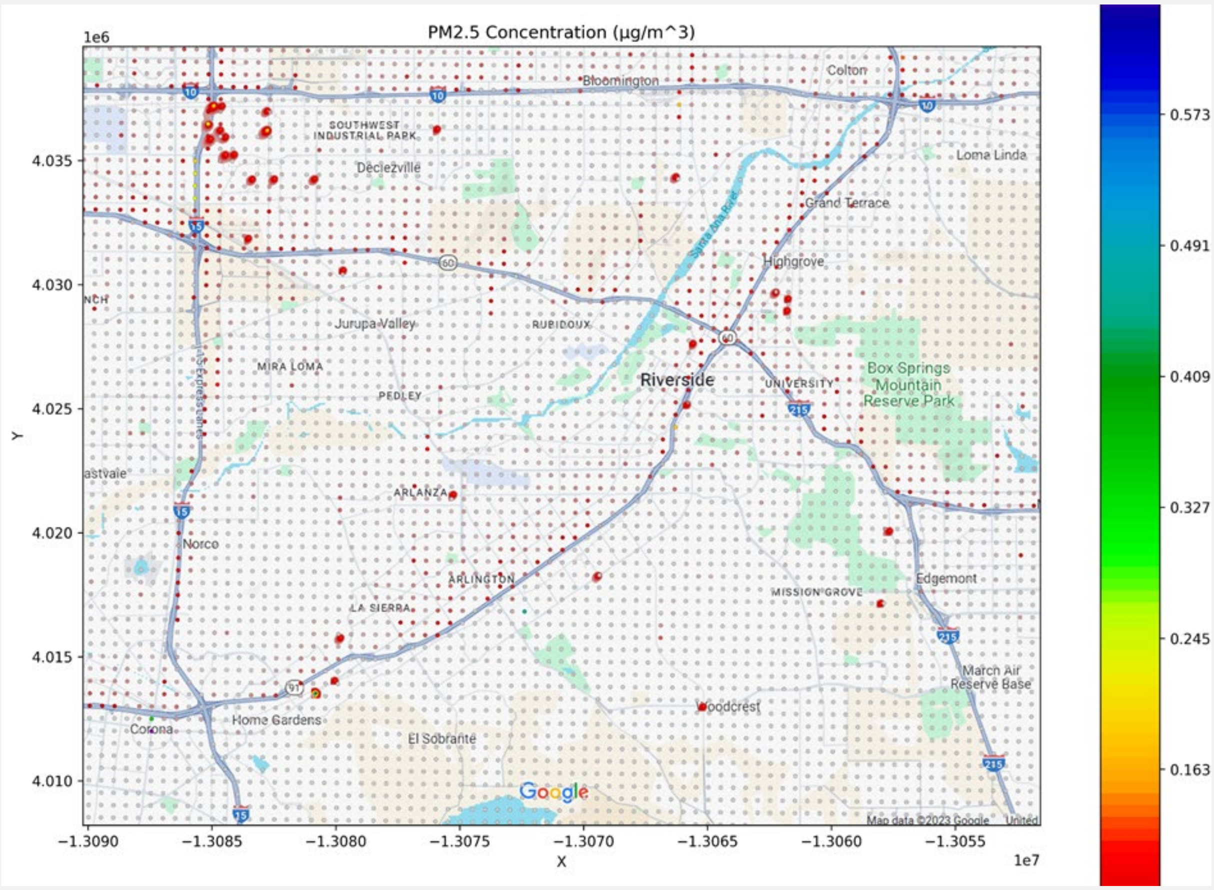
ENHANCING THE MODELING OF EMISSION DISPERSION FROM IDLING AND SLOWLY MOVING TRUCKS



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16. Abstract

This report investigates the dispersion of emissions from idling and slowly moving trucks, addressing the environmental impact of such activities in urban settings. Utilizing an integrated simulation platform, the study enhances existing models to capture the nuanced dynamics of truck emissions. Key components of the platform include the Behavior, Energy, Autonomy, and Mobility model, EMission FACtor Model, Research LINE-source (R-LINE) Dispersion Model, Motor Vehicle Emission Simulator, and a grid-based dispersion model. Field data from Riverside, California, were used to evaluate the performance of the platform, revealing significant pollutant concentrations near areas of intense truck activity. This Enhanced Truck Dispersion Simulator provides policymakers and urban planners with a robust tool to assess and mitigate the impact of truck emissions, promoting the adoption of sustainable transportation technologies.

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Executive Summary

The increasing complexity of urban transportation systems and the proliferation of truck activity in cityscapes have raised significant concerns regarding their environmental impact. Our study addresses the critical issue of emission dispersion from trucks, especially those idling or moving slowly in urban areas. Recognizing the limitations of existing models in capturing the detailed dynamics of these emissions, our research team has developed an integrated simulation platform to provide a more nuanced understanding of the environmental impact of truck activities.

This advanced platform, named the Enhanced Truck Dispersion Simulator, comprises several integral components that collectively analyze the intricate patterns of truck emissions. The key modules include:

- Behavior, Energy, Autonomy, and Mobility (BEAM) Traffic Simulation: This module focuses on macroscopic traffic modeling, essential for understanding the movement of trucks between urban locations and their associated on-road emissions.
- EMission FACtor (EMFAC) Model: Employed for detailed emission analysis, EMFAC evaluates emissions based on factors like vehicle types, speeds, and operational modes, contributing to a comprehensive emission profile.
- R-LINE Model: R-LINE complements our analysis by modeling the dispersion of emissions from moving trucks, offering a spatial understanding of emission distribution.
- Motor Vehicle Emission Simulator (MOVES): MOVES is specifically tasked with microscopic emission modeling, particularly crucial for analyzing emissions from trucks in idling states within warehouses.
- Grid-based Dispersion Model: Developed to visualize and analyze the spatial dispersion of emissions, this model uses calibrated parameters based on real-world measurements.

Our case studies, conducted in Riverside, California, were pivotal in applying these models to practical scenarios. We explored various truck movement patterns and operations strategies, including scenarios with centralized and decentralized pickup and drop-off locations. These studies revealed that areas with concentrated truck activities exhibited significantly higher pollutant levels, underscoring the impact of truck emissions on urban air quality.

One of the most striking outcomes of our research is the visualization of emission dispersion patterns. This aspect of our study not only enhances the understanding of pollutant spread in urban environments but also provides essential data that can inform policy and planning decisions.

While this study advances our understanding of truck emissions and their dispersion, it lays the groundwork for further research rather than concluding definitive impacts. The findings serve as a basis for more detailed future studies, particularly in relation to the long-term health and environmental implications of these emission patterns.

In summary, our study represents a significant leap forward in modeling truck emissions in urban settings. The Enhanced Truck Dispersion Simulator provides a multi-faceted tool that can aid policymakers and urban planners in evaluating and mitigating the impact of truck emissions, contributing towards more sustainable and healthier urban environments.

Acknowledgments

This research was funded by the Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH), project number 05-58-UCR. The authors would like to thank Dr. Yifan Ding and Dr. Ji Luo for the support of field data collection and insightful discussion. The authors also acknowledge California Air Resource Board for providing PEAQS to measure CO_2 concentration as well as valuable feedback from Dr. Shaohua Hu. The contents of this paper reflect only the views of the authors, who are responsible for the facts and the accuracy of the data presented herein.

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INTRODUCTION

The environmental impact of vehicular emissions has been a topic of significant concern in recent years [1]. As urban areas continue to grow, the number of vehicles on the road increases, leading to heightened levels of pollutants in the atmosphere [2]. These pollutants, primarily originating from vehicle exhaust, have been linked to a range of environmental and health issues, including air quality degradation, respiratory diseases, and global climate change [3]. Particularly, emissions from idling and slowly moving vehicles, such as trucks, play a crucial role in this scenario due to their prolonged operational durations in congested areas and specific emission characteristics [4].

The primary objective of this study is to enhance the modeling of emission dispersion from idling and slowly moving trucks. Accurate modeling is crucial for understanding the spatial and temporal distribution of these emissions, which in turn informs mitigation strategies and policy decisions. Traditional models often fall short in capturing the intricacies of emissions from stationary or slow-moving sources, necessitating a more refined approach.

This report delves into the complexities of truck emissions, exploring both the generation and dispersion phases. By integrating field data with advanced modeling techniques, we aim to provide a comprehensive tool that can accurately predict emission patterns under various conditions. Such a tool is not only valuable for researchers but also for urban planners, environmentalists, and policymakers looking to improve air quality in areas affected by truck emissions.

The rest of this report is organized as follows: the next section reviews the existing literature on traffic simulators, emission models, and dispersion models, highlighting their significance in understanding vehicular emissions. This is followed by a detailed exploration of our field data collection and the analyses derived from it. Subsequently, we discuss the development of an enhanced dispersion model tailored for trucks, and its application in a case study that quantifies the impact of truck activities on city-wide air quality. The final section offers conclusions and potential directions for future research.

LITERATURE REVIEW

Macroscopic Traffic Simulators

Traffic simulation tools replicate real-world traffic situations and are employed to analyze and enhance vehicular movement patterns. These simulators are generally divided into two main categories: Microscopic, focusing on the actions of individual vehicles, and Macroscopic, capturing the overall traffic flow and dynamics. In this research, we predominantly concentrate on macroscopic simulators. POLARIS, renowned for its in-depth traffic flow analytics, has become indispensable in the spheres of urban planning and infrastructure decision-making [5]. SIGOP-II, another significant macroscopic model, boasts algorithms and frameworks adept at addressing complex traffic issues [6]. BEAM stands out for its agent-centric design, which ensures a nuanced capture of the intricate dynamics of transportation systems by emulating individual agent behaviors [7]. Furthermore, BEAM's assimilation of discrete choice models facilitates the simulation of evolving human preferences in the face of emerging technologies and policies. Its capabilities extend to energy analysis, predicting the potential repercussions of electric vehicle integration and comprehending the challenges posed by fully autonomous vehicles on our streets. Additionally, BEAM's proficiency in evaluating urban mobility and its synergy with other modeling tools positions it as a robust option in transportation analysis.

Truck Emission Models

Vehicular emission models are designed to estimate the emission rates and factors of motorized vehicles, considering various traffic conditions and driving cycles. These models play a crucial role in understanding the environmental impact of vehicular emissions, especially from heavy-duty trucks, which are significant contributors to air pollution. Depending on the granularity of data and the level of detail, these models can be broadly classified into microscopic and macroscopic categories.

Microscopic models delve into the intricacies of individual vehicle movements, capturing the nuances of their behavior on a second-by-second basis. Examples of microscopic models include the Comprehensive Modal Emissions Model (CMEM) [8], which was initially designed for light-duty vehicles but has been adapted for heavy-duty diesel vehicles [9], and the Passenger Car and Heavy-duty Emission Model (PHEM) [10], which provides insights into emissions from both passenger cars and heavy-duty vehicles. Additionally, VT-Micro is another microscopic model that estimates emissions based on detailed vehicle operation data. It uses second-by-second vehicle speed and acceleration inputs to calculate emissions and fuel consumption, making it highly precise for capturing the impact of various driving behaviors and conditions. [11].

On the other hand, Macroscopic models provide a broader perspective, focusing on aggregate data and average behaviors. The EMFAC (EMission FACtor) model, developed by the California Air Resources Board, is a prominent example. Tailored for California's unique vehicular and environmental landscape, EMFAC combines emission factors from various vehicle classes, using data such as average speeds and vehicle miles traveled [12]. OPERT, widely used in Europe, is another significant macroscopic model. Developed by the European Environment Agency (EEA) and managed scientifically by the European Commission’s Joint Research Centre, COPERT calculates emissions for different vehicle categories and operational modes. It is recognized for its detailed and comprehensive data, supporting policy decisions, air quality modeling, and environmental assessments by providing emission factors for a wide range of pollutants [13].

The Motor Vehicle Emission Simulator (MOVES), developed by the U.S. Environmental Protection Agency (EPA), is a versatile emission modeling system designed for both macroscopic and mesoscopic analysis and can also be applied to microscopic analysis under certain conditions. MOVES is widely used for national, state, and county-level emissions inventories. It estimates emissions for mobile sources, including cars, trucks, and buses, considering various pollutants such as greenhouse gases, criteria air pollutants, and air toxins. This versatility makes MOVES a powerful tool for broad, regional, and statewide emissions assessments, as well as detailed project-level analyses when integrated with other models [14][15].

In this study, we focus on the MOVES and EMFAC models for several reasons. MOVES is chosen for its comprehensive and flexible approach to emissions modeling. Its ability to operate at multiple scales allows it to provide detailed emissions estimates for various scenarios, from regional to project-level analyses. MOVES incorporates real-world driving conditions and modal activity-based assessments, making it highly accurate and reliable for diverse applications. On the other hand, EMFAC is specifically designed to address California's vehicular emissions, considering the state's unique environmental policies and vehicle mix. EMFAC's detailed regional insights and robust dataset make it an essential tool for analyzing emissions within California. By leveraging the strengths of both models, we can ensure a holistic and accurate analysis of heavy-duty vehicle emissions, making MOVES and EMFAC the preferred choices for this study.

Truck Dispersion Models

Understanding the dispersion of truck-related emissions is crucial for accurately assessing their impact on urban air quality. Various models have been developed to estimate the dispersion of emissions from trucks, each with specific applications and varying levels of precision. These models can be categorized based on their source type—point or line source—and their temporal behavior—steady-state or transient.

Within the realm of point source models, the steady-state category includes models like AERMOD [16], known for its prowess in handling complex terrains by harnessing the intricacies of atmospheric boundary layer turbulence. However, its effectiveness diminishes for durations of less than an hour. On the other hand, BLP [17] focuses on industrial emissions, especially plume rise and downwash effects, but its broader applicability remains questionable.

The transient class of point source models brings forward tools like CALPUFF [18]. It is versatile, accounting for various emission sources and aligning with changing meteorological conditions. Yet, its precision falters in dense urban environments or short-interval analyses. The model proposed by Zegeye offers commendable computational efficiency, ideal for real-time microscopic evaluations [19]. Still, its widespread application potential remains under-explored.

In the arena of line source models, CALINE3 [20] stands out in the steady-state domain, adeptly gauging emissions from less complex highway terrains. However, when urban traffic intricacies are introduced, its reliability diminishes. Models such as CAL3QHC and CAL3QHCR [21] aim to bridge this gap, adapting to intricate traffic behaviors, notably at intersections. Yet, their adaptability across diverse urban settings needs further validation. R-LINE maintains a steady-state approach, focusing on near-surface releases in urban areas [22]. The transient line source model, Line Source Gaussian Puff (LSGP) [23], while effective in assessing freeway emissions, has limitations when delving into the microscopic specifics of individual vehicles.

In addition, Computational Fluid Dynamics (CFD) models represent a unique category. They simulate gas flows and interactions, offering detailed insights into pollutant dispersion, especially in complex urban environments. Shi et al. [24] used CFD to analyze vehicle-induced turbulence in street canyons, demonstrating its value for understanding urban air quality. However, CFD's computational intensity can limit its use in real-time or large-scale applications.

In our study, we integrate both line source and point source models to enhance the accuracy and comprehensiveness of emission dispersion estimation. This integrated approach allows for a more detailed and holistic analysis of truck emissions, considering both moving and idling trucks in urban environments. By combining these models, we aim to provide a robust tool for analyzing and addressing truck-related air pollution, ultimately aiding in the development of targeted mitigation strategies.

FIELD DATA COLLECTION AND ANALYSES

Experiment Setup for Data Collection

In our field study conducted at the Dependable Highway Express (DHE) distribution center in Ontario, California, as shown in Figure 1, we focused on examining truck emissions. We chose CO_2 as the tracer for tailpipe emissions, primarily because its concentrations near the truck's tailpipe were markedly higher than the background concentration of 430 ppm. To gather comprehensive data, we used three CO_2 receptors to measure CO_2 concentrations at different heights and distances from the rear of an idling truck. Complementing these concentration readings, we employed a sonic anemometer to capture 3-D wind patterns, ensuring a holistic understanding of the emission dispersion.

Figure 1. DHE distribution center in Ontario, CA.

1. Vehicle Setup

Central to the experiment is a Volvo VNR 300 truck, as shown in Figure 2, fitted with a D11 engine. This engine is a Direct Injection Diesel type with a displacement of 10.8 liters. Its six in-line cylinders have a bore and stroke of 4.84 inch x 5.98 inch, and it operates with a compression ratio of 17:1. Impressively, the D11 engine can churn out up to 425 horsepower and deliver a maximum torque of 1550 lb-ft. Notably, this engine is designed to be fuel-efficient and lightweight, characteristics that influence emission profiles and the subsequent dispersion in the environment. With such an engine powering the Volvo VNR 300, our goal was to understand the emission and dispersion patterns in real-world conditions at the DHE center.

Figure 2. Volvo VNR 300 truck.

2. Receptors Setup

To ensure precise and comprehensive data collection for our study, we utilized a suite of advanced receptor equipment, all generously provided by the California Air Resources Board: The Portable Emissions Acquisition System (PEAQS), the LI-840A CO_2 Analyzer, and the LI-820 CO_2 Analyzer, as depicted in Figure 3. Before initiating the data collection process, all three receptors were calibrated to guarantee accuracy in their readings.

(a) (b) (c)

Figure 3. Receptors: (a) PEAQS, (b) LI-840A CO_2 Analyzer, and (c) LI-820 CO_2 Analyzer.

PEAQS stands as a state-of-the-art system tailored for real-time measurements of emissions. It excels in gauging CO_2 concentrations at various distances and elevations from the emission source, with an integral feature being its compatibility with specific CO_2 gas analyzers, ensuring meticulous control and data acquisition. The LI-840A CO_2 Analyzer is a high-performance instrument renowned for its precision and reliability. It employs a dual-cell infrared gas analyzer, enabling simultaneous measurements of CO_2. Its rapid response time and consistent results under fluctuating conditions make it a cornerstone in our data collection toolkit. Lastly, the LI-820 CO_2 Analyzer, another part of the LI-COR series, is designed for scenarios demanding high precision. Its streamlined approach to CO_2 analysis ensures quick and direct measurements, proving indispensable in our study.

Building on the equipment's capabilities, our experimental setup captured a broad spectrum of data. In accordance with Figure 4, a polar coordinate system was adopted for the measurements. Concentrations of emissions were recorded at varying distances from the rear of the truck: 1 m, 2 m, 3 m, 4 m, 5 m, and 6 m. These measurements were taken at specific angular orientations of 60°, 90°, and 120°. Furthermore, vertical data were also captured at heights of 1 m, 2 m, 3 m, and 4 m above the ground level, providing a comprehensive spatial understanding of the emissions from the truck.

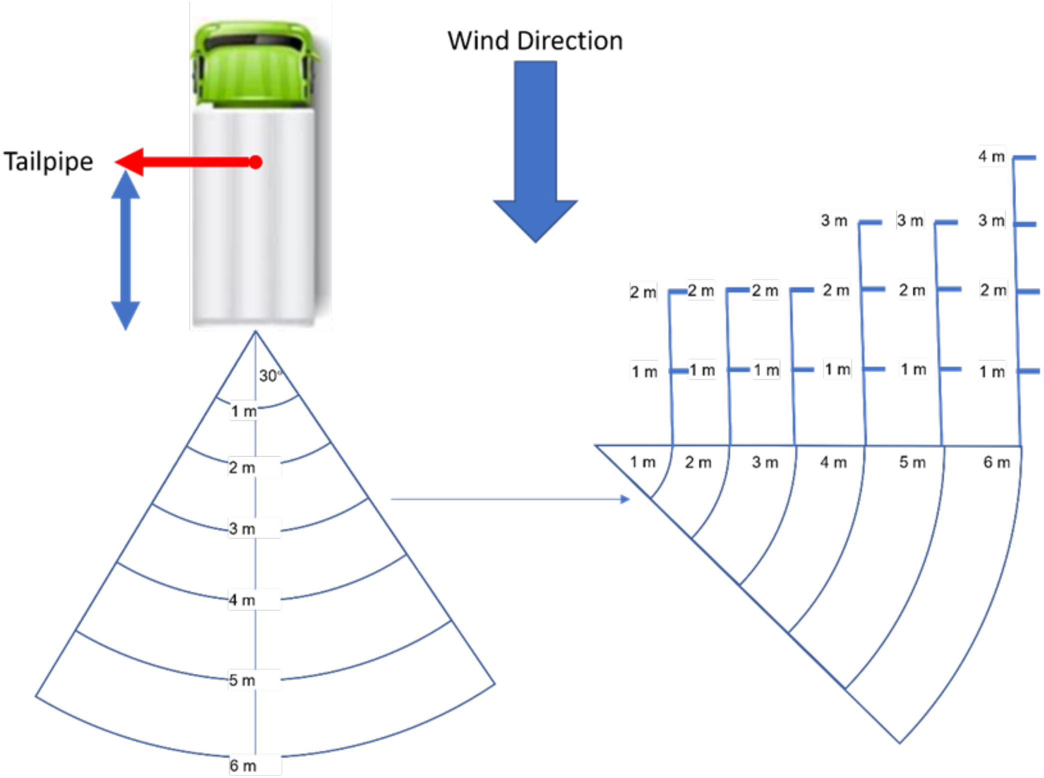

Figure 4. Experiment setup map.

In our experiment, each receptor inlet was affixed to a movable pillar, allowing us to adjust the distance and height for different sampling groups, as shown in Figure 5. The three receptors were deployed at the same distance behind the truck and at an equal height, capturing CO_2 concentration data as one "sampling group." During each sampling group, data were collected for 4–5 minutes to obtain a stable average plume signal. A pause of 1–2 minutes was incorporated between consecutive sampling groups to ensure a stable plume condition for the next set of readings.

Figure 5. Real-world experiment setup.

3. Meteorological Measurements

Meteorological measurements were meticulously conducted using a CSAT3 3-D sonic anemometer, which was mounted at a height of 2 m. Operating at a sampling frequency of 20 Hz, this instrument was positioned to the north of the truck, ensuring it was downwind and thus optimally placed to capture the prevailing wind patterns. The sonic anemometer was instrumental in recording both the wind direction and speed. The data collected over an interval of 5 minutes were then averaged and are presented in Figure 6 for a detailed overview, showcasing the wind direction in degrees and the wind speed in meters per second.

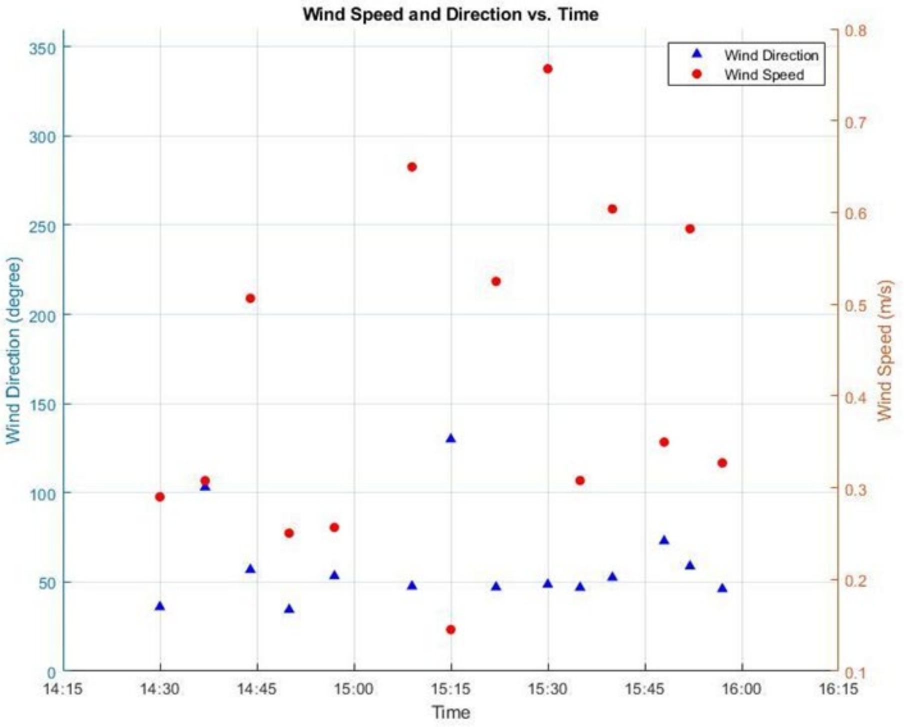

Figure 6. Wind direction and velocities from the sonic anemometer averaged every 5 min.

4. Emission Estimation

For our emission estimation, we utilized the OBDLink MX Bluetooth, as shown in Figure 7, a state-of-the-art diagnostic tool. This advanced device, renowned for its precision and comprehensive data capture capabilities, allowed us to accurately collect the fuel consumption rate from the truck. The OBDLink MX Bluetooth is distinguished by its rapid installation, unique security features, and compatibility with a wide range of vehicles. Its ability to provide real-time performance monitoring and diagnostic scans makes it an invaluable asset in our study. Using the data collected, we estimated the emission rates, assuming complete combustion of the fuel, in line with guidelines from EPA (2018).

Figure 7. OBDLink MX Bluetooth.

Result Analyses

This section provides a detailed description of our analytical approach, emphasizing the meticulous procedures employed to maintain the accuracy of our results. From preliminary data evaluation to the concluding comparative analyses, our objective was to offer a comprehensive and clear representation of the observed emission patterns.

In the preliminary stage of our analysis, we prioritized thorough data cleaning. Given the challenges inherent in collecting field data, especially in fluctuating environments like vehicular emissions, it was essential to address and remove any anomalies and outliers. This step laid a solid foundation for the ensuing phases of the analysis. We set a lower boundary at 400 ppm, considering the background CO_2 concentration hovers around 430 ppm. Additionally, an upper limit of 2000 ppm was established to account for potential extreme values that might arise from inaccurate readings.

Following the cleaning, data pre-processing was undertaken. This phase encompassed the normalization of the emission rates (C/Q) to ensure uniformity and comparability across varied measurement scales. Additionally, any potential biases or systematic discrepancies identified during data acquisition were addressed.

After pre-processing, we proceeded to data synchronization. This step involved aligning data from various sources: receptors, anemometers, and the OBD. To ensure accurate alignment, we matched the timestamps from these devices, checking for any discrepancies in recording times. By synchronizing the timestamps, we ensured that the data collected by different devices at the same moments are accurately aligned. This allowed for seamless integration of the datasets, ensuring that the model outputs and actual measurements corresponded accurately to the same time intervals and environmental conditions. This meticulous synchronization process was crucial for the reliability and validity of our subsequent analyses.

Figure 8 displays the comparison between the model predictions and the actual measurements taken at the receptors. The modeled C/Q, derived mainly from meteorological factors, does not account for processes like pollutant deposition and chemical changes as they move from the source to the receptor. However, given the short distance (just a few meters) from the tailpipe, these processes likely have minimal influence on the concentrations of most vehicle-related pollutants.

The data shown in Figure 8 highlight the model's capability in capturing the distribution of measured concentrations. The close match between the model's estimates and the actual data, after our detailed data cleaning, pre-processing, and synchronization, emphasizes the model's accuracy and its potential in predicting truck emission patterns in real-world scenarios.

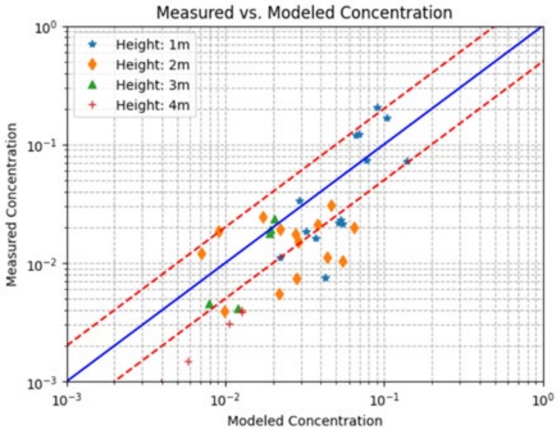

Figure 8. Comparison between model estimates and corresponding measured concentrations normalized by emission rates.

Figure 9 depicts the relationship between plume rise and distance to the source aligns well with our predictions. It clearly demonstrates a rapid initial rise in the plume close to the emission source. However, as the plume progresses further from the source its ascent begins to decrease, eventually stabilizing. This observed behavior is consistent with our understanding of plume dynamics and reinforces the accuracy of our predictive models regarding vehicular emission dispersion.

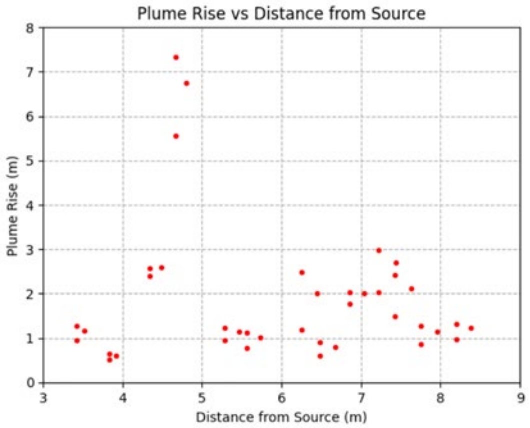

Figure 9. Plume rise versus distance from source.

ENHANCED TRUCK DISPERSION SIMULATOR DEVELOPMENT

In the development of the Enhanced Truck Dispersion Simulator, a bifurcated methodology was adopted to accurately model emission dispersion from trucks (Figure 10). For the first component, BEAM, a macroscopic traffic simulator, was employed to generate truck trips with origins and destinations between warehouses. The emissions from these moving trucks were then calculated using the EMFAC model, which considers the velocity and volume of the traffic. The resulting emission data were fed into the R-LINE dispersion model to estimate the dispersion along streets and roads.

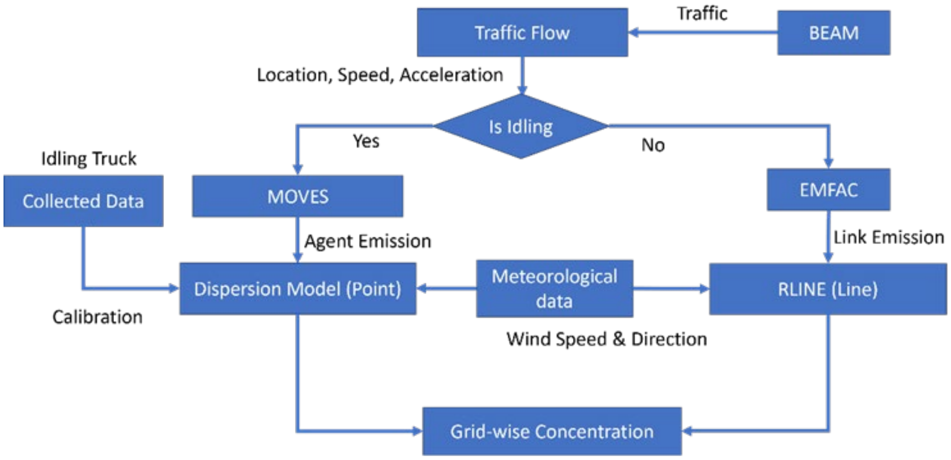

Figure 10. Enhanced Truck Dispersion Simulator architecture.

Concurrently, the second component of the simulator focused on trucks within warehouse environments. Here, the number of trucks idling in warehouses was determined, and each was assigned a specific idling time. A specialized low-speed movement profile was developed to represent the trucks' activities inside the warehouses. This profile was utilized in the MOVES model to compute the emission factors for these idling trucks. The emissions data from MOVES were then processed through our custom-developed grid-based dispersion model. This model created mesh areas around each warehouse to capture the emission dispersion, with overlapping meshes being combined to form larger areas for a more accurate representation.

The final stage of the simulator's development involved strategically placing receptors to aggregate the dispersion results from both on-road emissions (calculated via EMFAC and R-LINE) and warehouse emissions (derived from MOVES and our grid-based model). This integration allowed for a comprehensive assessment of pollution levels, accounting for both the dynamic and stationary phases of truck activities.

CASE STUDY

BEAM Traffic Simulation

In this study, BEAM traffic simulation was used to generate transportation levels of traffic within the city of Riverside and adjacent cities in California. This simulation relied on real origin-destination (OD) data to ensure an accurate representation of daily vehicle movements. To represent the real-world traffic patterns in this target area, an integrated activity-based model for passenger and freight transportation was developed, as shown in Figure 11. This innovative model merges the strengths of both the activity-based and trip-based methodologies, offering a comprehensive portrayal of traffic dynamics within the designated study area. In the activity-based segment of this model, as shown in Figure 11, the first step involves synthesizing a demographic population, a process rooted in detailed census information. This procedure involves disaggregating population data from an aggregate or broader level down to a high-resolution level, such as the census block group level. This disaggregation process provides a more granular view of the population, enabling the model to accurately simulate individual travel behavior. Subsequently, passenger vehicle activities are generated from this detailed, synthesized population data. The generation of these activities is based on the principle that travel is essentially a derived demand, arising from individuals' need to undertake activities such as returning home, commuting, or engaging in recreational activities. On the other hand, the model treats truck activities in a separate way. Instead of applying an activity-based approach, these activities are generated based on the regional truck OD demand data derived from the trip-based methods. An additional component ensures that the model can simulate local activities inside the model network, the inbound/outbound trips, along with the through traffic that merely passes through the area without originating or ending there. By combining passenger vehicle activities, truck activities, and through traffic, the model aligns with traffic monitoring data and presents a more holistic and accurate reflection of real-world traffic conditions. Figure 12 illustrates the OD distribution of truck traffic, which accounts for approximately 10 percent of the total traffic in this area. The size of each circle reflects the popularity of the warehouses, with larger circles denoting higher traffic. The yellow tips of the lines represent the starting points of the trips, and the red tips indicate the destinations.

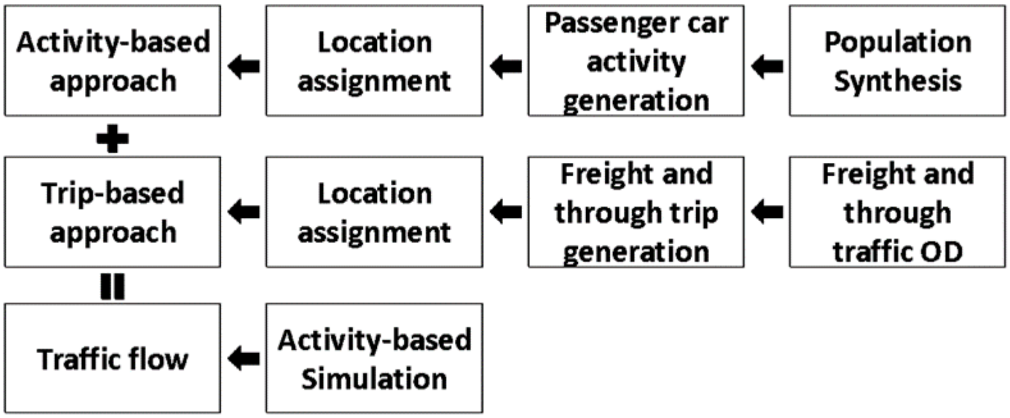

Figure 11. Integrated activity-based framework for passenger car and freight activity generation.

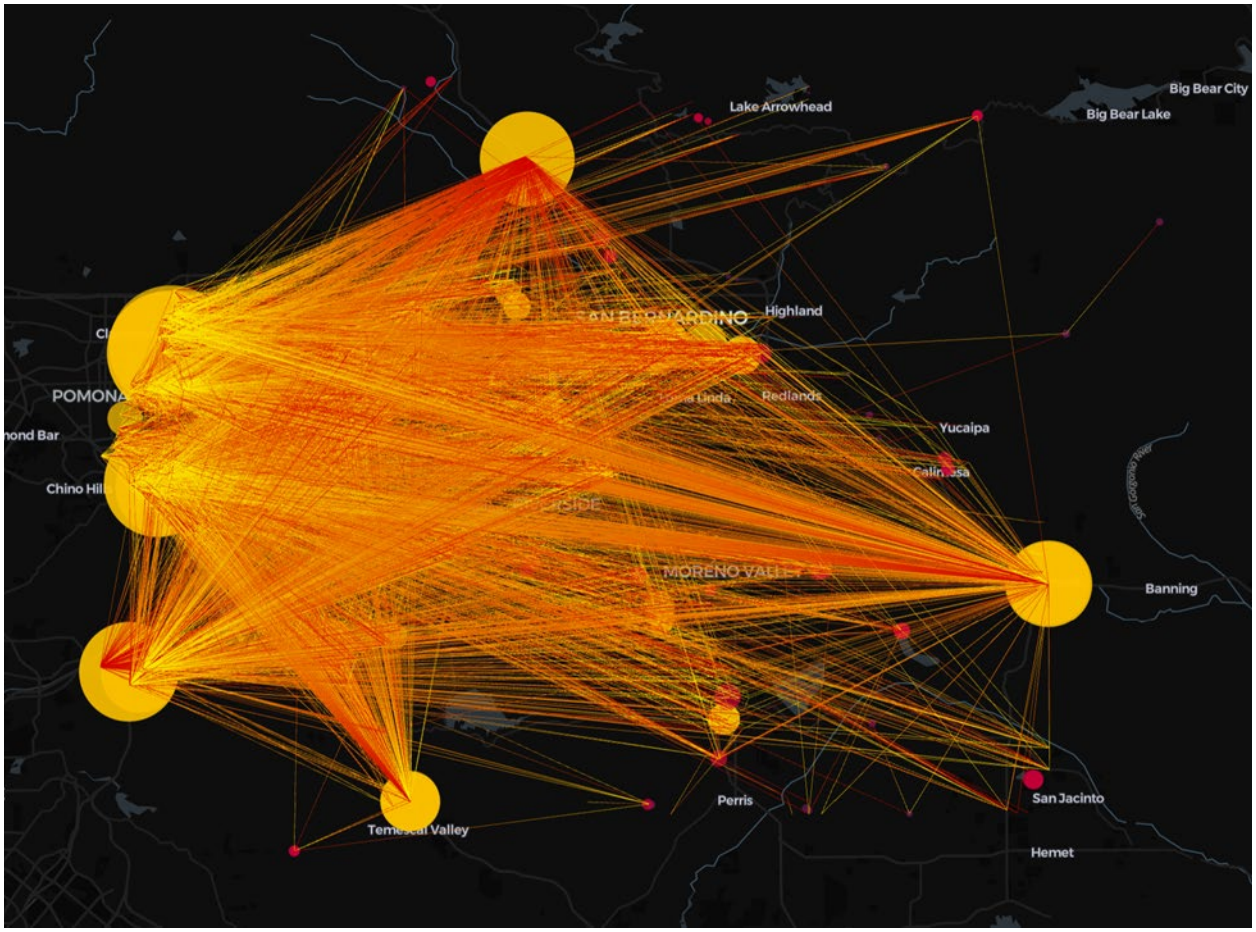

Figure 12. Illustration of 10 percent truck OD in this area.

A particular emphasis was placed on the dynamic traffic flow scenarios of 15,329 trucks and a total of 153,046 trips simulated in a 24-hour period. These scenarios were crucial for understanding the impact of both truck and passenger vehicle movements on local traffic dynamics and congestion patterns.

Traffic Volume Validation

Validating the traffic volumes against real-world data was essential to establish an accurate traffic model for this area. To achieve this, we utilized the PeMS database [25], which collects traffic statistics across all California highways. These data were used to compare the simulated traffic in the BEAM model with actual traffic observations. Figure 13, generated using VIA software[1], visualizes the simulated traffic within BEAM, which was used for validation against the real-world traffic data provided by PeMS. Subfigures 14(a) through 14(d) display the comparisons between the simulated traffic volumes and the actual traffic volumes recorded by PeMS. Given that the target area is a hub of the prosperous logistics industry, with numerous warehouses particularly around highways I-10 and SR-60, validating traffic volumes on these routes was crucial for an accurate representation of the area’s traffic dynamics. The comparison revealed a noticeable discrepancy in traffic volumes before 5:00 a.m., indicating a disparity in traffic patterns depending on the time of day. Although the calibration and validation

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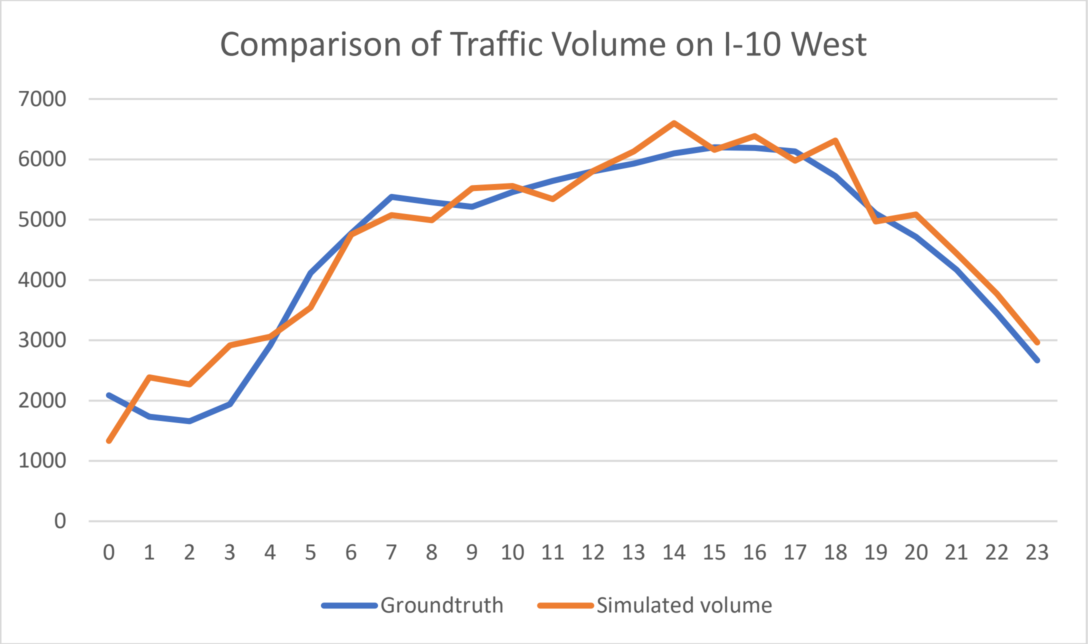
[1] Simunto. https://www.simunto.com/via/. Accessed Aug 2024.

processes were demanding, the simulated traffic volumes post-5:00 a.m. closely align with the real-world data, reflecting high-quality simulation outcomes.

Figure 13. The visualization of simulated traffic in VIA.



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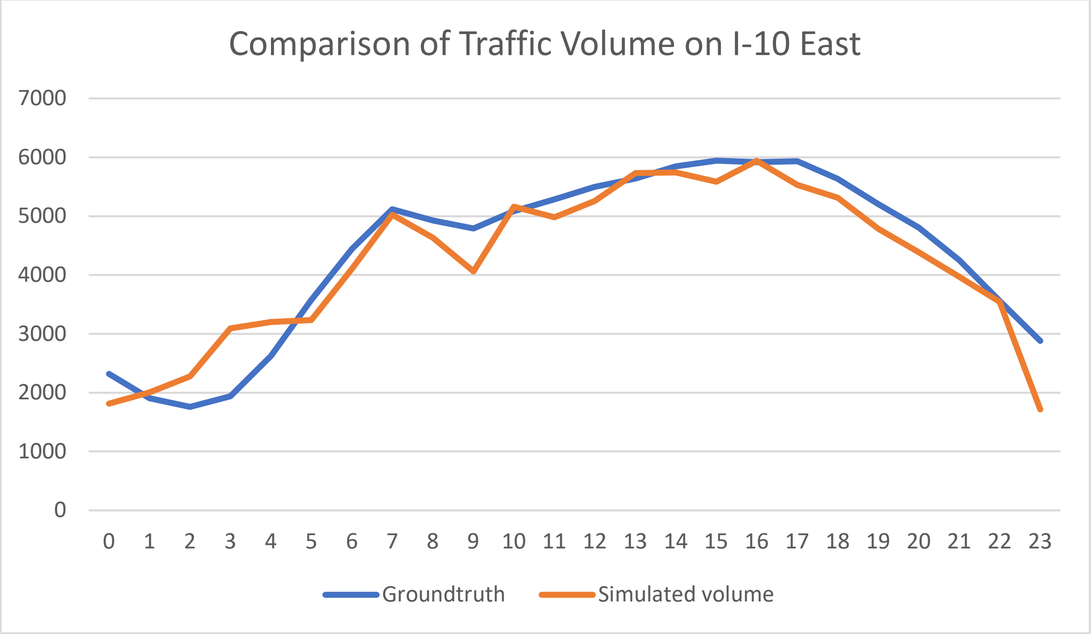
Comparison of Traffic Volume on I-10 East
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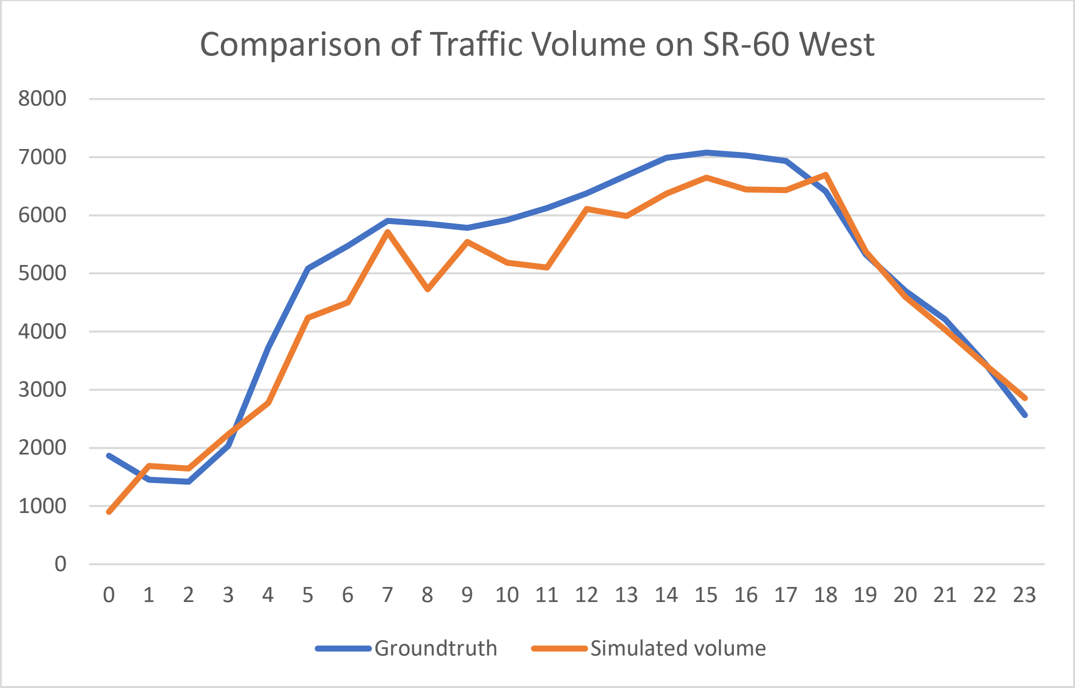
Groundtruth
Simulated volume

(b)


Comparison of Traffic Volume on SR-60 West
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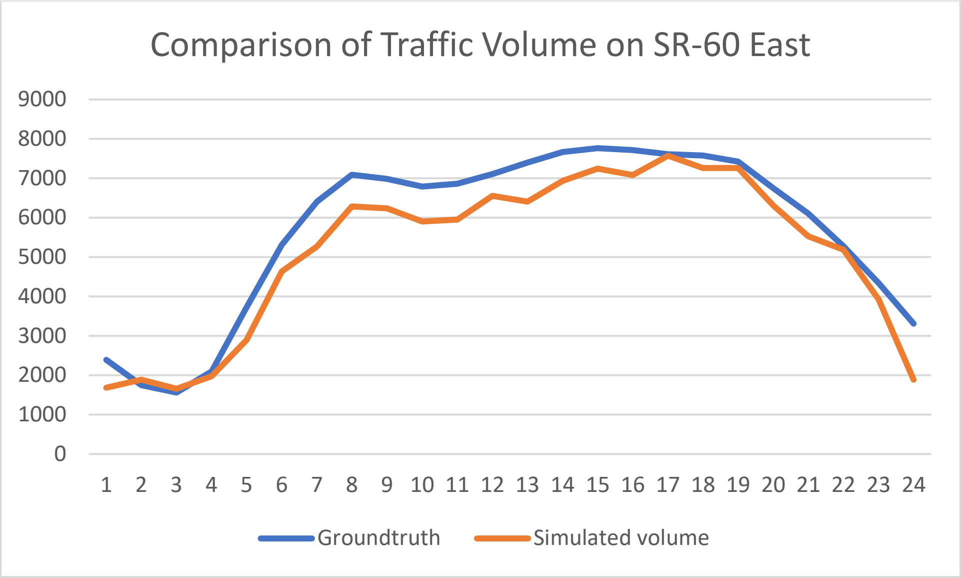
Groundtruth
Simulated volume

(c)



(d)

Figure 14. Comparison of simulated traffic volume with ground truth from PeMS.

Emission Dispersion for Moving Trucks

Following the traffic flow simulation, we calculated emissions using the EMFAC model. This step was critical to accurately estimating emissions from simulated traffic. Our emissions calculations were based on detailed traffic flow characteristics such as link, line, and traffic flow velocities given by BEAM traffic simulation, as shown in Figure 15. While our primary focus was on truck emissions, passenger vehicles were also included to provide a comprehensive emissions profile. We then applied the R-LINE model, a sophisticated line source dispersion model, to our emission estimates. This application was pivotal in analyzing how emissions from moving vehicles, including both trucks and passenger vehicles, dispersed in Riverside's urban environment. The R-LINE model's output provided us with detailed concentrations of key pollutants like particulate matter ($PM_{2.5}$) and nitrogen oxides (NOx), crucial for assessing the environmental impact of urban traffic in terms of air quality.

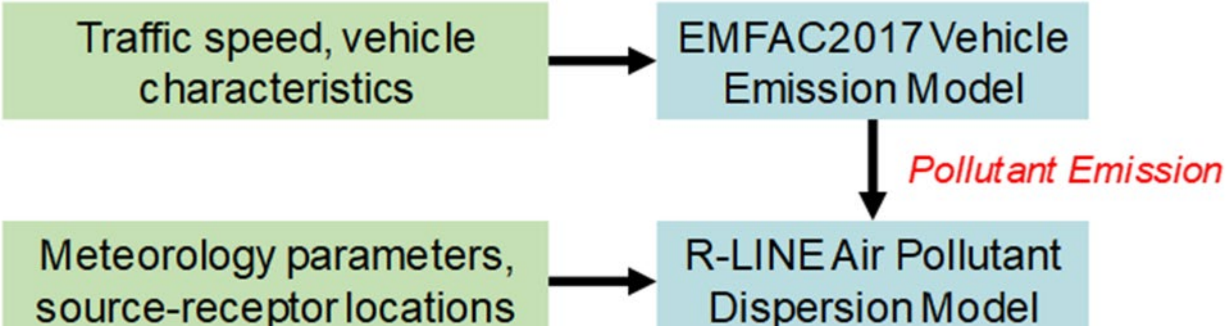


Figure 15. Methodological framework for estimating emission dispersion.

Figure 16 displays the NOx concentration (µg/m³) across the Riverside area, derived from BEAM data. The receptors, spaced 500 m apart, capture NOx levels at various points across the map. The color scale on the right indicates NOx concentrations, ranging from 0 to 7 µg/m³.

In the Riverside region, major roads and highways are clearly marked, and the color-coded dots represent the concentration levels at each receptor location. The higher concentrations of NOx are primarily observed along major highways and urban areas, reflecting significant emission sources and their dispersion patterns. This detailed spatial representation helps in understanding the distribution of NOx pollution and its potential impact on the area.

Similarly, Figure 17 for $PM_{2.5}$ concentration provides insights into particulate matter pollution, with higher concentrations likely observed along major highways and urban centers. By comparing this figure with the NOx concentration map, both derived from BEAM data, we can gain insights into the different dispersion patterns and sources of these pollutants.

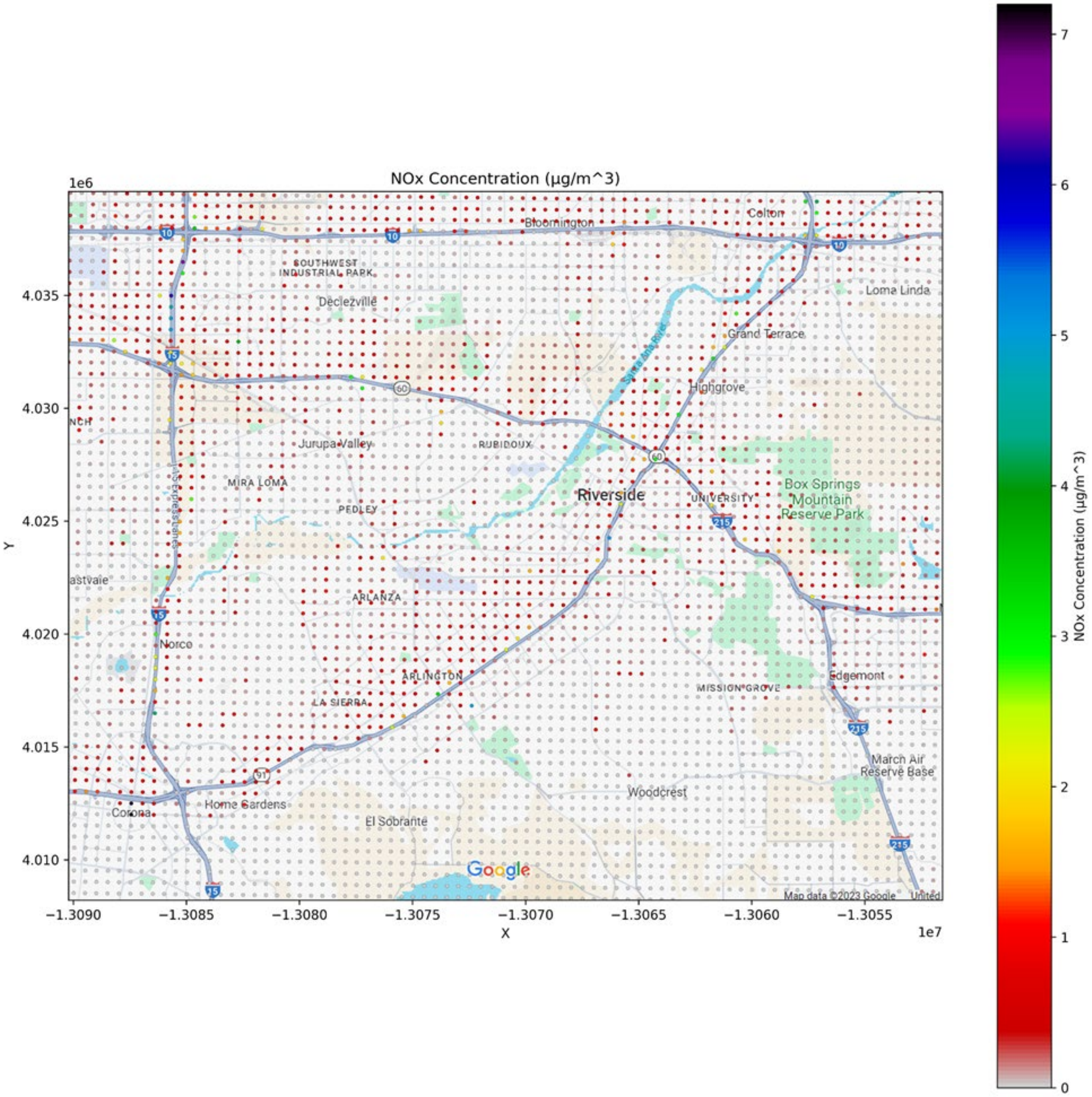


Figure 16. NOx concentration estimated from BEAM.

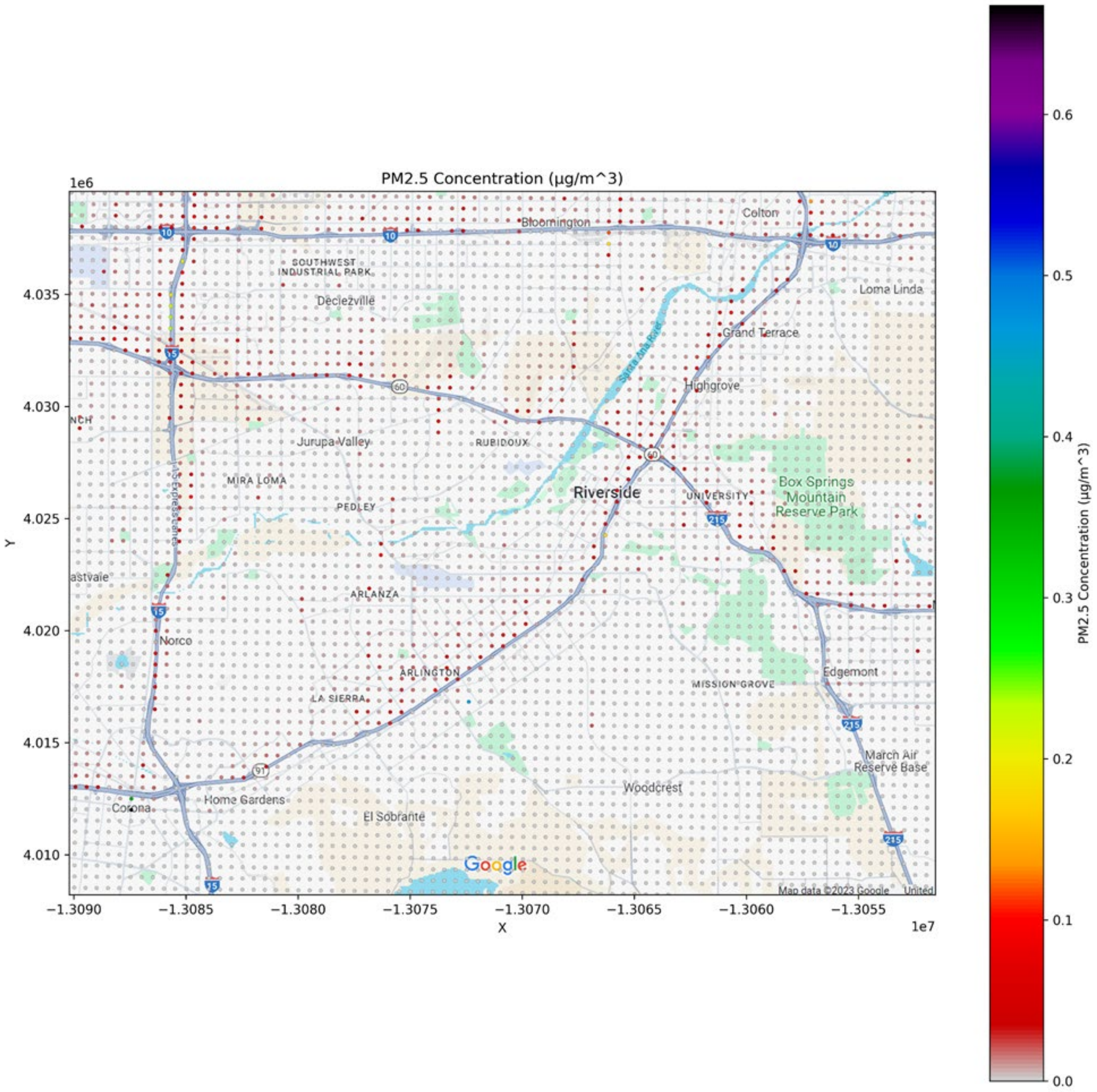


Figure 17. PM$_{2.5}$ concentration estimated from BEAM.

Emission Dispersion for Trucks in Warehouses

In our simulation, trucks staying within warehouses typically engaged in activities such as loading, unloading, or simply idling with the engine running. To accurately represent the duration of these activities in a realistic manner, the idling time of each truck was modeled using a Gaussian distribution, as shown in Figure 18. This distribution was characterized by a mean of 1,800 seconds, representing the average expected idling time, and a standard deviation of 300 seconds, which acknowledges the inherent variability in the duration of these activities. The choice of a Gaussian distribution was deliberate since it effectively captures the normal variations in operational times due to factors such as differences in loading or unloading speeds, the efficiency of warehouse operations, and truck-specific factors.

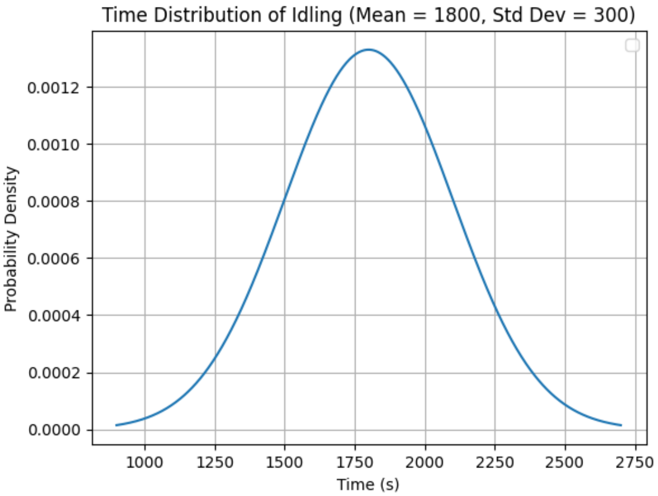


Figure 18. Trucks' idling time distribution.

To simulate truck idling or slow-moving activities, we incorporated a low-speed movement profile for trucks within the warehouse environment, as shown in Figure 19. It encompassed a range of activities, including slow movements as trucks navigate to and from loading docks, periods of idling as they wait for cargo to be loaded or unloaded, and other similar low-speed maneuvers that are characteristic of warehouse operations. This profile was vital for the simulation since it provides a more nuanced representation of truck behavior as opposed to just considering them as stationary sources of emissions.

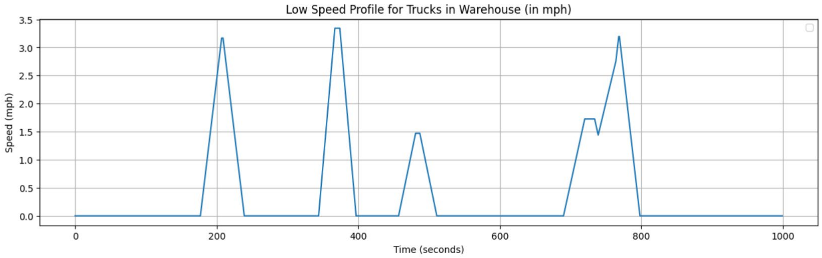


Figure 19. Trucks' idling profile.

The emission calculations in our model were further refined by integrating this low-speed movement profile with the probabilistic idling time data in the MOVES model. MOVES, with its capability to model emissions from a wide range of vehicular activities, utilized this combined data to compute emission factors. These factors were specifically tailored to reflect the conditions of slow movements and idling within warehouses. By incorporating both the idling time distribution and the low-speed movement profile, MOVES can generate more accurate and representative emission factors for trucks in warehouse scenarios. These emission factors are crucial for understanding the environmental impact of truck activities within warehouse compounds and were a key component of our overall emission dispersion analysis in the simulation.

Once emission factors were obtained, the next critical step in our simulation involved the spatial representation of these emissions around each warehouse. This was achieved through the development of a grid-based dispersion model. The model functions by generating a mesh grid around each warehouse, effectively capturing the dispersion pattern of emissions from idling trucks.

For the emission dispersion modeling around each warehouse, the simulation utilized a grid size of 50 x 50, with each individual grid cell measuring 10 x 10 meters. This structured approach ensured a detailed spatial representation of emission dispersion from the warehouses.

When constructing these grids for each warehouse, the simulation placed a 50 x 50 grid around the warehouse's location. Each grid cell within this larger grid represents a 10 x 10-meter area, allowing for a granular analysis of emission spread. This level of detail was crucial in capturing the nuances of emission dispersion, especially in varying warehouse layouts and operational scales.

In instances where the dispersion areas of nearby warehouses intersect, the simulation's approach was to merge the overlapping sections of their respective grids. This merging process involved checking the relative positions of the grids. If two or more grids overlapped due to the proximity of the warehouses they represent, the simulation combined these overlapping grid cells into a larger composite grid as shown in Figure 20. This process was done systematically, ensuring each 10 x 10-meter cell in the combined grid accurately reflects the cumulative emission dispersion from the overlapping warehouses.

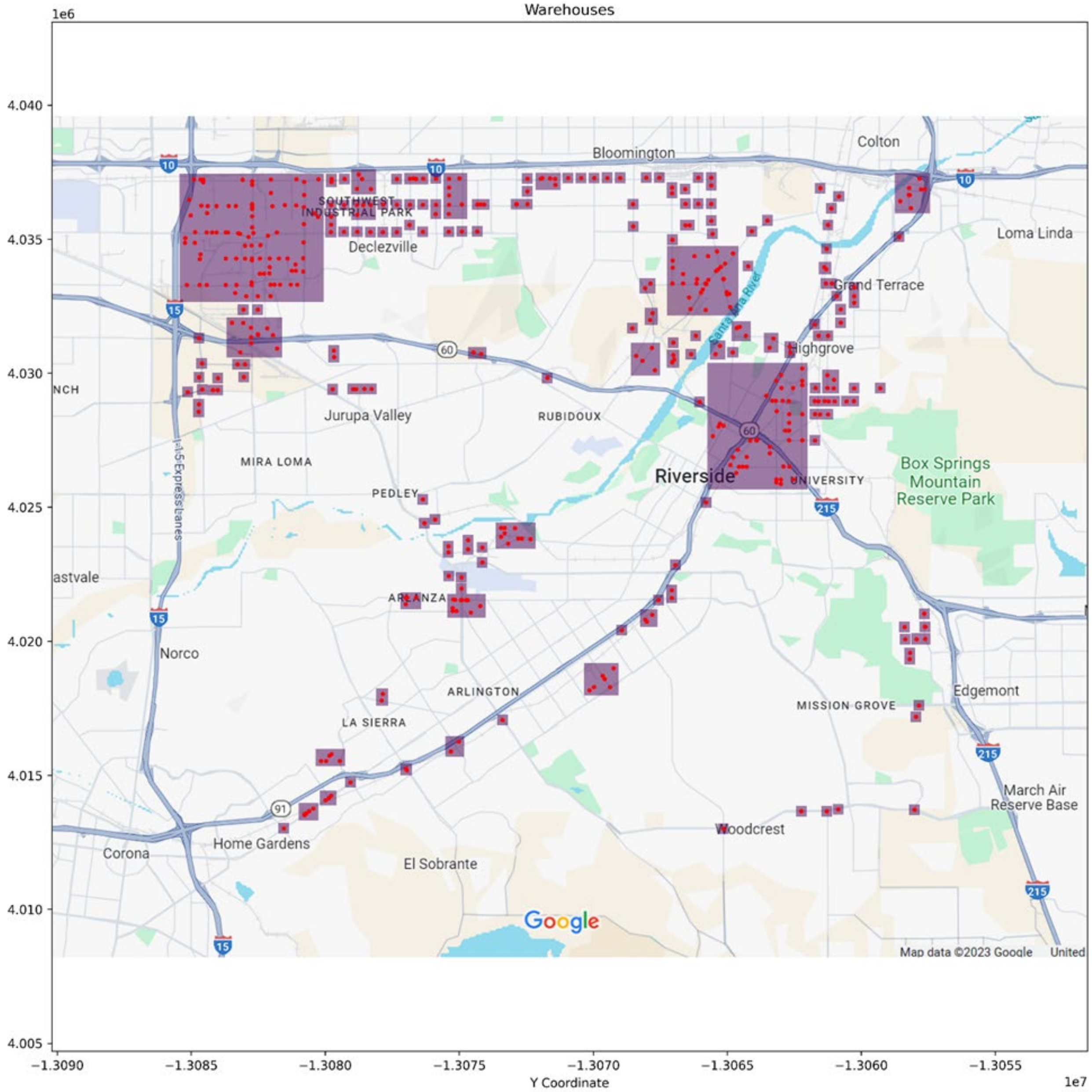


Figure 20. Combined warehouse mesh.

Next, we utilized the calculated emission factors from the MOVES model to feed into the grid-based dispersion model. This process was critical for translating the emission data into a spatial format that represents how pollutants disperse in and around warehouse areas.

Once the emission factors were determined for each truck, reflecting both idling and low-speed operational modes, these values were inputted into our dispersion model. This model was structured around the 50 x 50 grids, with each cell measuring 10 x 10 meters, as previously established. The emission factors were applied to the respective grid cells based on the location and activity of the trucks within the warehouse premises. This step ensured that each cell in the grid represented the emission intensity accurately, considering the specific activities and operational patterns of the trucks in that area. The emissions concentrations are shown in Figure 21 and Figure 22.

The grid-based dispersion model then computed how these emissions spread within and beyond the warehouse environment. This calculation took into account various factors such as wind patterns, atmospheric conditions, and the physical layout of the warehouse area. The model employed algorithms to simulate the dispersion of pollutants from their source points, allowing us to map out the concentration of emissions across the grid. This mapping provided a detailed picture of the emission spread, highlighting areas with higher concentrations and identifying potential zones of concern.

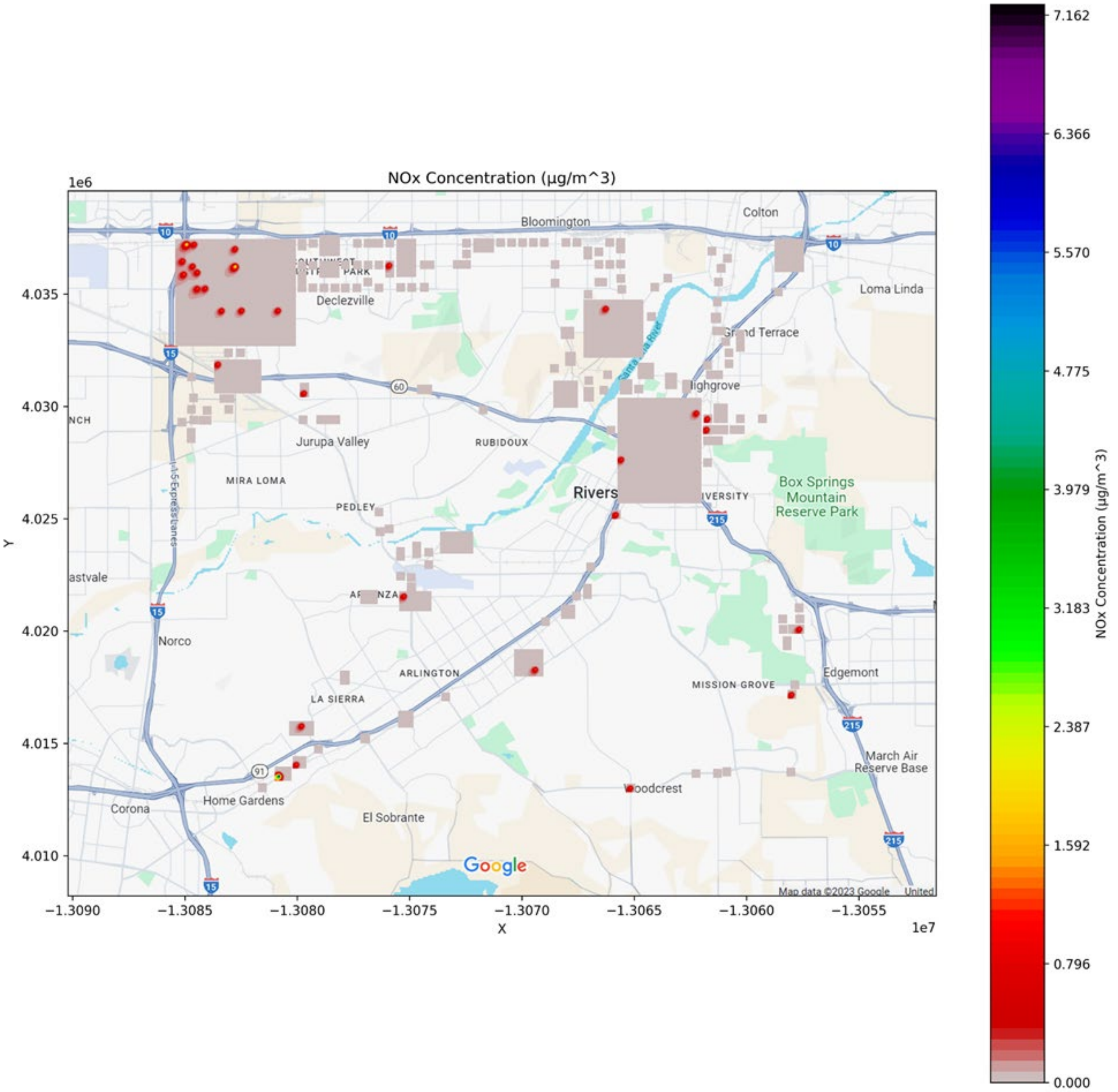


Figure 21. Warehouse NOx concentration (ug/m^3).

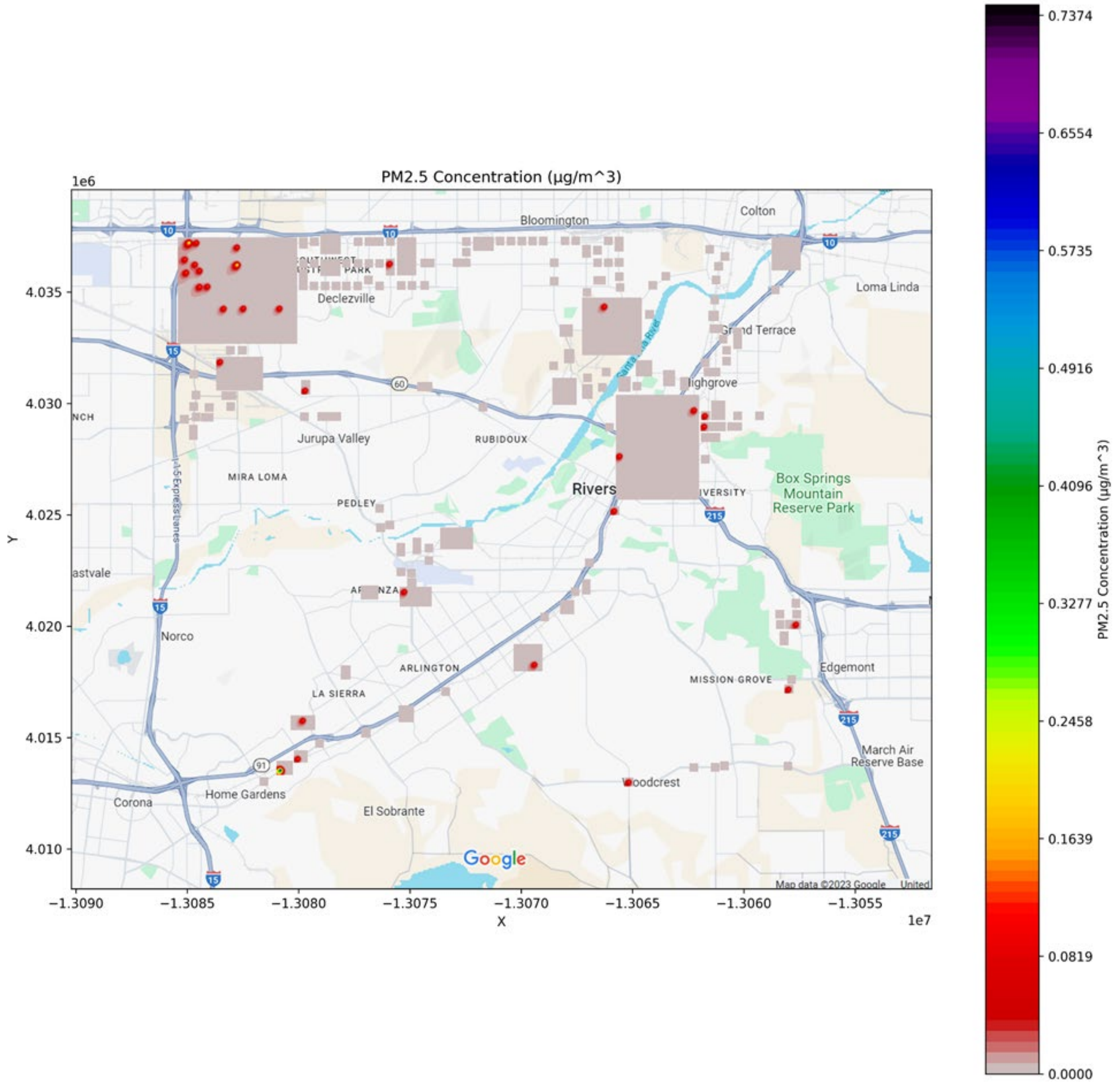


Figure 22. Warehouse PM2.5 concentration (ug/m³).

Combined Results

We integrated the emission patterns of trucks both on the road and in warehouse environments. This integration, vividly represented in Figure 23 and Figure 24, revealed comprehensive insights into the combined concentration levels of key pollutants, specifically NOx and $PM_{2.5}$.

Through the meticulous combination of on-road emissions data from the BEAM macroscopic traffic simulator with the MOVES model's warehouse emissions analysis, we were able to develop a nuanced understanding of the spatial distribution and intensity of these pollutants. The dispersion models, specifically R-LINE for on-road emissions and our custom-developed grid-based model for warehouse emissions, provided the framework to accurately quantify and visualize the dispersion.

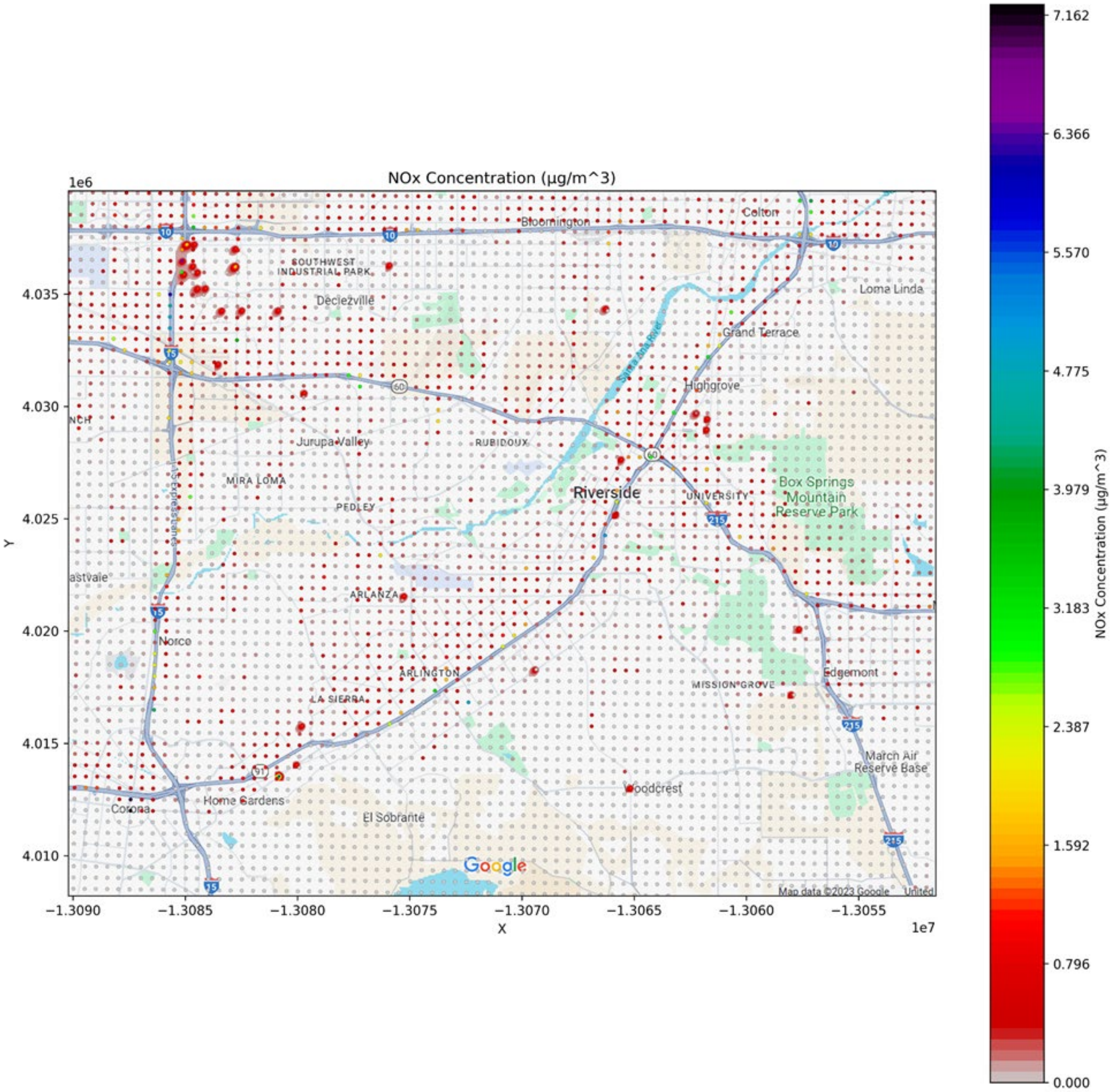


Figure 23. Combined NOx concentration (ug/m^3).

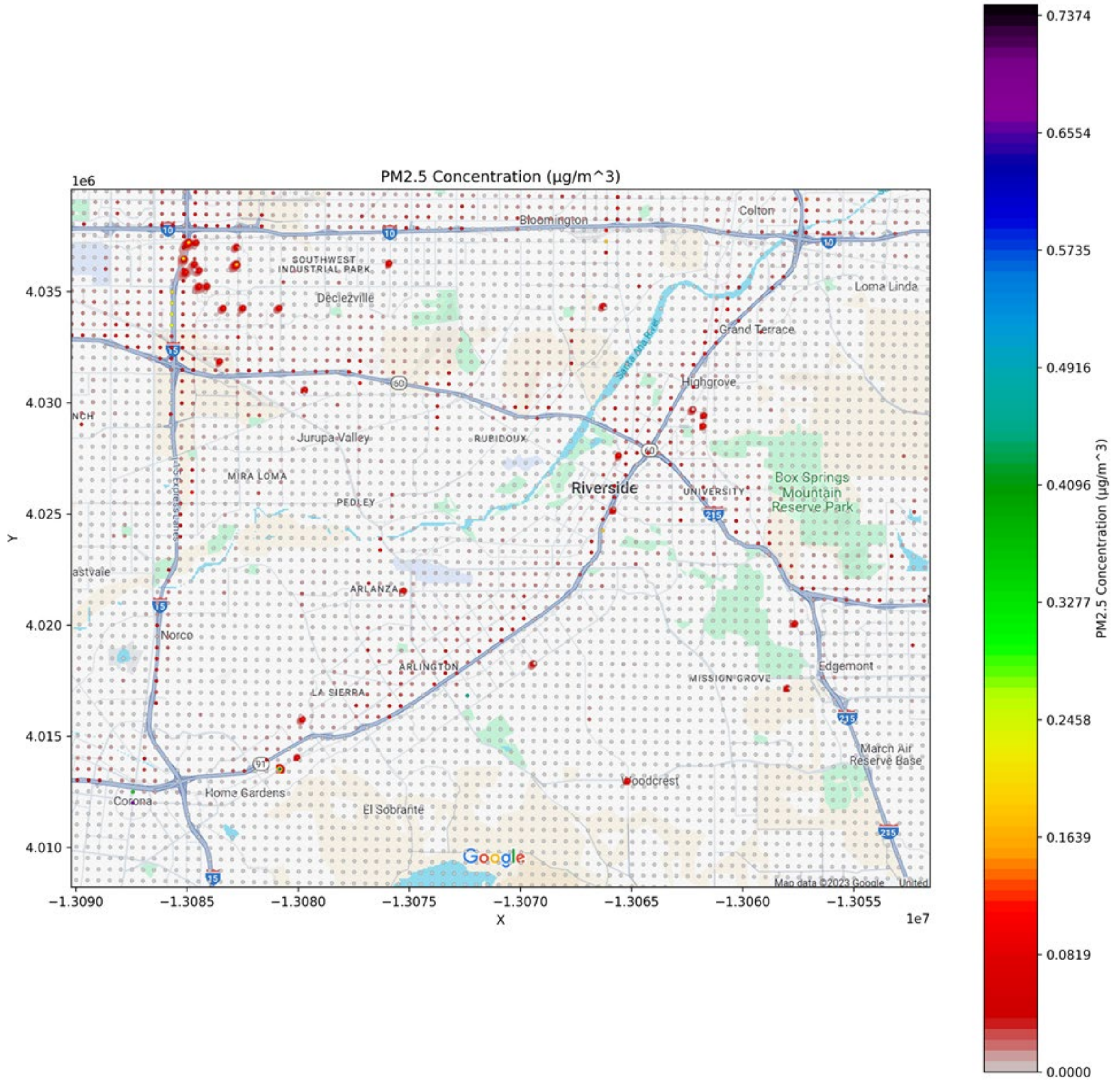


Figure 24. Combined $PM_{2.5}$ concentration (ug/m^3).

In Figure 23, we observe the spatial concentration distribution of NOx, which illustrates a higher concentration of this pollutant along major traffic routes and around warehouse facilities. This pattern indicates the significant contribution of truck activities, both in transit and during idling or low-speed movements in warehouse areas, to the overall NOx levels in the urban environment. The concentrated NOx emissions around warehouses particularly highlight the environmental impact of stationary truck activities, underscoring the need for more efficient operational practices within these areas.

Similarly, Figure 24 focuses on the distribution of $PM_{2.5}$, revealing a pattern that aligns closely with the traffic and warehouse operational dynamics. The higher concentrations of $PM_{2.5}$ in proximity to warehouses and along busy routes emphasize the compounded effect of truck emissions in these zones. The dispersion of $PM_{2.5}$, a pollutant known for its adverse health impacts, further stresses the importance of integrated strategies that address both traffic flow and warehouse operations to improve air quality.

The combined analysis presented in these figures not only demonstrates the effectiveness of our integrated modeling approach but also serves as a crucial tool for urban planners and policymakers. By understanding the areas with heightened levels of NOx and $PM_{2.5}$, targeted interventions can be implemented to mitigate the health and environmental impacts of truck emissions. Additionally, these results provide a foundation for further research, particularly in exploring the long-term effects of these pollutants and the effectiveness of various mitigation strategies.

CONCLUSIONS AND RECOMMENDATIONS

This study represents a significant advancement in modeling and understanding emission dispersion from idling and slowly moving trucks within urban environments. The Enhanced Truck Dispersion Simulator integrates multiple modeling frameworks, including BEAM for traffic simulation, EMFAC for emission estimation, and R-LINE for dispersion modeling. Field tests conducted at the DHE distribution center provided valuable real-world data that validated our models. The results revealed high concentrations of pollutants, particularly in areas with concentrated truck activities and warehouse operations, underscoring the critical impact of truck emissions on urban air quality. The simulation of emissions from trucks idling in warehouse environments highlighted significant pollutant concentrations around these facilities, emphasizing the need for effective emission control measures. These findings highlight the need for targeted mitigation strategies to reduce the environmental and health impacts of truck emissions, both on the road and within warehouse environments.

To address the significant impact of truck emissions on urban air quality, particularly around warehouses, several targeted strategies are recommended. These include adopting advanced emission control technologies, implementing stricter zoning policies, enhancing infrastructure to support truck operations, and creating designated areas to reduce idling. More specifically:

- Encourage the adoption of advanced emission control technologies in trucks to reduce emissions from idling and low-speed operations.
- Implement zoning policies that restrict the location of warehouses and distribution centers away from densely populated areas.
- Establish designated truck parking areas with electrification options at warehouses to reduce the need for engine idling during loading and unloading.
- Invest in infrastructure enhancements such as dedicated truck lanes and optimized traffic signal timings to reduce congestion and improve traffic flow around warehouses.

These measures should be able to mitigate the environmental and health impacts of truck emissions effectively.

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RESEARCH OUTPUTS, OUTCOMES, AND IMPACTS

None

TECHNOLOGY TRANSFER OUTPUTS, OUTCOMES, AND IMPACTS

- Experimental Data Sets
  https://drive.google.com/drive/folders/1PbI0CB-Mr9hW-yV6CIGYHnbcNQ09xnu6?usp=drive_link
  The data sets include field data on meteorological conditions, CO_2 concentrations, and truck fuel consumption.
- Warehouse Information
  https://drive.google.com/file/d/15r2-90s66LhirqwS9GLaklVTgXVNMzJr/view?usp=drive_link
  Contains data on warehouse locations within the study area.
- Truck Trips Information
  https://drive.google.com/file/d/1zZmqKt-1nh-YWY_lShwOXxRgURLzD2C5/view?usp=drive_link
  The data sets provide OD data for truck movements, including leaving and arriving locations, as well as departure and arrival times.
- BEAM Dispersion Dataset
  https://drive.google.com/drive/folders/1S5GgpzMehlgBMVkkO-G3nsOgJQkPMUZ-?usp=sharing
  Outputs from the BEAM traffic simulation, including emission concentration from on-road trucks.
- Dispersion Model Output Sample Data Sets
  https://drive.google.com/drive/folders/1WQSiHhiD4o9yGwTylCiWPaFHjTLVt6o5?usp=drive_link
  Outputs from the grid-based dispersion model, including emission concentration from warehouse trucks.

EDUCATION AND WORKFORCE DEVELOPMENT OUTPUTS, OUTCOMES, AND IMPACTS

This study was mainly conducted by graduate students from the Electrical & Computer Engineering (ECE) Department at University of California at Riverside. More specifically:

- Xuanpeng Zhao, a fourth year PhD student in the ECE Department, focused on conducting field experiments (for data collection), processing data, and developing the numerical dispersion model at the microscopic level.

- Yejia Liao, a fourth year PhD student in the ECE Department, performed emission and dispersion modeling, as well as data analyses using BEAM at the macroscopic level.