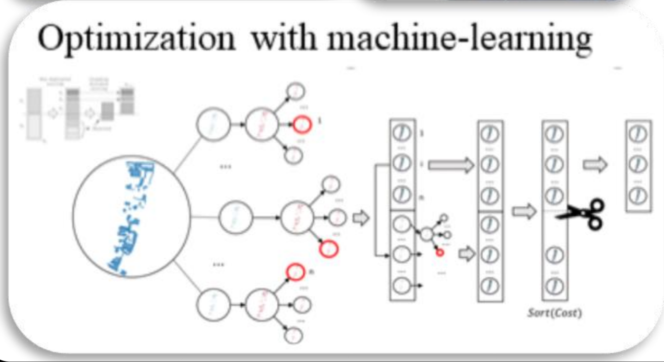
# On-going Research

## Big Data Based Policy Making System

- Integrated logistics simulation platform based on big data, AI, simulation
- Support decision making through digital-twin & multi-criteria analysis

Infrastructure


Integrated logistics simulation platform




Logistics solutions

Smart mobility


# Thank you!