THESIS

EVALUATING VEHICLE RESUSPENSION EMISSIONS BASED ON ROADWAY AND VEHICLE CHARACTERISTICS

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ABSTRACT

EVALUATING VEHICLE RESUSPENSION EMISSIONS BASED ON ROADWAY AND VEHICLE CHARACTERISTICS

Vehicle related particulate matter (PM) emissions remain a significant air quality concern despite substantial reductions in tailpipe emissions over recent decades. As exhaust controls have improved and vehicle electrification has increased, non-exhaust emissions, including road dust resuspension, have become a growing contributor to traffic-related particulate matter. However, the mechanisms governing vehicle induced resuspension are not fully understood, particularly at the individual vehicle level. Existing regulatory and modeling approaches largely rely on fleet-averaged assumptions and often emphasize vehicle weight without fully accounting for aerodynamic effects, operating conditions, or measurement methodology. This research investigates vehicle induced particulate resuspension through a controlled experimental framework designed to isolate vehicle level and operational influences.

Three primary research questions guided this study. First, how does sensor location influence the measured spatial distribution of particulate matter concentrations around a moving vehicle? Second, how does vehicle weight, speed, and road surface type affect resuspension emissions? And third, beyond vehicle weight, how do aerodynamic differences between vehicles influence particle resuspension generated by vehicles?

To address these questions, a factorial experimental design was implemented using five vehicles representing internal combustion, hybrid, and battery electric platforms. Testing was conducted on both gravel and asphalt road segments at controlled speeds of 30 mph and 50 mph.

Each vehicle was evaluated under base and increased weight conditions (+624 lb.). Four sensor locations were employed on each vehicle, front bumper, rear bumper, front tire, and rear tire, to evaluate spatial variability in particulate concentrations. Steady-state driving segments were isolated and subdivided into repeated 30-second trials for statistical consistency (N=10 per experimental condition). Analysis of variance (ANOVA) was applied to evaluate main effects and interactions across experimental factors.

Results demonstrate that sensor location significantly influences measured particulate concentrations. Rear-mounted sensors consistently recorded higher PM2.5 concentrations than front-mounted sensors, reflecting the concentration of resuspended particles within the vehicle wake rather than uniform distribution around the vehicle body. This finding highlights the importance of sensor placement in experimental design and exposure assessment, as measurements are highly dependent on sampling location.

Vehicle speed and road surface type were identified as dominant factors influencing resuspension emissions. Gravel surface produced substantially higher particulate concentrations than asphalt, and higher vehicle speeds amplified resuspension across both surfaces. The addition of vehicle weight produced measurable but comparatively smaller effects within the tested conditions. Importantly, statistically significant differences ($p < 0.05$) were observed between vehicles under identical speed and road conditions, suggesting that aerodynamic and geometric characteristics beyond mass contribute to resuspension behavior.

Overall, this research demonstrates that vehicle-induced resuspension is governed by combination of operational, environmental, and vehicle-specific factors. The findings challenge simplified assumptions that mass alone dictates non-exhaust emissions and highlight the importance of controlled experimental methodologies for isolating vehicle level effects. From a systems engineering perspective, this work integrates sensing, experimental design, data processing, and statistical modeling to better characterize a complex transportation environment interaction. The results provide insight for future regulatory frameworks, vehicle design considerations, and measurement strategies aimed at reducing non-exhaust particulate emissions in an increasingly electrified transportation system.

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Chapter 1. Introduction

1.1. Overview

Airborne particulate matter (PM) is a major contributor to urban air pollution and represents a major concern for environmental and human health (Rienda & Alves, 2021). While regulatory efforts and technological innovations have successfully reduced tailpipe emissions from combustion engines and industrial sources, non-exhaust emissions, including vehicle induced resuspension of road dust, have emerged as a comparatively less examined but increasingly important contributor to ambient particulate matter concentrations (Pant & Harrison, 2013). These non-exhaust emissions occur when vehicular activity disturbs settled dust and debris on the road surface, moving the particles back into the atmosphere. Resuspension emissions are a significant source of airborne PM, especially in areas with elevated traffic like urban environments and in proximity to highways.

Multiple factors contribute to resuspending PM, including road surface condition, tire composition, vehicle speed, and environmental conditions such as humidity and wind. However, vehicle design characteristics (e.g., ride height, undercarriage geometry, rear bumper overhang) may also play a significant role in amplifying or mitigating the resuspension process. Despite this, most research has focused on seasonal or regional patterns (Amato et al., 2011), with little attention being made to the traffic and roadway specific mechanisms behind resuspended particulate matter at the vehicle level.

1.2. Motivation

Vehicle resuspension emissions represent an under-recognized yet critically important source of airborne particulate matter, especially in urban areas characterized by dense traffic and paved surfaces. While significant progress has been made in reducing exhaust emissions through stricter regulations and cleaner vehicle technologies, non-exhaust sources like road dust resuspension, brake wear, and tire wear have emerged as dominant contributors to ambient PM concentrations (Alfano et al., 2020; Denby et al., 2013). These emissions occur when vehicle-induced turbulence and mechanical action lift particles from road surfaces back into the atmosphere, creating a persistent and difficult-to-regulate source of pollution. Understanding and mitigating these emissions is essential for protecting human health, achieving air quality standards, and addressing climate related challenges.

1.2.1. Human Health Impacts

Particulate matter resuspended by vehicles is a complex mixture of road dust, tire and brake wear debris, metals such as copper and zinc, and various organic pollutants (Thorpe & Harrison, 2008). There have been numerous studies that have established the strong association between exposure to traffic-related PM and adverse health outcomes. Respiratory diseases are among the most well-documented effects, with increased concentrations of PM linked to higher incidences of asthma, bronchitis, and reduced lung function, particularly in vulnerable populations like children and the elderly (WHO, 2021). Furthermore, cardiovascular impacts are significant, as exposure to resuspended PM elevates blood pressure, increases the risk of coronary heart disease, and has been associated with higher rates of stroke (Brook et al., 2010).

Beyond respiratory and cardiovascular effects, chronic exposure to PM from vehicle activity is linked to cancer and other systemic diseases. Long-term inhalation of traffic derived particles, including those from resuspension, has been correlated with increased risks of lung cancer and diabetes (Raaschou-Nielsen et al., 2013). More recently, research has highlighted neurological impacts, with evidence suggesting that fine particulate matter impairs cognitive development in children, accelerates cognitive decline in adults, and may contribute to neurodegenerative diseases such as Alzheimer's and Parkinson's (Calderón-Garcidueñas et al., 2018). These health effects translate to increased premature mortality, with thousands of early deaths annually attributed to traffic-related PM pollution, of which resuspension is a significant component (Hoek et al., 2013).

1.2.2. Environmental Consequences

The environmental implications of vehicle induced resuspension emissions extends beyond human health risks. One major consequence is reduced visibility, as airborne dust and fine particles contribute substantially to urban haze, a problem that was once primarily associated with exhaust emissions but now persists due to non-exhaust sources (Kupiainen & Pirjola, 2011). Additionally, certain resuspended particles, such as black carbon, play a role in climate change by absorbing solar radiation and altering local energy balances (Bond et al., 2013). Resuspended dust can also settle on soil and water bodies, introducing heavy metals and persistent organic pollutants into ecosystems, which may negatively affect biodiversity and contaminate food and water sources (Amato et al., 2011)

Finally, despite significant reductions in tailpipe emissions, many cities struggle to meet national and international air quality standards, particularly for PM10 and PM2.5. This difficulty largely stems from the lack of effective regulatory frameworks for non-exhaust emissions and the absence of standardized measurement and mitigation strategies (Grigoratos & Martini, 2014). Addressing this gap is essential for sustainable urban air quality management.

1.3. Research Objectives

This thesis investigates the mechanisms associated with resuspended particulate matter generated by vehicles, with particular emphasis on the roles of vehicle operation, roadway surface characteristic, measurement location, and vehicle aerodynamic characteristics. By examining how these design elements either amplify or reduce the generation of resuspended particles, the study enhances our understanding of the physical mechanisms behind resuspension. These insights can support the development of more effective regulations and design modifications to minimize non-exhaust particulate emissions from vehicles. The following research questions are addressed in this study:

- **RQ1:** How does sensor location influence the measured spatial distribution of particulate matter concentrations around a moving vehicle?
- **RQ2:** How does vehicle weight, speed, and road surface type affect resuspension emissions?
- **RQ3:** How do aerodynamic differences between vehicles influence particle resuspension generated by vehicles?

To answer these questions and achieve the stated objective, the study undertook a series of research tasks, beginning with a comprehensive literature review of resuspension mechanisms, vehicle aerodynamics, and particulate emissions. Next, experimental studies of resuspension involving particle sensors to measure PM concentrations under varied vehicle configurations and environmental conditions. Finally, the data was analyzed to identify relationships between design parameters and resuspension levels that will help form vehicle designs that will mitigate non-exhaust particulate emissions.

The remainder of this thesis is structured as follows. Chapter 2 presents a review of the relevant literature on non-exhaust particulate matter emissions, with emphasis on vehicle induced resuspension, measurement methodologies, and factors influencing particulate generation. Chapter 3 describes the development of the air quality sensing system used in this study, including system requirements, hardware configuration, and software implementation. Chapter 4 outlines the pilot testing conducted to refine the experimental methodology and inform the final study design, while Chapter 5 details the final experimental setup and data collection procedures. Chapter 6 presents the results of the field experiments, organized around the three research questions above. Chapter 7 discusses the results and explores their implications for measurement practices and emissions characterization. Finally, Chapter 8 provides recommendations for future research, sensor deployment strategies, and potential applications of the findings.

Chapter 2. Literature Review

The purpose of this literature review is to provide a comprehensive examination of the current state of research on vehicle resuspension emissions. This review examined the current state of research on vehicle-induced particulate resuspension, encompassing fundamental resuspension mechanisms, non-exhaust particulate matter contributions to air quality, the influence of road surface and operational factors, measurement and sensor methodologies, and the role of vehicle design and aerodynamic characteristics in shaping resuspension behavior. By focusing on these critical themes, the review produced a clear understanding of the current research landscape, identified limitations in the existing body of knowledge, and highlighted opportunities for novel contributions that address the gap in vehicle induced resuspension dynamics.

2.1. Resuspension Emission Sources and Impacts

Resuspension emissions occur when dust that has settled on road surfaces is re-introduced into the atmosphere by vehicle induced forces. These particles originate from a variety of sources, including tire and brake wear, pavement degradation, and atmospheric deposition. Studies such as Nicholson (1988) and Amato et al. (2014) have shown that these particles can contribute significantly to local concentrations of PM10 and PM2.5 (i.e., particles with diameters ≤ 10 μm and 2.5 μm, respectively), particularly during dry conditions and in regions with limited street cleaning. One article estimated that, in some environments (e.g., highway exits and streets with more dust), resuspension emissions can contribute more to ambient particle matter levels than tailpipe emissions (Abu-Allaban et al., 2003), underscoring the importance of non-exhaust emissions considerations in contemporary air quality management.

The material composition of resuspended particulate matter is strongly influenced by road surface type and roadway usage patterns. Lundberg et al. (2020) showed that road surface composition plays a critical role in determining both the quantity and chemical makeup of resuspended particles, with differences observed between asphalt, concrete, and gravel surfaces. Similarly, Ha et al. (2012) demonstrated that traffic intensity, vehicle class, and braking frequency significantly affect the accumulation and resuspension of road dust, particularly in urban environments. Road surface abrasion, tire erosion, brake wear, and wear from vehicle components such as internal combustion engines and transmission systems all contribute to the particulate material available for resuspension (Denier van der Gon et al., 2013). Each of these sources produces particles with distinct morphologies and chemical signatures, often including trace metals such as iron, copper, zinc, and manganese.

Non-exhaust particulate emissions, including resuspension, tend to produce larger and more chemically complex particles than tailpipe emissions, and thus travel through and impact the environment differently. Pant and Harrison (2013) reported that non-exhaust sources are often enriched with metallic and mineral components, reflecting their mechanical origin. These particles are typically dominated by the coarse and fine size particles smaller than 100 μm in diameter, with particular emphasis on PM10 and PM2.5, which are most relevant for human exposure and health outcomes (Rienda & Alves, 2021). This is in contrast to the ultrafine particles (< 0.1 μm) that comprise most tailpipe emissions.

The health implications of resuspended particulate matter are well documented and can be severe. Unlike larger, macro-scale dust particles, the thoracic fraction (PM10) of resuspended debris can penetrate beyond the upper respiratory tract and depositing in the bronchi and lungs without being effectively filtered by the nose or mouth (Brown et al., 2013). That is to say that the larger resuspended particles, which may include metallic and other mineral components (Pant & Harrison, 2013), can entrain in the airways and cause respiratory impacts. The respirable fraction (PM2.5) is of particular concern because these particles can reach the alveolar regions of the lungs, where they may interfere with gas exchange and trigger inflammatory responses (Brook et al., 2010). Within the lungs, inhaled air passes from the bronchial tubes into progressively smaller airways called bronchioles, which terminate in microscopic air sacs known as alveoli. These alveoli are arranged in cluster and provide a large surface area where oxygen is transferred from inhaled air into the bloodstream (Cleveland Clinic, 2022). Because of their small size and thin walls, alveoli are particularly vulnerable to deposition of small particles, such as PM2.5, and the resulting inflammation can cause difficulty breathing and long-term health effects. Thus, deep lung penetration of fine particulate matter is a significant health concern.

Studies have linked exposure to traffic-related particulate matter, including resuspended road dust, to respiratory diseases, cardiovascular effects, and increased mortality, especially among sensitive populations such as children, the elderly, and individuals with pre-existing conditions (Hoek et al., 2013; Atkinson et al., 2014). Global burden analyses further demonstrate that uncertainty in PM2.5 exposure estimates directly translates into uncertainty in mortality attribution, underscoring the importance of accurately characterizing the fine particulate sources and transport mechanisms (Kodros et al., 2017). The presence of metals and other toxic constituents in resuspended particles further amplifies their potential health risks, reinforcing the need to better characterize the sources, transport mechanism, and exposure pathways associated with vehicle-induced resuspension (Pant & Harrison, 2013). These studies identify a clear need for action on resuspension emissions in addition to tailpipe emissions for curbing the harmful health effects of vehicles. However, simply understanding the particulate source and effects of resuspension emissions does not necessarily support meaningful interventions. There are several factors that influence the resuspension of road-bound particulate matter.

2.2. Influencing Factors

The magnitude of resuspension emissions (i.e., the concentration of various PM) is influenced by a complex interplay of environmental, road, and vehicle-related factors. Environmental conditions such as humidity, precipitation, and wind speed affect the adhesion of dust particles on road surfaces and their likelihood of being lifted into the air. For example, Gulia et al. (2019) found that dry, windy conditions significantly enhance the potential for particle resuspension, while rainfall temporarily suppresses it.

Road surface characteristics, including material composition, surface roughness, dust loading, and maintenance condition, further govern resuspension potential. Unpaved and degraded paved roads typically exhibit higher dust reservoirs and are therefore associated with elevated PM10 and PM2.5 emissions under traffic influence (Denier van der Gon et al., 2013; Kupiainen & Pirjola, 2019). The U.S. Environmental Protection Agency (EPA) has similarly identified poorly maintained and unpaved roads as dominant contributors to resuspension emissions, particularly in regions with limited dust control practices (EPA, 2016).

Vehicle-related factors provide the mechanical and aerodynamic forcing required to entrain and transport particles. Increasing vehicle speed enhances tire-road shear forces and turbulence intensity within the vehicle wake, leading to greater resuspension, particularly for coarse particles that require higher energy to become airborne (Grigoratos & Martini, 2014;

Piscitello et al., 2021). These findings highlight that resuspension emissions arise from coupled surface vehicle atmosphere interactions rather than any single controlling variable.

2.3. Measurement and Monitoring Techniques

Measuring the resuspended particles presents numerous challenges due to its dependence on variable conditions and moving sources, and particularly due to the power of environmental factors. Numerous articles have used a wide range of methods to assess the resuspended emissions. On-road mobile monitoring platforms, like what was used by Abu-Allaban et al. (2003), offer valuable insights into real-time emission levels under traffic conditions. Stationary monitors, often deployed near roadways provide continuous data but can be limited by spatial coverage. Mobile testing platforms like SCAMPER (System for the Continuous Aerosol Measurement of Particulate Emissions from Roads) (Fitz et al., 2020) and SNIFFER (Pirjola et al., 2009) are useful, but cost-prohibitive, solutions to studying single-vehicle resuspension. Recent work by McKercher et al. (2017) and Chen et al. (2020) have explored the use of low-cost air quality sensors, offering more affordable options for widespread deployment, although highlighting the trade-offs between cost, accuracy, and calibration requirements.

Alfano et al. (2020) conducted a comprehensive review of these low-cost sensors, particularly evaluating their effectiveness in environments where resuspension emissions are prevalent, such as urban roadways and high traffic zones. The study emphasized that while these sensors provide an affordable and scalable option for monitoring the PM values, their performance can vary widely due to environmental interferences, calibration drift, and inconsistent measurement standards across manufacturers (Alfano et al., 2020). In contexts where the particle concentrations are often highly dynamic and sensitive to localized disturbance, these limitations became especially pronounced. As a result, Alfano et al. (2020) strongly advocated for the development and adoption of standardized testing protocols and calibration procedures to improve the accuracy, comparability, and reliability of PM sensor data, especially when used for regulatory or research purposes related to non-exhaust vehicle emissions.

Despite advancements in monitoring technologies and sensor standardization efforts, most current approaches remain limited in their ability to isolate the contribution of specific vehicle features to resuspension emissions. Much of the non-exhaust literature emphasizes fleet-level assessments and regional emission inventories rather than vehicle-specific aerodynamic or geometric influences (Karagulian et al., 2015; Denier van der Gon et al., 2013). As exhaust emission standards have tightened, non-exhaust sources, including brake wear, tire wear, and resuspension, have become increasingly important contributors to urban particulate matter; however, distinguishing among these sources under real world traffic conditions remains methodologically challenging (Amato et al., 2016). Comprehensive reviews have further emphasized that airborne concentration measurements attributed to individual non-exhaust mechanisms are often confounded by mixed traffic fleets, meteorological variability, and background particle loading, particularly in uncontrolled field environments (Fussell et al., 2022). Harrison et al. (2021) similarly noted that while monitoring platforms can detect transient particulate spikes associated with vehicle activity, attributing these spikes to distinct vehicle characteristics requires more controlled experimental frameworks than are typically used in ambient monitoring studies. Consequently, the literature increasingly calls for experimental designs capable of isolating vehicle-level aerodynamic and mechanical effects on resuspension emissions, rather than relying solely on regional or fleet-averaged monitoring strategies (Harrison et al., 2021; Fussell et al., 2022). Such controlled methodologies are essential for advancing mechanistic understanding of vehicle specific resuspension dynamics.

2.4. Modeling Approaches

Resuspension emissions have been modeled using empirical (i.e., experimentation and observation), semi-empirical (i.e., experimental data with theoretical models), and physically based approaches (i.e., modeling or designing systems based on real-world physical laws). One of the most widely used regulatory tools is the U.S. Environmental Protection Agency's (EPA's) Compilation of Air Pollutant Emission Factors (AP-42), which provides standardized emission factor equations for estimating particulate matter emissions from paved and unpaved roads (EPA, 2016). These formulations relate emissions to variables such as silt loading, vehicle weight, and vehicle speed. However, as acknowledged by the EPA, these emissions factors are derived from average fleet conditions and do not account for aerodynamic wake structure, underbody flow, or vehicle-specific geometry (EPA, 2016). As a result, AP-42 remains useful for inventory level estimates but lacks the resolution required to assess micro-scale vehicle design influence.

More advanced semi-empirical models have attempted to incorporate physical mechanisms governing road dust loading and suspension. A prominent example is the NORTRIP (Non-Exhaust Road Traffic Induced Particle) model developed by Denby et al. (2013), which integrated road surface moisture, dust accumulation, meteorology, and traffic activity to simulate non-exhaust emissions. NORTRIP represents a significant improvement over simple emission factor approaches by dynamically modeling dust availability and resuspension processes. However, even this model relies primarily on fleet average parameters and does not explicitly resolve vehicle wake aerodynamics or geometric variation between vehicle types.

Recent work has further refined modeling approaches by combining statistical frameworks with physical configurations. For example, Kupiainen and Pirjola (2011) highlight that non-exhaust emissions are highly sensitive to traffic composition, meteorology, and surface conditions, complicating the development of universal predictive models. Hybrid statistical physical approaches have therefore emerged into integrate environmental control variables with emission factors, improving regional scale predictions while still operating at combined fleet levels.

At the micro-scale, computational fluid dynamics modeling has been applied to investigate airflow structures and particle transport within vehicle wakes. Studies examining vehicle aerodynamics demonstrate that recirculation zones, underbody flow acceleration, and rear-end geometry significantly affect particle entrainment and transport behavior (Harrison et al., 2021). While computational fluid dynamics provides detailed insight into turbulence and particle trajectories, such simulations are computationally intensive and rarely integrated with regulatory emission inventories. Moreover, few computational fluid dynamics studies explicitly couple aerodynamic wake modeling with road dust entrainment mechanics in real-world driving environments.

A critical limitation across modeling approaches is the reliance on fleet averaged emission factors and simplified representations of vehicle characteristics. As electric vehicles and larger utility vehicles become more prevalent, differences in curb weight, ride height, undercarriage configuration, and rear geometry may influence wake turbulence and particle transport in ways not captured by traditional models (Fussell et al., 2022). The increasing divergence between modern vehicle design and the historical datasets used to develop emission factors suggests a growing gap between modeled emissions estimates and actual vehicle-level contributions.

Consequently, while empirical and semi-empirical models remain valuable for regional air quality planning, they fall short of resolving vehicle-specific aerodynamic, geometric, and operational influences on resuspension emissions. Most existing approaches rely on fleet-averaged assumptions and do not isolate the effects of vehicle design, speed, loading condition, or measurement location on particulate transport within the vehicle wake. Bridging this gap requires controlled experimental studies capable of systematically isolating vehicle level effects under defined road and operating conditions, which directly motivates the research presented in this thesis.

2.5. Regulatory Landscape and Importance

Non-exhaust emissions, including particle resuspension, are projected to become the dominant source of vehicular particulate pollution in the coming future, given continued advancements in exhaust after-treatment systems and vehicle electrification. Multiple studies have demonstrated that, while tailpipe emissions of particulate matter have declined substantially due to regulatory controls, non-exhaust sources such as tire wear, brake wear, and road dust resuspension now represent a growing fraction of traffic related PM2.5 and PM10 (Timmers & Achten, 2016; Harrison et al., 2021). The Organization for Economic Co-operation and Development (OECD, 2020) similarly reports that in many urban regions, non-exhaust emissions may already equal or exceed tailpipe contributions, and their relative importance will increase as vehicles electrify.

Electric vehicles (EVs), while eliminating tailpipe emissions, do not eliminate non-exhaust emissions. In fact, due to battery mass, and structural reinforcement requirements, EVs are often heavier than comparable internal combustion engine vehicles (ICEVs), potentially increasing tire wear and road dust generation (Timmers & Achten, 2016; Hooftman et al., 2016; Good et al., 2016). This has led to growing discussion within the policy community regarding EVs may contribute disproportionately to non-exhaust particulate emissions relative to their regulated exhaust footprint. However, the mechanisms driving resuspension are not fully understood and may not be governed solely by vehicle mass. Factors such as geometry, wake formation, speed, and road surface condition have suggested as potential contributors, but their relative importance remains unclear. Without a mechanistic understanding of these factors, regulatory approaches that rely only on vehicle mass risk oversimplifying the problem.

Complicating this regulatory landscape is the evolving structure of transportation funding. In many jurisdictions, roadway infrastructure has historically been funded primarily through fuel taxes (Kirk & Mallett, 2015). Because EVs do not consume gasoline, their owners contribute little or nothing to these fuel tax-based funding streams, raising concerns about long-term transportation revenue sustainability as fleet electrification increases (Congressional Budget Office, 2023). In response, policymakers have explored alternative taxation mechanisms, including vehicle-miles-traveled (VMT) fees, annual EV registration surcharges, and road use charges designed to more directly reflect roadway usage (Congressional Budget Office, 2023).

If future air quality regulations were to target non-exhaust emissions, including resuspension, there is a risk that vehicles could be penalized primarily based on weight, particularly electric vehicles, without sufficient evidence regarding the physical mechanisms responsible for particle entrainment and transport. Empirical and modeling studies suggest that aerodynamic wake structure, undercarriage geometry, and operational factors such as speed may be equally or more important drivers of resuspension than mass alone (Harrison et al., 2021). Therefore, before implementing weight based regulatory or taxation frameworks intended to mitigate resuspension emissions, it is critical to isolate and quantify specific vehicle characteristics that govern particulate entrainment and wake accumulation.

The absence of vehicle design considerations in current regulatory models presents a significant gap for policymakers aiming to address urban air quality comprehensively. Bridging this gap requires controlled experimental research capable of distinguishing the relative influence of speed, road surface type, loading condition, and aerodynamic geometry on resuspension behavior. Such mechanistic understanding is essential to ensure that future regulations equitably and effectively target the true drivers of non-exhaust particulate emissions rather than relying on simplified proxy metrics.

2.6. Gaps in the Literature

Despite decades of research on non-exhaust particulate emissions, significant gaps remain in the understanding of resuspension dynamics at the scale of individual vehicles. Much of the existing literature has focused on regional inventories, roadside monitoring, or fleet-averaged emission factors (Denier van der Gon et al., 2013; EPA, 2016; Karagulian et al., 2015). While these approaches are valuable for air quality planning and regulatory modeling, they do not resolve the micro-scale physical mechanisms that govern particle entrainment and transport within the vehicle wake.

First, there is a limited body of controlled experimental research isolating the influence of individual vehicle characteristics on resuspension emissions. Most field studies rely on uncontrolled traffic environments, where meteorology, mixed vehicle fleets, and variable driving behavior confound attribution. As a result, vehicle specific features such as ride height, undercarriage geometry, and wake structure are rarely examined independently. Existing emission factor models, including AP-42 and related frameworks, rely primarily on parameters such as silt loading, average vehicle weight, and speed, but do not incorporate aerodynamic flow structures or geometric variation between vehicle types (EPA, 2016).

Second, measurement methodology remains inconsistent across studies. Stationary roadside monitors, while useful for capturing ambient concentration spikes, are limited in their ability to characterize short-duration, vehicle-specific plumes. Sensor response time, placement height, and spatial positioning strongly influence observed concentrations, yet standardized wake-region sampling protocols are lacking. Few studies systematically evaluate how sensor placement alters interpretation of resuspension magnitude, despite the importance of wake-dominated particle accumulation behind vehicles.

Third, the rapid evolution of the vehicle fleet introduces new uncertainty into resuspension modeling. Electric vehicles, sport utility vehicles, and light-duty trucks differ substantially from the vehicle classes used to develop historical emission factors. Changes in curb weight, battery placement, underbody shielding, and aerodynamic shaping may influence wake turbulence and particle transport in ways not reflected in legacy datasets. However, empirical data comparing modern vehicles under controlled conditions remain scarce.

Finally, while road surface type and speed are widely recognized as important drivers of resuspension, few studies quantify their relative influence within a controlled experimental design that simultaneously accounts for weight, vehicle type, and sensor location. Without such controlled comparisons, it is difficult to determine whether mass aerodynamics, or surface conditions are the dominant mechanisms governing particulate entrainment.

Together, these gaps highlight the need for controlled, vehicle-mounted experimental studies capable of systematically isolating the effects of road surface, speed, weight, and vehicle geometry on resuspension emissions. Addressing these limitations is essential for advancing mechanistic understanding and improving both regulatory modeling and policy development.

2.7. Contributions of this Study

This study directly addresses the methodological and mechanistic gaps identified in Section 2.6 through the development and implementation of a controlled, vehicle-mounted resuspension measurement framework.

First, this research introduces a mobile, multi-sensor measurement platform capable of capturing continuous particulate matter concentrations during sustained vehicle motion. By relocating sensors from stationary roadside configurations to vehicle-mounted positions, including front bumper, tire-adjacent, and rear wake regions, the study systematically evaluates how measurement location influences observed resuspension behavior. This approach provides empirical evidence that wake-region measurements are essential for accurately characterizing vehicle-induced particulate entrainment.

Second, the study employs a structured experimental design that isolates and quantifies the effects of road surface type (gravel vs. asphalt), vehicle speed (30mph vs. 50mph), vehicle weight (loaded vs. unloaded), and vehicle type under like conditions. Repeated runs across 1.2-mile gravel and 3-mile paved segments allow statistical comparison using ANOVA and post-hoc testing, enabling clear separation of dominant drivers from secondary effects. This level of control reducing confounding variability commonly present in open traffic observational studies.

Third, the research provides comparative evaluation across multiple vehicle types with distinct geometries and curb weights, including electric vehicles and internal combustion vehicles. While results indicate that road surface and speed dominate resuspension magnitude, the study demonstrates that vehicle geometry may modulate wake-region concentrations under higher-resuspension conditions. These findings help clarify the relative importance of aerodynamic versus mechanical mechanisms in particle transport.

Fourth, the study contributes to policy-relevant discussions by providing empirical evidence that vehicle weight alone is not a statistically dominant predictor of resuspension within the tested range. This finding is particularly important in the context of electric vehicle regulation and weight-based taxation discussions. The results suggest that simplified weight-based regulatory approaches may overlook the stronger influence of road surface condition and vehicle speed.

Finally, this research advances methodological best practices for future resuspension studies by:

- Demonstrating the critical importance of rear wake sensor placement
- Highlighting limitations of tire-mounted and roadside-only sampling
- Establishing minimum roadway length requirements for steady-state speed analysis
- Emphasizing the need for dry surface controls

Collectively, these contributions provide a vehicle-scale mechanistic perspective that bridges the gap between fleet-level emissions inventories and aerodynamic flow dynamics. By integrating controlled experimentation, statistical modeling, and wake-based measurement strategy, this thesis advances understanding on non-exhaust particulate emissions and provides a foundation for improved modeling, regulatory evaluation, and vehicle design considerations.

Chapter 3. Air Quality Sensor Development

This chapter describes the development of a portable, low-cost air quality sensing system used to collect particulate matter data for this study. The system requirements that guided the design process are first outlined, followed by a description of the overall system architecture, including hardware selection, sensor integration, and data logging capabilities. Subsequent sections detail the hardware and software implementation used to ensure mobile, reliable, and time-aligned data collection.

3.1. System Requirements

The development of air quality sensor system began with clearly defined engineering requirements derived from both operational and research needs. The system had to be portable, low-cost, and capable of accurately capturing particulate matter and environmental data in real time. From a systems engineering perspective, this meant each component had to satisfy functional, power, and data requirements aligned with the overall project objectives (Blanchard & Fabrycky, 2010). The Arduino microcontroller was chosen as the central processing unit due to its opensource nature, affordability, and compatibility with a variety of environmental sensors. Specifically, it needed to support external data logging to a microSD card or USB drive, operate using a compact power source such as a 9V battery, and enable straightforward assembly and modifications with minimal soldering (Banzi & Shiloh, 2022).

3.2. System Design

The high-level design of the sensor system integrates hardware and software into a compact configuration. An Arduino microcontroller served as the central controller, managing power distribution, sensor communication, and data logging. Particulate matter and environmental data were collected using a Sensirion Sen5x, which interfaced with the Arduino via the digital I2C pins. The system was powered by a 9V battery and included a microSD card module for onboard data storage. A real-time clock module was integrated to provide timestamps for each recorded data point, ensuring proper temporal alignment across all measurements. In total, four of these systems were used to collect continuous PM data during experimentation.

3.2.1. Materials Selection

The core of this system was the Arduino. The Arduino Uno Rev3 microcontroller was selected as the core processing unit due to its stability, low power demand, and compatibility with a wide range of digital and analog sensor. Its open-source architecture and well-documented libraries made it ideal for both research and educational applications (Banzi & Shiloh, 2022). The Uno's 14 digital pins and 6 analog inputs offered sufficient flexibility for interfacing with multiple modules simultaneously. In addition, the device's ability to be powered via USB or an external 9V battery enabled deployment in mobile environments.

To monitor particulate emissions, the Sensirion SEN5x series sensor was selected. The SEN5x is an environmental sensing node capable of simultaneously measuring multiple air quality parameters, including particulate matter (PM1.0, PM2.5, PM4, PM10), volatile organic compounds (VOCs), humidity, and temperature (Sensirion, 2022). Unlike optical sensors that require individual modules for each parameter, the SEN5x integrates multiple sensing elements in a single compact unit, reducing wiring complexity and enhancing accuracy through onboard temperature and humidity compensation. The I2C interface enabled seamless integration with the Arduino Uno, supporting stable and high-speed digital communication. This sensor met key project requirements such as long-term measurement stability, self-cleaning mechanisms to reduce dust accumulation, and minimal calibration drift under varied environmental conditions (Sensirion, 2022).

For time stamping of the sensor data, a DS3231 Real Time Clock (RTC) module was integrated into the system, which was powered by its own lithium-ion coin cell button battery (LIR2032H). Accurate timekeeping was critical for temporal analysis of air quality data, particularly when correlating resuspension events with external variables such as vehicle speed, ambient conditions, GPS coordinates, and synchronization across different PM sensor locations. The DS3231 was chosen due to its time capability and the compatibility to the Arduino.

To enable onboard data storage, a HiLetgo Micro SD TF Card Adapter Module was incorporated. This module was selected for its compatibility with 3.3V-5V logic levels and built in level shifting circuitry, ensuring safe connection with the Arduino Uno’s 5V logic. The use of a removable microSD card provided flexibility for data collection and post processing while maintaining data security during power interruptions. Data were logged in comma-separated value (CSV) format, facilitating direct import into analytical software such as R or Excel for subsequent analysis.

Lastly, in addition to the physical sensing hardware, a mobile app was used. The SensorLog mobile application was utilized as an auxiliary data acquisition tool to record real-time positional and dynamic information during testing. Available on the Apple App Store, SensorLog is a data logging application that captures high-frequency reading from a smartphone’s built-in sensors, including GPS position, velocity, altitude, acceleration, and timestamped data. This application was selected for its reliability, accessibility, and ability to export data in standard CSV formats. This enabled seamless integration with the particulate matter data collected from the Arduino-based Sensirion SEN5x system. By pairing the

SensorLog data with the air quality measurements, the study was able to accurately align particulate concentration changes with vehicle motion profiles, such as speed fluctuations, and stop and go, providing a more complete understanding of the conditions influencing vehicle resuspension emissions. Furthermore, the use of a smartphone-based platform minimized the need for additional onboard GPS hardware, simplifying the system architecture and improving portability. The combined use of the SensorLog app and the sensor array thus provided both spatial and temporal context to the collected PM data, enabling more precise correlations between vehicle characteristics and resuspension behavior.

Finally, the entire system was designed to be modular and easily assembled with minimal soldering. All components communicate via standard I2C or SPI protocols, allowing for efficient power distribution and minimal wiring complexity. This modular approach simplifies maintenance. Collectively, these decisions ensured that the system met its operational goals, delivering accurate, reproducible, and cost-effective measurements of vehicle resuspension emissions in both laboratory and field settings. Table 1 provides a summary of these key components and their purpose.

Table 1. Summary of Materials Used

Component	**Purpose**
Sensirion SEN5x	Collect PM data
Arduino Uno Rev3	Central processing unit
DS3231 Real Time Clock Module	Keep time
HiLetgo Micro SD TF Card Adapter Module	Log data to microSD card
ELEGOO Dupont Wires	Connect hardware components
MicroSD Card (32 GB)	Store data
9V Battery	Power supply
LIR2032H Battery	Power clock module
Plastic 8.75” x 5.75” x 2.375” Container	Housing unit for sensor
NEEWER Dual Suction Cup Car Mount Kit	Mount unit to vehicle
SensorLog App	Record GPS and speed

3.2.2. Hardware Setup

The particulate matter sensing system was assembled using hardware configuration centered on an Arduino Uno Rev3 microcontroller, a Sensirion SEN5x particulate matter sensor, a DS3231 Real Time Clock (RTC), and a microSD card data logging module. The system was designed to enable synchronized particulate matter measurement, accurate time-stamping, and reliable onboard data storage during vehicle operation under real-world driving conditions.

All components were connected directly to the Arduino using wires made for the Arduino. A schematic representation of the complete hardware configuration is shown in Figure 1, illustrating the wiring between the Arduino Uno, SEN5x, RTC, and the microSD.

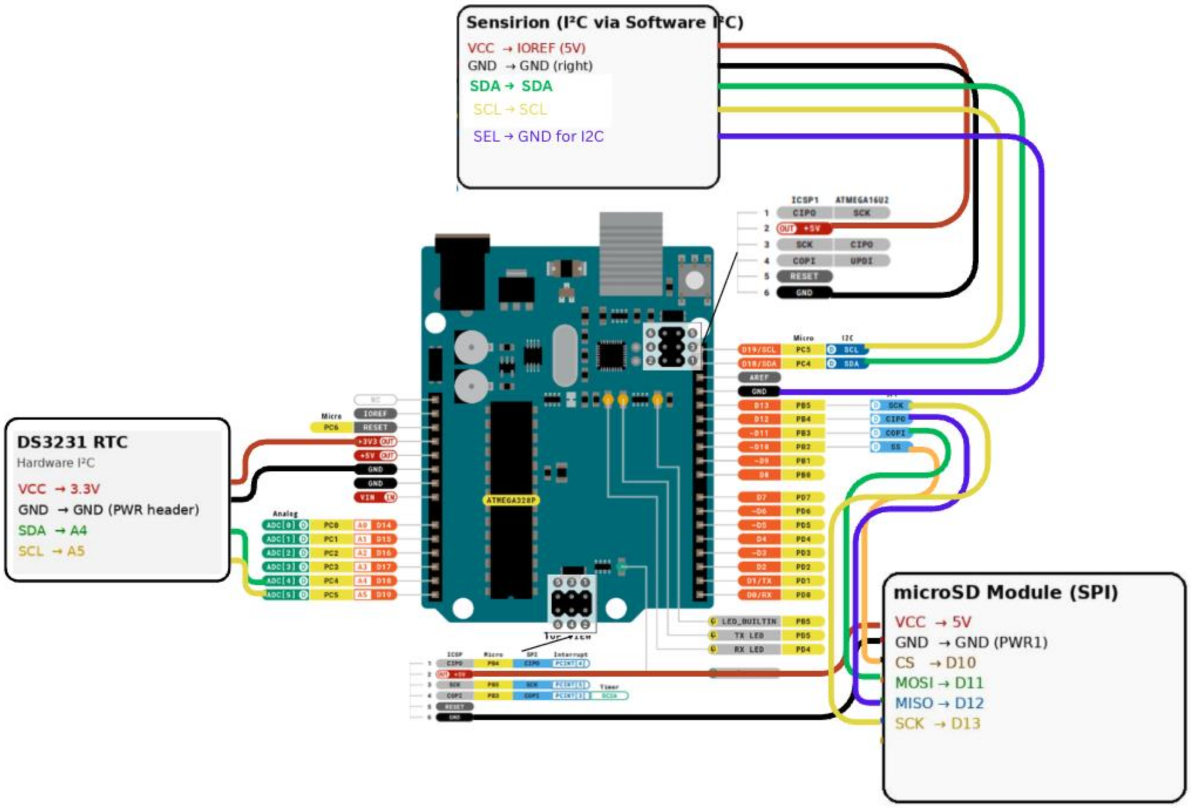

Figure 1. Schematic of Sensor, MicroSD, and RTC Wiring

The SEN5x sensor was configured to operate in I2C, allowing it to share the data and clock lines with the RTC module (see Table 2). Power for the SEN5x was supplied from the Arduino’s regulated 5V output, and the SEL pin on the sensor was tied to ground to force I2C communication. Standard I2C pins on the Arduino Uno were used to ensure compatibility and stability.

Table 2. SEN5x Sensor Connections to Arduino Uno Rev3

SEN5x pin	Arduino Pin	Jumper Wire Color
VCC	5V	Red
GND	GND	Black
SDA	SDA	Green
SCL	SCL	Yellow
SEL	GND(I2C)	Blue

Data logging and time synchronization were handled by a microSD card and an RTC. The microSD module communicates with the Arduino using the SPI protocol (see Table 3), while the RTC uses the I2C (see

Table 4). The RTC is powered at 3.3V, while the SD cards were reformatted prior to deployment to prevent file system errors and ensure reliable data storage.

Table 3. Data Logging Module Connection

Signal	Arduino Pin
5V	5V
GND	GND
SCK	D13
MISO	D12
MOSI	D11
CS	D10

Table 4. Timekeeping Module Connection

Signal	**Arduino Pin**
VCC	3.3V
GND	GND
SDA	A4
SCL	A5

Each sensing unit was assembled into a compact plastic enclosure to protect electronic components from environmental exposure, vibration, and debris during vehicle operation. The SEN5x sensor was mounted directly through an opening in the enclosure lid, ensuring unobstructed airflow to the sensor inlet while minimizing flow interference from the housing. The Arduino, RTC, and microSD modules were secured inside the enclosure using tape to hold them down so there would be no movement during testing.

The completed sensor assemblies were mounted to vehicles using a NEEWER Dual Suction Cup Car Mount that were duct taped onto the plastic box. This mounting approach allowed consistent, repeatable placement of sensors across different vehicles and sensor locations, including the front bumper, rear bumper, and tire-adjacent regions. The suction cup mounting system enabled rapid installation and removal while maintaining stable positioning throughout each test run.

This integrated hardware setup provided a robust, repeatable platform for mobile particulate matter measurement, supporting synchronized PM data collection with accurate timestamps and reliable onboard storage under a wide range of vehicle speeds, road surface types, and environmental conditions.

3.2.3. Software Setup

The software for the PM sensing system was developed using the Arduino Integrated Development Environment (IDE) and written in C++ using standard Arduino libraries. The program was designed to initialize all hardware components, continuously collect particulate matter and environmental measurements (once per second), timestamp each observation using the RTC, and log the resulting data onto the microSD card. The complete source code was used for data collection is provided in the Appendix A.

Several external libraries were required to support communication with the system hardware. These included the *Wire* library for the I2C communication, the *SensirionI2CSen5x* library for interfacing with the SEN5x particulate matter sensor, the *SPI* and *SD* libraries for microSD card access, and the *RTClib* library for real-time clock functionality. All libraries were installed through the Arduino Library Manager to ensure version consistency and ease of replication.

The Arduino Uno Rev3 was selected as the target board within the Arduino IDE, and the appropriate serial port was specified prior to uploading the program. A serial baud rate of 115200 was used to provide real-time diagnostic output during system initialization and operation.

To allow communication in the code, there first needed to be an initialization between the Arduino and the Sensirion Sen5x. During startup, the software needed the first initialized serial communication to establish the I2C bus. After the SEN5x sensor was then reset. Error checking is performed immediately following sensor initialization to ensure that measurements have begun successfully; if initialization fails, the system halts execution to prevent logging invalid data.

The real-time clock is initialized next. The RTC time was set manually once during initial deployment by temporarily enabling a line of code that assigns the compilation timestamp to the RTC. After the time was set, this line was then commented out and the program reuploaded to prevent unintended time resets during power cycles.

The microSD card module is then initialized using the SPI interface. If the SD card fails to initialize, the program halts to avoid data loss. Upon successful initialization, a CSV file is opened, or created if it does not already exist, and a header row describing each data field is written to the file. This ensures that all recorded datasets are immediately compatible with post-processing and statistical analysis workflows.

Once initialization is complete, the program enters a data loop. Measurements are collected at a fixed interval of one second, providing sufficient temporal resolution to capture changes in particulate concentrations during vehicle emotion while maintaining manageable file sizes.

At each sampling interval, the software retrieves the current timestamp from the RTC and reads particulate matter concentrations, PM1.0, PM2.5, PM4.0, and PM10, temperature, relative humidity, and air quality from the SEN5x sensor. All data is then written to the SD card in comma-separated format, .csv.

After compilation, the program was uploaded to the Arduino using a USB connection. Successful upload and execution were verified through serial monitor output prior to enclosure sealing and field deployment. Once validated, the system was powered using an external supply during vehicle operation, and data logging proceeded autonomously without user intervention.

This software architecture provided a stable and repeatable framework for synchronized particulate matter measurement and logging during mobile field experiments. By combining real-time clock synchronization, structured data output, and onboard storage, the software supported robust data collection across varying road types, vehicle speeds, and sensor locations.

Chapter 4. Pilot Testing

4.1. Introduction

This chapter presents the results of initial pilot testing conducted to refine the methodology and instrumentation used in assessing vehicle resuspension emissions. The goals of these preliminary trials were to evaluate the feasibility of the measurement setup, validate sensor functionality, and identify potential sources of error or viability in data collection. Through structured field experiments, we tested multiple vehicle configurations, roadside infrastructure instrumentation, and road conditions to understand how PM resuspension could be reliably captured under controlled conditions.

The pilot studies provided essential insights that guided the refinement of both the experimental design and the instrumentation setup for the final research phase. Key lessons included understanding the spatial distribution of road debris following vehicle passing and optimize sensor location to capture as much PM as possible as the vehicle is in motion. Overall, the pilot tests provided a methodological foundation, confirming that sufficient particulate matter was present for testing and that it could be effectively captured by the sensors. The resulting successes and failures helped refine the study, leading to a clearer and more stable framework for achieving optimal results.

4.2. Distribution of Road Debris

The first pilot test focused on quantifying the distribution and redistribution of road debris under controlled vehicle passes. The objective was to evaluate how repeated vehicle movement at different speeds affected the resuspension and redeposition of particulate matter in a given area of road. These experiments were performed within a defined 10-foot x 10-foot testing area consisting of a dry paved surface with uniform dust and dirt coverage. The site that was chosen was a parking lot of an elementary school, which was selected to minimize external disturbances such as local traffic.

4.2.1. Setup

A flat section of blacktop pavement was selected to serve as a representative surface for a typical roadway condition. A 10-foot x 10-foot test area was precisely measured and marked using tape to define the sampling boundary (see Figure 2). The surface within this area was initially swept clean to establish a baseline and to allow for controlled redistribution of collected material prior to testing. A sample of road debris and dust was collected, weighed, and approximately evenly distributed back onto the test area. A Tesla SUV and a Ford F-150 pickup truck were each driven across the test section at two constant speeds: 25 mph and 40 mph, with each speed run repeated three times per vehicle. After each pass, displaced surface debris within the marked area was collected and weighed to quantify the extent of particulate resuspension caused by vehicle movement.

Figure 2. Test Area Outlined with Duct Tape

4.2.2. Results

The debris redistribution test demonstrated measurable changes in surface particulate mass following repeated vehicle passes over the defined test area, shown in Table 5. The initial debris mass within the 10-ft x 10-ft section was 591.9 g. Overall, the debris mass changes across all tests were relatively small (within 30 g or 0.07 lb), reflecting the limited amount of loose particulate matter available on the paved surface. Variability among runs is likely linked to unavoidable sources of experimental error, including inconsistencies in sweeping, differences in vehicle speed control, small deviations in driving path, and uneven redistribution of material back onto the pavement between sequences. Environmental factors such as asphalt texture, wind gusts, humidity, and barometric pressure may also have influenced particulate movement and deposition. Despite these limitations, the results confirmed that vehicle movement, even at moderate speeds, can measurably redistribute particulate matter on dry paved surfaces. However, the modest mass changes observed also highlighted the inherent constraints of performing resuspension analysis on a low debris asphalt surface, motivating the subsequent comparison against a dirt or gravel roadway in later testing.

Table 5. Mass of Collected Road Debris Before and After Vehicle Passes

Condition	**Trial**	**Debris Mass (g)**		
		Before Drive	**After Drive**	**Delta**
Tesla Model Y at 25 mph	1	591.9	622.4	+ 30.5
	2	622.4	611.1	- 11.3
	3	611.1	617.9	+ 6.8
Tesla Model Y at 40 mph	1	599.4	618.3	+ 18.9
	2	618.3	616.4	- 1.9
Ford F-150 at 25 mph	1	617.9	599.4	- 18.5

4.3. Measurement of Particulate Matter from Local Traffic

The next pilot test was to evaluate whether resuspended road dust and vehicular emissions could be effectively captured and quantified. An OPC-N3 PM sensor system was deployed adjacent to a roadway in Fort Collins, CO with active local traffic. The objective of this setup was to determine if the sensor could detect and measure particulate matter generated by vehicle movement.

4.3.1. Site Selection

The monitoring site was selected based on consistent traffic flow, minimal obstruction from vegetation or nearby buildings, and proximity to a paved roadway where particulate resuspension was expected to occur. The location provided a regular flow of vehicles going 25 mph to 30 mph and a bike lane where the setup can be placed out of the way of traffic.

4.3.2. Sensor Installation

The OPC-N3 sensor was deployed at three different heights (ground, 3 feet, and 5 feet above the ground) approximately 3 feet from the lane edge, to capture the vertical distribution of particulate matter within the near surface boundary layer. This arrangement was designed to assess how particulate concentrations vary with height. The hypothesis for this setup was that particles emitted from or disturbed by traffic tend to be most concentrated close to the road surface, where mechanical turbulence from tires and wind shear resuspended dust and other fine materials. By placing sensors at incremental heights, it was possible to evaluate if particulate concentrations decrease with distance from the source.

Additionally, the sensor at ground level provided data representative of the immediate emissions zone, while the sensors at 3 and 5 feet offered insight into human exposure levels at approximately the breathing height of pedestrians. This vertical gradient analysis helped determine both the effectiveness of particulate resuspension from local traffic and the potential exposure risk to individuals near the roadway.

A vehicle parked next to the road was used to position the sensor at three locations: (1) on the ground adjacent to the vehicle, (2) on the rear tire, and (3) on the truck bed. This configuration was designed to minimize distraction to passing vehicles, as drivers were unlikely to notice a vehicle parallel parked along the side of the road. This setup is shown in Figure 3.

Figure 3. OPC-N3 at Ground Level, 3-feet, and 5-feet

4.3.3. Purpose and Expected Outcome

The primary goal of this experimental setup was to verify whether the sensor system could reliably detect and characterize particulate matter associated with local traffic activity. Establishing the presence of measurable resuspended emissions was a necessary step before proceeding with the experiment. Results from this pilot setup were expected to confirm the feasibility of using this method to capture and analyze traffic-related particulate emissions.

4.3.4. Results

The OPC-N3 particulate matter sensor successfully detected measurable fluctuations in airborne particle concentrations in response to local traffic activity. The time series data, shown in Figure 4, displays several distinct peaks in PM 10 levels during the monitoring period, indicating that vehicular movement and the resuspension of road dust had a direct and observable impact on particulate concentrations near the roadway. The recorded pattern demonstrates that the sensor system was sensitive enough to capture short-duration particulate events associated with the passage of vehicles, validating its performance under real-world conditions.

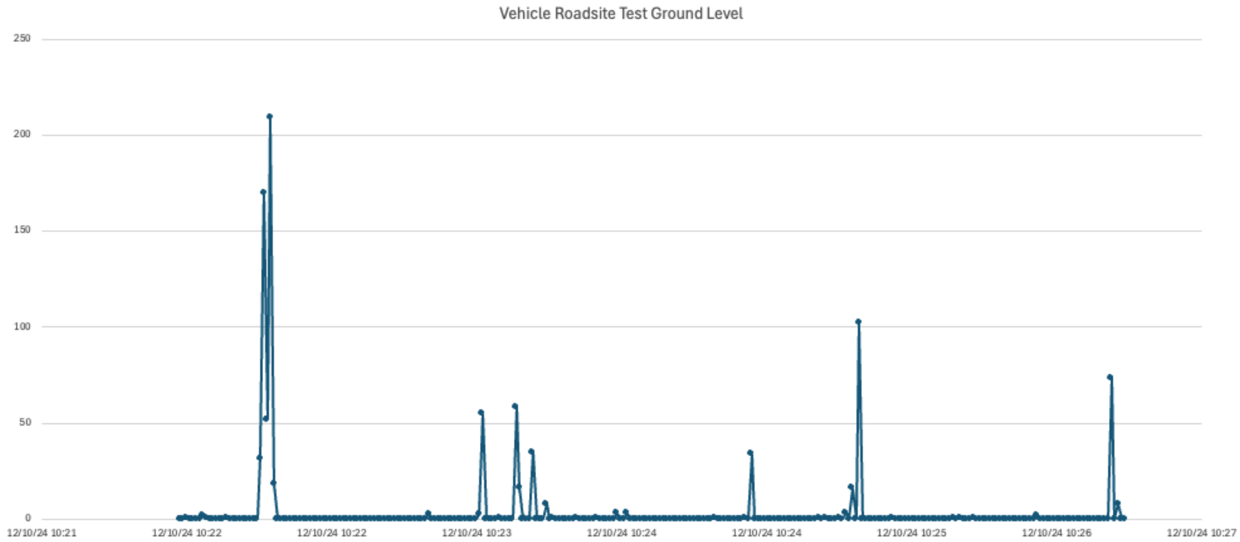

Figure 4. Vehicle Roadside Test Results (PM10) at Ground Level

Several sharp increases in particulate concentration were recorded throughout the test, with the most significant peak reaching approximately 200 µg/m³ at around 10:22 am. These elevated readings coincided with visible vehicle activity, supporting the interpretation that the detected particulate spikes corresponded to vehicle passing through the monitoring zone. Between these events, concentrations dropped rapidly to near background levels, suggesting that particulate emissions from traffic were highly transient and primarily linked to immediate mechanical and exhaust disturbances rather than persistent ambient conditions.

The temporal sequence of peaks observed in the dataset further supports this conclusion, as the timing and magnitude of these events reflected variations in traffic flow and vehicle characteristics. Heavier vehicles such as trucks and SUVs appeared to generate more pronounced particulate matter peaks, likely due to stronger turbulence and greater resuspension of surface dust particles. In contrast, smaller passenger vehicles such as sedans produced relatively smaller peaks. These differences align with expected patterns of mechanical resuspension behavior, where greater mass of larger vehicles increase the likelihood of dislodging fine particles from the pavement surface.

Following each particulate event, PM levels declined sharply, indicating that the suspended particles were quickly dispersed by ambient airflow and vehicle induced turbulence. This rapid decay in concentration suggests that traffic related particulate emissions are localized and short lived, with limited accumulation under the observed environmental conditions. The results also imply that momentary exposure to elevated PM levels can occur near active roadways, particularly at pedestrian breathing height, but the intensity and duration of such exposure decrease substantially with both time and distance from the emission source.

4.3.5. Key Findings

The results confirm that the OPC-N3 sensor system effectively captured transient particulate events associated with local vehicle movement. The distinct and repeatable spikes in PM concentrations validate the sensor’s capability to measure real time changes in particulate levels due to resuspended dust and exhaust emissions. Peak concentrations reaching approximately 200 µg/m³ demonstrate that even moderate traffic flow can generate significant short-term increases in particulate matter near road surfaces.

These findings also highlight that resuspension from vehicle activity is a major contributor to near-surface particulate matter, particularly under dry roadway conditions. The clear temporal relationship between traffic movement and PM spikes supports the hypothesis that mechanical disturbances from tires and aerodynamic turbulence are key mechanisms for dust mobilization. Furthermore, the rapid decline in concentration following each event indicates effective dispersion processes that minimize long term particle accumulation but still result in brief exposure spikes for individuals near the roadway.

Overall, the observed patterns confirm the feasibility of using the OPC-N3 sensor for localized air quality monitoring the quantification of vehicular contributions to airborne particulate matter. The data demonstrate both the short-term variability and vertical dispersion dynamics of traffic induced particulates, providing a foundation for further testing under controlled conditions and for assessing human exposure risks in urban environments.

4.4. Roadside Infrastructure Data Collection

The next pilot phase focused on testing the data acquisition system under near-real roadside conditions to evaluate its reliability in capturing dynamic particulate emissions during vehicle motion. This trial assessed the hardware stability of the Arduino, SEN5x sensor, the RTC timestamp module, and the SD chip module assembly.

4.4.1. Setup

The pilot roadside sensing system was constructed and deployed to evaluate how vehicles of different geometries influence particulate resuspension near the roadway. A temporary monitoring station was established adjacent to a low traffic paved road section, where two adjustable tripod stands supported a horizontal mounting bar to keep the distance of the two tripods constant. Sensirion SEN5x particulate sensors are mounted at two different heights, one near the ground, about 1 foot above the ground, and another one mounted at a height of 5 feet with the other tripod 5 feet away with another sensor at the same height (see Figure 5). All sensors, datalogging electronics, and power systems were secured to the frame using brackets to enable rapid reconfiguration if needed. Power supplied by a 9V battery, and data were logged to a microSD card, with the RTC module maintaining time synchronization across data files. Simultaneous measurements were collected from the SEN5x measuring PM 2.5, PM 10, and environmental variables. The system is portable allowing quick set up and take downs.

Figure 5. Roadside Infrastructure with Sensors on Top of Green Boxes

4.4.2. Data Collection Procedure

During the testing, each vehicle traveled through the sensing plane at controlled speeds while the SEN5x sensors continuously recorded particulate matter mass concentrations and environmental variables. A synchronized timestamp system ensured that the exact moment a vehicle crossed the sensing frame could be aligned with peaks observed in the PM data.

4.4.3. Results

This test revealed that the sensing setup was not able to reliably capture the rapid particulate plumes generated during vehicle passage. Although the system functioned correctly from the OPC-N3 sensor, the SEN5x sensor could not create a response time quick enough to capture the short duration of resuspension events. Because vehicles passed through the sensing plane within a fraction of a second, the sensor was unable to accumulate enough particulate matter within its sampling chamber to register meaningful PM spikes. As a result, the collected data showed only minor fluctuations rather than the distinct, transient peaks expected from traffic-induced resuspension.

This limitation led to inconsistent and incomplete measurements, particularly at the lower sensor height where the strongest particle plumes were anticipated. In several trials, the sensor recorded delayed or smoothed responses that did not correspond to the timing of the vehicle pass, indicating that the integration time of the sensor exceeded the duration of the particulate event itself. Consequently, no clear differences in resuspension were detectable between vehicle types or speeds during this test.

Overall, the pilot test demonstrated that the sensing configuration, in its current form, was not suitable for capturing short-lived, high velocity particulate plumes. These finding informed the redesign and methodological adjustments described in Section 4.5.

4.5. On Road Route Testing

The limitations identified in Section 4.4 demonstrated the need for a measurement approach capable of capturing continuous particulate data rather than relying on brief, roadside sampling intervals. To address this challenge, a vehicle mounted sensing strategy was developed in which the particulate sensors were affixed directly to the test vehicle, allowing uninterrupted acquisition of PM concentrations during motion. In parallel, an appropriate test route was selected that included both a low-traffic roadway segment and a busier urban corridor, ensuring that data could be collected under varying traffic and environmental conditions. This configuration was designed to evaluate the feasibility and performance of the vehicle mounted system, assess whether it could produce consistent and interpretable particulate measurements, and determine its effectiveness in capturing vehicle induced resuspension at different operating speeds.

4.5.1. Setup

The testing vehicles were equipped with four Sensirion SEN5x particulate matter sensors, each mounted at strategically selected locations to capture a comprehensive spatial profile of resuspension behavior. Sensors were positioned at the front bumper, front tire well, rear tire well, and rear bumper (see Figure 6). This arrangement enabled comparisons between tire proximal positions, where mechanical turbulence and shear forces are expected to be the strongest, and bumper mounted positions, which primarily capture airflow-driven background resuspension influenced by vehicle aerodynamics.

Figure 6. Vehicle Equipped with Sensors (3 Visible)

The test route (see Figure 7), located within a residential and collector road network, included several distinct speed-controlled segments intended to assess PM behavior across a range of velocities. The vehicle first traveled in a rectangular loop within the new development neighborhood, which was actively being built. Although the roads were fully completed in the neighborhood, no building construction had started in the immediate vicinity of the testing, resulting in nearly no traffic and a safe environment for testing various speeds. This loop included a 30-mph segment repeated three times and a 40-mph segment repeated three times to evaluate PM signal consistency and variability across identical conditions. The test vehicle then traveled along a major arterial road at 50-mph followed by a 35-mph residential segment, each traveled once.

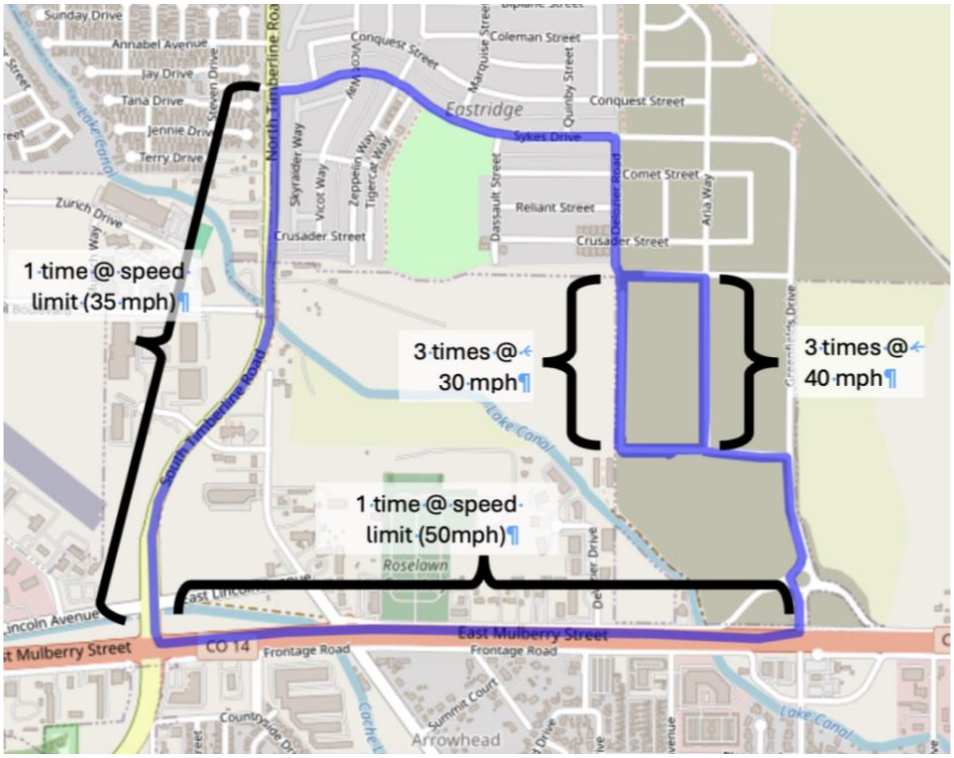

Figure 7. Testing Route

Testing was conducted under clear skies, low wind speeds, and stable ambient conditions to minimize any interference with particulate measurements. The roadway consisted entirely of asphalt surfaces characteristic of. suburban neighborhoods.

4.5.2. Data Collection Procedures

Data collection followed a standardized protocol to ensure consistency and replicability across all test runs. Before each set of passes, all air quality sensors were powered on simultaneously and allowed warm up time to stabilize baseline PM readings. Additionally at this time, the SensorLog smartphone application was activated to record GPS position, vehicle speed, and timestamped motion data. This supplemental dataset enabled precise alignment of PM measurements with vehicle dynamics during post-processing.

During the driving phase, the vehicle was brought to the designated speed for each segment and maintained at that speed for as long as allowed by the road geometry. Cruise control was utilized, when possible, to reduce speed fluctuations. Due to the neighborhood loop containing frequent stops signs and sharp turns, opportunities for holding 30 or 40 mph were limited to only about 10 second segments at best. After completing the required passes, data was then offloaded from each microSD card and inspected to verify successful recording. Any inconsistencies, missing readings, or timestamp misalignments were documented to ensure that system robustness could be evaluated as part of the test.

4.5.3. Results

The pilot test results indicated that the sensor array was capable of detecting particulate matter associated with resuspension events at various vehicle speeds. However, despite the ability to read the peaks in the data, the dataset exhibited considerable variability across runs. This variability was largely attributable to the limited duration spent at steady state speeds along the test route. Because the constant speed sections lasted only a few seconds, the sensors were exposed to brief, transient particulate plumes rather than extended, stable conditions that would allow clear differentiation of speed dependent resuspension patterns. As a result, PM spikes were difficult to interpret consistently, and the short exposure time hindered the ability to calculate reliable averages or make meaningful comparisons between runs and across different speed categories.

4.5.4. Key Findings

One of the most significant findings from this pilot test was that the neighborhood route did not offer sufficient length for stable, sustained driving at the target speeds. At 30-mph and

40-mph, the vehicle typically held a constant speed for only a few seconds before needing to stop or turn. Even at the major arterial road, there were frequent stops preventing any data collection that could be reproduced. These durations were inadequate for generating interpretable PM averages and made it difficult to isolate speed dependent resuspension effects from short term fluctuations.

The entirely paved asphalt surface, with negligible daily traffic, generated relatively low levels of loose particulate matter, and likely unrealistic, resulting in smaller and less distinct resuspension events. One of the goals of the test was to determine how vehicle geometry influences resuspension, but the limited availability of debris on asphalt hindered the ability to detect meaningful differences between vehicle types or speeds. To address this limitation, the study highlighted the need to compare results with a gravel or partially unpaved road, where higher concentrations of loose particulate matter would amplify resuspension events and allow for clearer observation of the effects of vehicle size, ride height, and tire characteristics. Including a dirt road segment in the test plan would provide a more sensitive environment for evaluating the interaction between vehicle geometry and particle displacement.

The pilot test also highlighted the importance of a roadway that provides long, uninterrupted stretches for controlled speed driving at 30-mph and a faster speed. The neighborhood route lacked this capacity, making it unsuitable for a study centered on speed dependent particulate behavior. By moving the testing to a different location, a faster speed (e.g., 50-mph) could be tested to further differentiate between 30-mph and 50-mph.

4.6. Conclusion

The series of pilot tests conducted in this study provided critical insights that directly informed the design of the final experimental protocol for assessing vehicle induced particulate resuspension. The initial debris redistribution trials confirmed that vehicle movement generates measurable particulate matter from paved surfaces, with heavier vehicle and higher speeds generally producing greater resuspension. These findings established that particulate emissions are highly localized, transient, and strongly influenced by tire-surface interactions, supporting the rationale for capturing near surface PM at multiple strategic locations on the vehicle

Roadside PM monitoring using the OPC-N3 and SEN5x sensors demonstrated the feasibility of measuring real-time, traffic-induced particulate spikes. However, the tests also revealed key limitations of stationary roadside configurations. The brief duration of vehicle passage relative to the sensors' response time prevented consistent detection of short-lived PM plumes, and environmental factors such as ambient wind and limited debris availability further constrained data reliability. These results highlighted the need for a continuous, vehicle-mounted sensing approach to overcome the temporal and spatial limitations of roadside sampling.

On-vehicle pilot test reinforced the importance of selecting a test route that allowed for sustained, steady-speed driving. The initial neighborhood loop provided insufficient length to maintain constant speeds, limiting the sensors' ability to capture representative PM peaks and calculate reliable averages. For the final experimental design, a longer road length and incorporating a gravel road segment, would enable comparison of resuspension behavior across surfaces with markedly different particulate availability.

Overall, the pilot studies were instrumental in identifying both the methodological challenges and practical solutions necessary for capturing reliable, high-resolution data on vehicle-induced particulate matter. The lesson learned regarding sensor placement, response time, route selection, and surface type directly shaped the experimental protocol, resulting in a more effective and scientifically rigorous approach for quantifying the contributions of vehicle movement to airborne particulate concentrations.

Chapter 5. Methods

5.1. Overview of Final Experimental Design

The final experimental design was developed based on the limitations identified during the pilot testing phases of Chapter 4. Pilot trials revealed that the roadside monitoring and short test routes did not provide sufficient temporal or spatial resolution for capturing particulate resuspension. Also, a vehicle mounted sensing system paired with longer, continuous road segments were selected as the most effective method for generating reliable, high frequency particulate matter data.

This final setup enabled uninterrupted particulate sampling during vehicle motion, ensuring adequate time at steady state speeds, and provided multiple surface types for comparing roadway dependent resuspension behavior. The approach also supported controlled evaluation of added vehicle weight and its influence on particle emissions.

5.2. Environmental and Operational Controls

To minimize confounding environmental influences, all on-road testing was conducted under dry conditions. Specifically, data collection occurred only on days with no precipitation in the preceding 48 hours to ensure that roadway surfaces were fully dry and free from moisture-induced particle binding. Testing sessions were also scheduled during periods of low wind (i.e., less than 10 mph) to reduce cross-road transport of particulate matter. Ambient temperature, humidity, and pressure were monitored throughout each session using onboard sensors to account for variations in atmospheric stability that might influence aerosol behavior.

5.3. Roadway Selection and Surface Types

Two primary roadway surfaces were selected for testing: gravel and asphalt. This allowed direct comparison of particulate behavior across surfaces with dramatically different debris availability and texture. Each surface category was tested at two different speeds, low-speed (30 mph) and high-speed (50 mph), to assess the influence of vehicle velocity on particulate generation.

5.3.1. Gravel Road Segments (County Road 56)

Gravel testing was conducted on County Road 56 in Fort Collins, CO near the CSU Agricultural Research, Development and Education Center, which is a very low volume road (see Figure 8). This provided long, straight, uninterrupted sections suitable for steady-speed driving.

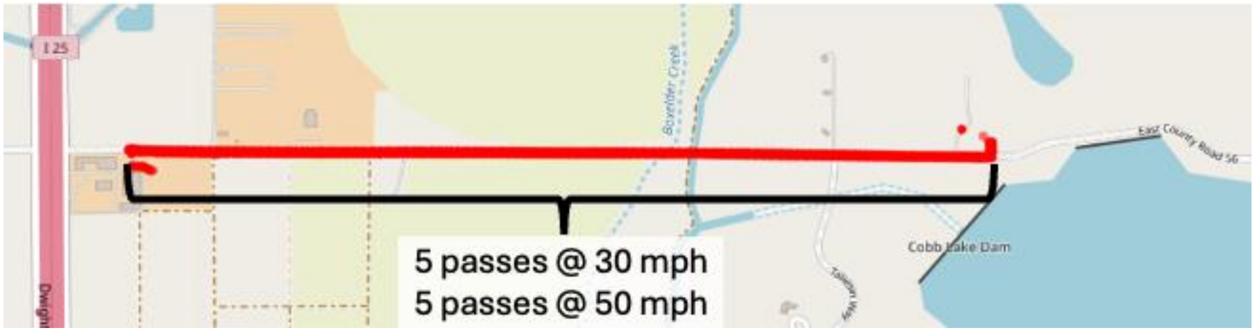

Figure 8. Map of Gravel Road Segment

The gravel surface was selected because its high debris availability and loose particulate layer produce strong, distinguishable resuspension signatures, making it ideal for evaluating how vehicle mass, geometry, and tire interactions influence PM levels.

This road provided a 1.2-mile segment of testing. However, the road included a short, paved bridge over a runoff ditch. Therefore, data was only used before and after this bridge.

Specifically, 0.7 miles from the Frontage Road to the paved bridge, followed by 0.5 miles after the paved bridge to the wildlife entrance. GPS and speed data from the SensorLog app were used to identify these areas of inclusion and exclusion.

5.3.2. Asphalt Road Segments (Vine Drive)

Asphalt testing was performed on a 3-mile stretch of Vine Drive in Fort Collins, CO, just east of I-25 to the border of Weld county and Larimer county (i.e., County Road 1), see Figure 9. This segment was chosen for its long, lightly trafficked straightaways and consistent pavement quality.

Figure 9. Map of Asphalt Road Segment

The asphalt environment enabled evaluation of resuspension under typical urban driving conditions. Because paved surfaces contain lower baseline debris loads than gravel, these tests were essential for understanding the minimum PM signal detectable by the sensing system under real-world paved road conditions.

5.4. Vehicles

There were five vehicles used in testing (see Table 6), selected for their unique attributes. Represented among the vehicles are traditional internal combustion engine vehicles (Ford F-250, Ford Mustang), plug-in hybrid electric (Jeep Wrangler), and battery electric (Tesla Model Y, Nissan Leaf). The vehicles also differ in type, representing sedan (Ford Mustang), compact SUV (Nissan Leaf), midsize SUV (Tesla Model Y, Jeep Wrangler), and large passenger truck (Ford F-250).

Table 6. Size Characteristics of Vehicles Used in Testing

Vehicle Make, Model, Year	**Curb Weight** *(lb)*	**Undercarriage Area** *(in^2)*	**Wheelbase** *(inches)*
Tesla Model Y (2020)	4,061	15,804.68	113.8
Nissan Leaf (2024)	3,900	12,436.20	106.3
Ford F-250 (2003)	6,133	19,783.24	156.2
Jeep Wrangler 4XE (2024)	5,138	13,922.76	118.4
Ford Mustang (2005)	3,375	13,882.40	107.1

5.5. Weight Addition to Vehicles

Each vehicle was evaluated under two weighted conditions: unloaded (i.e., base weight) and loaded (i.e., base weight plus 624 lb). This additional weight was added using six buckets filled with rocks and seven loose stone boarder rocks placed throughout the vehicle to simulate heavy, distributed load scenarios. This configuration enabled assessment of how increased vehicle weight influenced particulate resuspension.

Although the 624 lb loading was partially constrained by available materials, it corresponds to approximately 10-18% of the vehicles’ curb weights (approximately 15% on average). This magnitude is comparable to three adult occupants with modest cargo and represents a realistic operational loading scenario.

5.6. Testing Procedure

Each road segment (gravel and asphalt) was driven to get a total of approximately 7 miles at base vehicle weight and approximately 7 miles at base plus 624 lb. These repeated passes were designed to generate sufficient steady-state data for statistical analysis. Each pass consisted of a continuous 1.2-mile recording window on gravel and 3 miles recording window on paved, providing adequate duration at the target speed to capture stable particulate concentrations. During data processing, the steady-state portions of these five passes were subdivided into 30-second segments. From these segments, ten were randomly selected per condition, ensuring that each experimental configuration (road type x speed x weight x vehicle) was represented by ten comparable trial units for statistical evaluation.

The vehicle accelerated smoothly to the designated speed before entering the measurement segment, maintained the target speed for the full 1.2 or 3 miles, and then exited the segment before decelerating. This procedure minimized the transient effects associated with acceleration and braking, allowing collected PM data to correspond primarily to stable driving conditions.

Throughout each run, the PM sensors recorded data continuously throughout the testing segments. Sensor placements were placed throughout the vehicle at the front and back bumper and the front and back tire wells. This arrangement provided spatially distributed measurements to capture variations in particulate concentration arising from tire turbulence and aerodynamic wake effects.

5.7. Summary of Independent Variables

The final experimental design was structured to directly address the three primary research questions of this thesis outlined in Section 1.3. To answer the research questions, the study employed a multi-factor factorial design incorporating the following independent variables:

- **Road Type** (2 levels): Gravel and Asphalt
- **Speed** (2 levels): 30 mph and 50 mph
- **Weight Conditions** (2 levels): Base vehicle weight and Base + 624 lb
- **Vehicle** (5 levels): Tesla Model Y, Nissan Leaf, Ford F-250, Jeep Wrangler 4XE, and Ford Mustang
- **Sensor Location** (4 levels): Front bumper, Rear bumper, Front tire, and Rear tire

Road type, speed, and weight were experimentally controlled operational variables manipulated during field testing. Vehicle type represented a structural and aerodynamic factor, allowing comparison across differences in mass, ride height, undercarriage geometry, and wake formation. Sensor location was treated as a measurement factor, enabling assessment of spatial variability in particulate concentrations around the vehicle body.

This framework allowed the use of analysis of variance (ANOVA) models in Chapter 6 to evaluate:

- Main effects of road type, speed, weight, and vehicle characteristics
- Interaction effects among operational variables (e.g., speed x road type)
- Spatial differences in particulate concentration attributable to wake region dynamics

By structuring the experiment in this way, the design ensured that each research question could be addressed systematically while maintaining sufficient replication and temporal consistency for robust statistical interference.

5.8. Rationale for the Final Configuration

The final experimental setup was selected because it resolved the major limitations identified in Section 4. The final testing setup was structured to directly address the core research objectives that were discussed in Section 1.3. Pilot testing revealed that shorter neighborhood routes and stationary monitoring approaches lacked sufficient stability and spatial control to isolate vehicle-induced resuspension behavior. In response, longer, uninterrupted road segments were selected to ensure that the sensing system operated under steady state conditions, allowing particulate concentrations within the vehicle wake to stabilize prior to evaluation.

This modification was critical for addressing the first research question, which focuses on how sensor location influences the measurement of spatial variability in resuspension emissions. Importantly, sensor placement does not affect the generation of particulate matter but instead determines where within the flow field concentrations are sampled. In particular, rear-mounted sensor captures a wake-dominated region and therefore represent a localized, worst-case concentration rather than a uniform representation of the surrounding environment.

The decision to use vehicle-mounted sensors rather than stationary roadside monitors further aligned the experimental design with the second and third research questions. Continuous, high-resolution measurement during vehicle motion allowed for direct comparison of speed, weight, and road surface effects while minimizing interference from background traffic and environmental variability. By incorporating both gravel and asphalt surfaces, the design enabled controlled comparison between high-debris and low-debris environments, directly addressing how roadway surface influences particulate resuspension. Similarly, repeated trials under both unloaded and loaded conditions allowed isolation of vehicle weight effects while maintaining consistency in other experimental variables.

Finally, the use of multiple vehicle types with varying geometry, ride height, and mass distributing ensured that the design could evaluate potential aerodynamic and structural influences on wake-region particulate behavior. While the final configuration was shaped by practical limitations encountered during pilot testing, it was deliberately selected to provide the level of experimental control necessary to answer the objectives of this thesis.

5.9. Data Cleaning

Following the completion of field testing, all datasets that were produced by each of the Sen5x sensors were subjected to a data cleaning and synchronization process prior to statistical analysis. Because each sensor operated independently on its own microcontroller and real-time clock module, minor differences in initialization time, timestamp alignment, and logging continuity were present across sensor locations. An analysis was then implemented to make sure that all sensors were consistent in temporal consistency, data integrity, and comparability across vehicles, road types, speeds, and weight conditions.

Raw data were recorded in Comma-Separated Value (CSV) format and stored locally on the microSD cards. Each file contained timestamped measurements of PM1.0, PM2.5, PM4.0, PM10, volatile organic compound (VOC) index, nitrogen oxide (NOx) index, relative humidity, and temperature. All files were imported into R and standardized to ensure consistent column naming and formatting. The timestamp variable was converted to a unified data-time format (i.e., POSIXct) to allow accurate temporal alignment across datasets.

The sensors were set to log data on time intervals of one second. However, because sensors were manually powered on prior to each run, small offsets, ranging from 1-5 seconds, existed between sensors start time for given trials. To ensure that comparisons between front bumper, rear bumper, front tire, and back tire locations represented the same moment in time, timestamp synchronization was performed. Timestamps were rounded to the nearest second, duplicate timestamps within individual files were removed, and datasets corresponding to the same run were merged using timestamp as the primary key. Only timestamps common to all relevant sensor locations were retained. This ensured that statistical comparisons were based on temporally matched measurements.

Logging frequency was verified by calculating differences between consecutive timestamps. Occasional single-second gaps were observed; however, these gaps were infrequent and did not exhibit systematic bias. No interpolation was applied, and analyses were conducted using recorded timestamps only.

Finally, datasets were segmented to include only steady-state measurements (e.g., consistent speed) at the specified speed intervals corresponding to the predefined gravel and asphalt test segments. Data recorded during acceleration, deceleration, or turning that is outside the designated measurement window were excluded. This ensured that the summary statistically reflected the driving conditions consistent with the experimental design described in Section 5.6 and 5.7. The dataset was segmented into 30-second trials for each unique combination of road type, speed, vehicle weight condition, and vehicle. Due to data cleaning procedures and differences in road segment lengths, the total number of 30-second trials varied across combinations. To ensure balanced comparisons, ten trials were randomly selected for each unique combination.

The cleaned and synchronized datasets were then reshaped into a standardized structure containing timestamp, vehicle, road type, speed, weight condition, sensor location, and particulate concentration. This final dataset formed the basis for the factorial ANOVA analyses presented in Chapter 6.

Chapter 6. Results

This chapter presents the results of the vehicle resuspension emissions study. The results are structured to evaluate how particulate matter (PM) concentrations varied as a function of road surface type (gravel vs. paved), vehicle speed (30mph vs. 50mph), vehicle weight condition (weighted vs. unweighted). In addition, Spatial variation in particulate concentrations is examined using multiple sensor mounting locations (front bumper, rear bumper, front tire, and rear tire). Comparisons are made across the vehicles tested to evaluate whether vehicle specific differences in geometry and wake formation influence resuspension behavior.

Measurements are reported in this chapter for fine particulate matter, PM2.5. This focus reduces repetitious reporting of strongly correlated results between PM2.5 and PM10 and acknowledges the significant health concerns associated with PM2.5. Appendix B through Appendix D includes the same statistics and visuals for PM10 as presented in this chapter. Specifically, the following research questions are addressed:

- **RQ1:** How does sensor location influence the measured spatial distribution of particulate matter concentrations around a moving vehicle?
- **RQ2:** How does vehicle weight, speed, and road surface type affect resuspension emissions?
- **RQ3:** How do aerodynamic differences between vehicles influence particle resuspension generated by vehicles?

6.1. Analytical Methods

The results presented in this chapter are derived from repeated trial runs (N = 10 per condition) and are summarized using mean PM concentrations and associated variability across trials. Statistical differences were evaluated using analysis of variance (ANOVA) for α = 0.05. When ANOVA results indicated a statistically significant main effect, Tukey's Honestly Significant Difference (HSD) post-hoc comparison were used to identify which specific groups differed while controlling for multiple comparisons.

6.2. Overview of Data

Summary statistics for the data are shown in Table 7. Subsequent sections perform a deeper analysis on each condition while controlling for relevant variables. Table 7 provides an initial descriptive overview of PM2.5 concentrations across the primary experimental factors, including speed, road type, weight condition, vehicle type, and sensor location. These statistics provide an initial overview of average PM2.5 levels and their variability prior to conducting formal statistical tests.

Table 7. Descriptive Statistics for PM2.5 Concentrations by Experimental Conditions

Variable	**Condition**	**Mean**	**Min**	**Max**	**Std. Dev.**
Speed	30	63.9	0.866	2806	166
	50	102	0.50	5567	310
Road Type	Gravel	112	0.50	1132	152
	Asphalt	54.1	0.866	5567	315
Weight	Base	90.3	0.866	5567	304
	Weighted	75.7	0.50	2372	180
Vehicle	Tesla Model Y	60.2	1.24	828	115
	Nissan Leaf	75.2	1.42	2806	237
	Ford F-250	57.3	0.761	561	98.7
	Jeep Wrangler	107	1.43	5567	446
	Ford Mustang	114	0.50	1132	172
Sensor Location	Back Bumper	176	1.60	5567	446
	Back Tire	61.2	2.03	837	101
	Front Bumper	3.35	0.50	16.9	2.10
	Front Tire	90.9	0.761	1317	149

6.3. Sensor Location Effects on Measured Resuspension Emissions

Sensor mounting location was consistently one of the strongest sources of variation in measured PM concentration differences across all test conditions. Across vehicles and conditions, the rear bumper sensor recorded substantially higher PM concentrations than the front bumper sensor for both PM2.5 and PM10. In many test configurations, front bumper PM values remained near background levels, while rear bumper values increased sharply, particularly on gravel surfaces and at higher speeds. This consistent separation suggests that the rear bumper sensor was positioned within the vehicle wake region, where resuspended particles generated near the road surface are transported and concentrated due to turbulent recirculation and aerodynamic flow structures behind the vehicle.

These differences are illustrated in Figure 10, which shows the distribution of mean PM concentrations across sensor locations under varying road type, speed, and vehicle loading conditions.

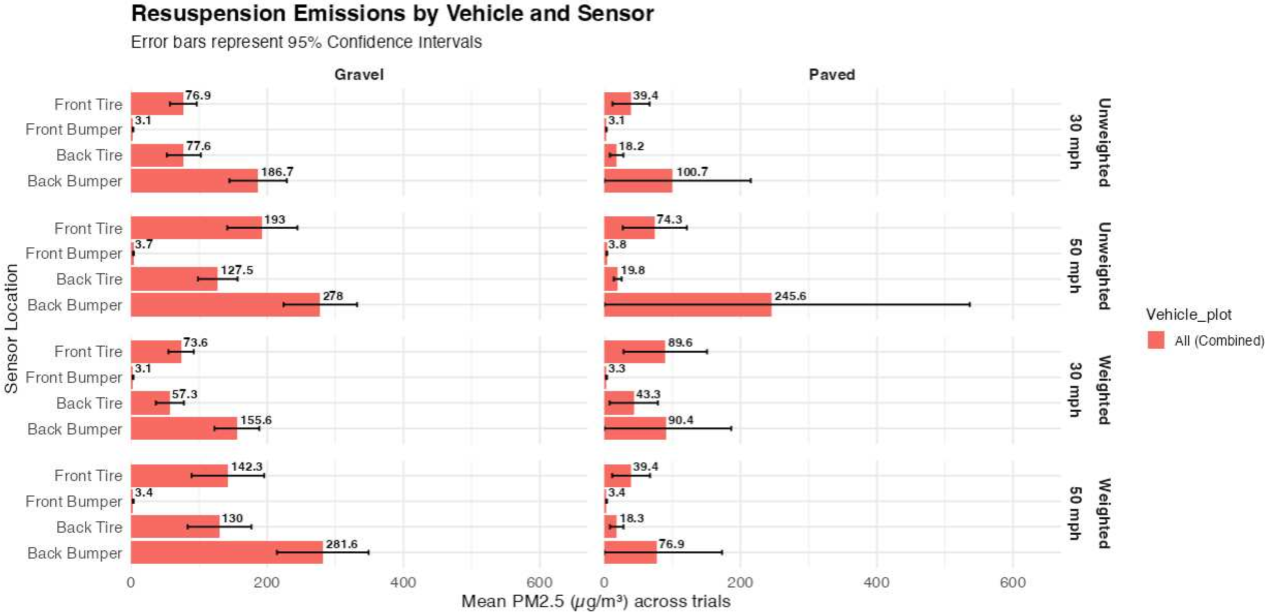

Figure 10. Comparison of Mean PM2.5 by Sensor Location across Conditions

The observed differences across sensor location indicate that resuspended particles are not uniformly distributed around the vehicle body during travel. Rear mounted sensors consistently recorded higher PM concentrations than front mounted sensors as shown in Figure 10. While aerodynamic wake formation was not a directly measured in this study, the observed spatial distribution is consistent with prior research describing turbulent recirculation and particle accumulation in vehicle wake regions (Harrison et al., 2021; Grigoratos & Martini, 2014). In contrast, front bumper measurements more closely reflect near-ambient conditions. These findings have important implications for experimental design, as rear mounted sensors capture wake-dominated, localized peak concentrations and therefore more sensitive to changes in speed, road type, and vehicle characteristics.

From a statistical standpoint, the ANOVA model (Table 8) for this research question tested whether mean PM concentrations were significantly different between sensor locations when controlling for other experimental factors (i.e., vehicle type, road type, speed, and weight). In other words, the ANOVA evaluated the null hypothesis that all sensor locations produced the same mean PM values. Rejection of this null hypothesis indicates that sensor placement meaningfully changes the measured concentration, confirming that measurement location is not interchangeable. Tukey testing (Table 9) then provided pairwise comparisons between sensor locations to identify which specific sensors differed from one another while controlling for the increased error associated with multiple comparisons.

Tukey results confirmed that rear bumper measurements were significantly higher than those from the front bumper, front tire, and rear tire locations, while differences between tire mounted sensors were smaller and often not statistically significant.

Table 8. ANOVA Results for Sensor Location (PM2.5)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Sensor Location	3	2070785	36.595	< 0.001
Vehicle	4	219823	3.885	0.0038
Road Type	1	1300268	22.978	<0.001
Speed	1	578615	10.225	0.0014
Weight	1	85510	1.511	0.219

Table 9. Tukey Results for Sensor Location (PM2.5)

Sensor Location	Mean	Front Tire	Rear Tire	Front Bumper
Front Tire	90.86	-	-	-
Rear Tire	61.33	p = 0.296	-	-
Front Bumper	3.51	p < 0.001	p = 0.003	-
Rear Bumper	176.57	p < 0.001	p < 0.001	p < 0.001

6.3.1. Rationale for Sensor Selection

Although four sensor locations were tested in early development and pilot testing, front bumper, front tire, rear tire, rear bumper, results demonstrated that the front bumper and rear bumper locations provided the most consistent and interpretable signals for comparing resuspension across vehicles and conditions. The front bumper sensor consistently recorded the lowest PM concentrations across road types, speeds, and weighing conditions, indicating that it primarily captured near-background particulate levels. Because the purpose of the analysis was to evaluate vehicle-induced resuspension, the front bumper location was excluded from the primary resuspension analysis. In contrast, the rear bumper sensor consistently recorded the highest PM concentrations and the greatest variability across trials, indicating that it captured wake-region resuspension where particles accumulate and remain suspended behind the vehicle. This consistent behavior supported the selection of the rear bumper as the primary sensor location for the main analysis.

6.3.2. Justification for the Exclusion of Tire-Adjacent Sensors

Tire-adjacent sensors were not selected as primary measurement locations because they did not provide a clear or consistent distinction in resuspension magnitude compared with the bumper-mounted sensors. As shown in Table 9, the front tire and rear tire sensors produced moderate PM concentrations that were higher than the front bumper but significantly lower than the rear bumper. In addition, the Tukey comparison indicated no statistically significant difference between the two tire locations (p-value = 0.296), suggesting that these positions captured similar particulate environments. The tire sensors also measure particulate concentrations within the immediate tire-road interaction zone, where local turbulence, debris impacts, and small differences in mounting geometry can influence measurements. As a result, tire-adjacent measurements may reflect localized disturbances rather than the broader resuspension plume produced by the moving vehicle. Because the objective of the analysis was to compare consistent resuspension behavior across vehicles and conditions, bumper-mounted sensors provided a clearer and more interpretable contrast. Consequently, the front tire and rear tire sensors were not used as primary measurement locations in the final resuspension analysis.

6.4. Road Type

Road type was evaluated to determine whether surface condition influenced resuspension emissions, particularly by altering the availability of loose particulate material. Gravel surfaces were expected to produce higher resuspension emissions than paved surfaces because gravel roads typically contain greater quantities of loose dust and debris that can be aerosolized by vehicle-induced turbulence. Road type comparisons were performed using the rear bumper sensor as the primary location because it captured the wake region where resuspended particles accumulate and remain suspended behind the vehicle. Figure 11 shows a comparison of rear bumper PM2.5 concentrations on gravel and paved roads under matched speed (30 mph) and loading (unweighted) conditions, averaged across all vehicles.

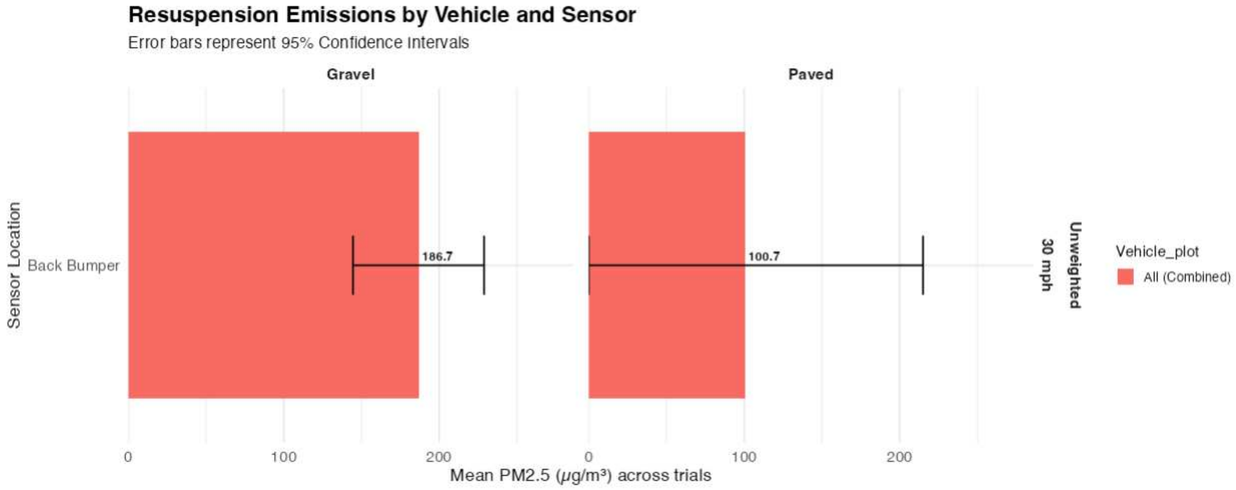

Figure 11. Comparison of Rear Bumper PM2.5 by Road Type

The ANOVA model (Table 10) tested whether mean PM concentrations differed significantly between gravel and paved road surfaces while accounting for speed, weight, and vehicle. For PM2.5 at the rear bumper, road type was statistically significant, indicating that the measured PM2.5 differed between gravel and paved surfaces beyond what would be expected from random trial-to-trial variability.

Table 10. ANOVA Results for Road Type (PM2.5)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Road Type	1	940,944	4.826	0.029
Weight × Road Type	1	146,633	0.752	0.386
Speed ×Road Type	1	44,260	0.227	0.634
Weight × Speed ×Road Type	1	238,685	1.224	0.269

The Tukey comparison (Table 11) quantified this difference directly and showed that paved surfaces produced significantly lower PM2.5 concentrations than gravel surfaces. The negative value indicates that gravel surfaces produced higher PM2.5 inventories than paved roads, and the confidence interval for this comparison did not include zero, supporting the conclusion that the road type effect was statistically meaningful.

Table 11. Tukey Results for Road Type (PM2.5)

Road Type	Mean	Gravel
Gravel	225	-
Paved	128	p = 0.029

These findings are shown visually in Figure 11which compares gravel and paved conditions under matched speed and sensor configurations. The road type effect was one of the strongest environmental contributors to resuspension emissions in this study and supports the conclusion that surface condition is a dominant driver of non-exhaust particulate generation.

6.5. Speed

Vehicle speed was evaluated to determine how increased kinetic energy and aerodynamic forcing influence resuspension emissions. Higher speeds were expected to enhance particulate resuspension by increasing tire road shear forces, turbulence intensity, and aerodynamic lift within the vehicle wake. Speed comparisons were performed using the rear bumper sensor as the primary measurement location, as this sensor captured wake-region concentrations where resuspended particles accumulate and remain suspended behind the vehicle.

Figure 12 illustrates mean PM concentrations measured at 30mph and 50mph on gravel surfaces under matched vehicle and loading conditions. As shown in Figure 12, higher vehicle speed resulted in increased particulate concentrations. This effect was visually apparent as a clear separation between 30mph and 50mph conditions.

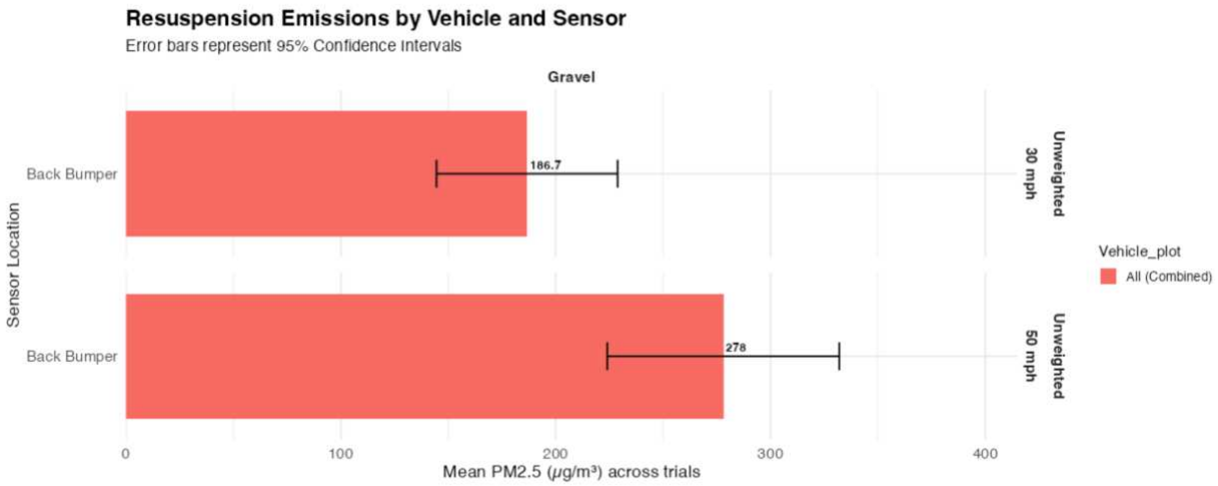

Figure 12. Comparison of Rear Bumper PM2.5 by Vehicle Speed

From a statistical perspective, the ANOVA model (Table 12) tested whether mean PM concentrations differed significantly between speed conditions while controlling for road type, vehicle, and weight. Results confirm that speed had a significant effect on PM2.5.

Table 12. ANOVA Results for Vehicle Speed (PM2.5)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Speed	1	750,616	3.850	0.050
Weight × Speed	1	93,021	0.477	0.490
Speed × Road Type	1	44,260	0.227	0.634
Weight × Speed × Road Type	1	238,685	1.224	0.269

Tukey comparisons (Table 13) quantified the magnitude of this effect and confirmed that 50mph conditions produced significantly higher PM concentrations than 30mph conditions, These results indicate that vehicle speed is a key driver of resuspension emissions, especially for coarse particulate matter, and that speed-related effects become more pronounced under conditions where loose surface material is available.

Table 13. Tukey Results for Vehicle Speed (PM2.5)

Speed	**Mean**	**30 mph**
30 mph	133	-
50 mph	220	p = 0.05

6.6. Vehicle Weight

Vehicle weight was evaluated to determine whether increased loading, which results in higher tire-load contact forces and surface disturbance, leads to increased resuspension emissions. Weighted vehicle configurations were expected to generate higher PM concentrations compared to unweighted due to enhanced mechanical entrainment of surface material. Weight comparisons were conducted using rear bumper measurements under conditions associated with elevated resuspension.

Figure 13 compares mean PM concentrations measured under weighted and unweighted vehicle conditions. While weighted configurations occasionally exhibited higher mean PM values, the differences were inconsistent across trials and generally smaller than those associated with road type or speed.

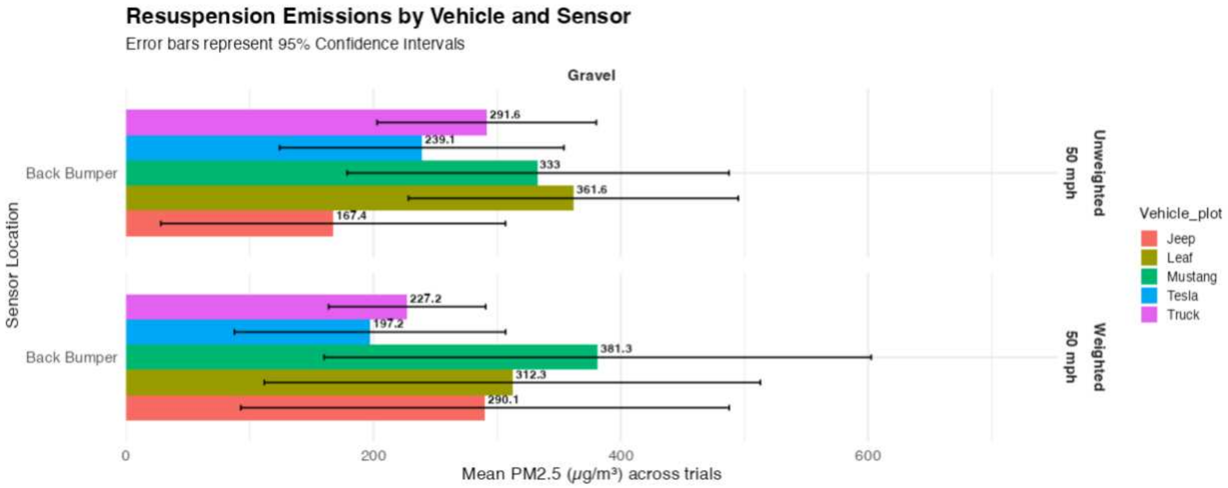

Figure 13. Comparison of Rear Bumper PM2.5 by Weight Condition

The ANOVA model (Table 14) tested whether mean PM concentrations differed significantly between weighted and unweighted conditions while accounting for speed, road type, and vehicle. For PM2.5 vehicle weight was not a statistically significant main effect, indicating that differences between weighted and unweighted configurations were not distinguishable from random variability at the tested loading levels. Interaction terms involving weight, including weight-by-speed and weight-by-road type interactions, were also not statistically significant.

Table 14. ANOVA Results for Vehicle Weight (PM2.5)

Variable	**Degrees of Freedom**	**Mean Square**	**F-statistic**	**p-value**
Weight	1	257,184	1.319	0.252
Weight × Speed	1	93,021	0.477	0.490
Weight × Road Type	1	146,633	0.752	0.386
Weight × Speed × Road Type	1	238,685	1.224	0.269

Tukey comparisons (Table 15) between weighted and unweighted conditions indicated no statistically significant difference in PM2.5 concentrations. Although mean concentrations were numerically lower under the weighted condition compared to the unweighted condition, the difference was not statistically significant, as reflected by the non-significant p-value. This suggests that within the tested loading range, vehicle mass did not meaningfully alter resuspension magnitude. Relative to the strong effects observed for road surface type and vehicle speed, weight appears to exert a comparatively minor influence under experimental conditions evaluated.

Table 15. Tukey Results for Vehicle Weight (PM2.5)

Weight Condition	Mean	Unweighted
Unweighted	202	-
Weighted	151	p = 0.251

6.7. Vehicle Types

Vehicle specific effects were evaluated to assess whether differences in vehicle geometry and aerodynamic wake formation influence resuspension emissions. Vehicles differ in height, frontal area, undercarriage geometry and rear end shape, all of which can affect airflow patterns and wake turbulence. To isolate aerodynamic and geometric effects from confounding factors, vehicle comparisons were conducted under controlled conditions, paved road surface, 30 mph speed, unweighted configuration, and looking at rear bumper sensor measurement placement.

Figure 14 presents mean PM2.5 concentrations measured at the rear bumper for each vehicle under these controlled conditions (i.e., unweighted at 30mph on paved road). Although mean concentrations varied among vehicles, substantial overlap in confidence intervals was observed.

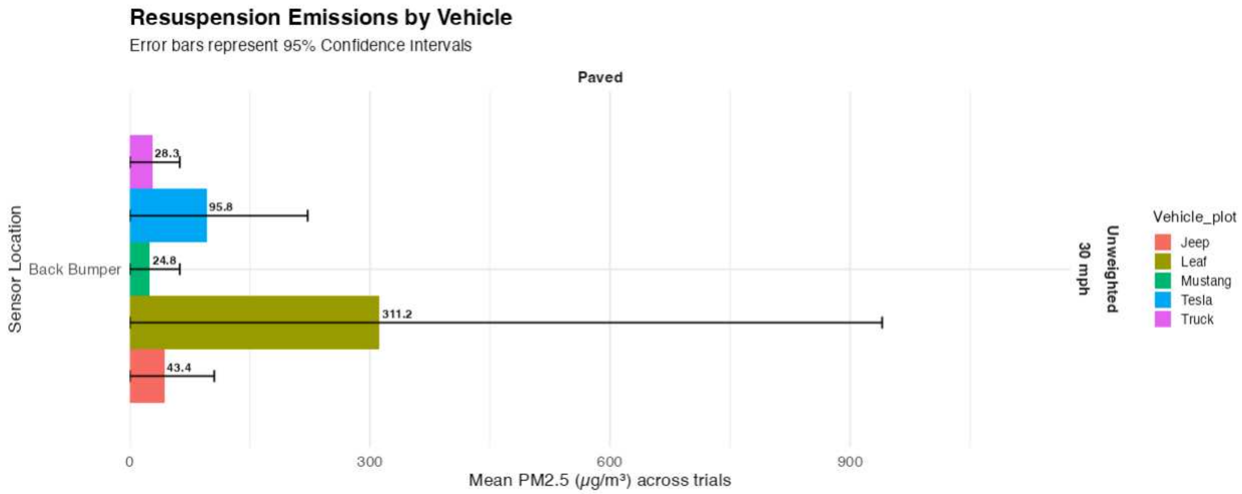

Figure 14. Comparison of Rear Bumper PM2.5 by Vehicle Type

Statistically, the ANOVA model (Table 16) tested whether mean PM concentrations differed significantly between vehicles when road type (paved), speed (30mph), and weight (unweighted) were held constant. The ANOVA results indicated that vehicle type was not a statistically significant main effect for PM2.5.

Table 16. ANOVA Results for Vehicle Type (PM2.5)

Variable	**Degrees of Freedom**	**Mean Square**	**F-statistic**	**p-value**
Vehicle	4	146,561	0.897	0.474

Tukey comparisons (Table 17) further showed that no pairwise vehicle comparisons were statistically significant, with all confidence intervals spanning zero.

Table 17. Tukey Results for Vehicle Type (PM2.5)

Vehicle Type	Mean	Ford	Jeep	Leaf	Mustang
Truck	28.3	-	-	-	-
Jeep	43.4	p = 0.999	-	-	-
Leaf	311.2	p = 0.527	p = 0.579	-	-
Mustang	24.8	p = 1.000	p = 0.999	p = 0.514	-
Tesla	95.8	p = 0.995	p = 0.998	p = 0.756	p = 0.995

These findings suggest that under low-resuspension conditions, such as paved roads at moderate speed, vehicle aerodynamic differences alone do not produce large or statistically distinguishable differences in resuspension emissions. However, the observed variability across vehicles indicates that aerodynamic effects may still contribute under more extreme conditions, such as gravel surfaces at higher speeds, were wake dynamics and underbody flow interactions are amplified. Thus, while vehicle geometry does not dominate resuspension behavior under controlled conditions, it may modulate emissions in conjunction with surface type and speed.

6.8. PM10 Measures

While PM2.5 is widely regarded as the more critical fraction from a public health perspective as discussed in Section 2.1, PM10 was also measured and analyzed throughout this study. As discussed in Section 2.1, PM2.5 is more strongly associated with cardiovascular and respiratory morbidity; therefore, the primary statistical analyses presented in Chapter 6 focuses on PM2.5 concentrations.

However, PM10 results were evaluated in parallel to determine whether trends observed for PM2.5 were consistent across broader particle size fractions. In general, the PM10 results mirrored the patterns observed for PM2.5. Specifically, higher speeds and gravel surfaces were associated with elevated concentrations, rear bumper measurements exceeded front-mounted measurements, and vehicle-specific differences were modest under controlled conditions. In several cases, the magnitude of the speed effect was more pronounced for PM10, which is consistent with the expectation that larger particles require greater mechanical and aerodynamic energy for resuspension.

Because the overall directional trends between PM2.5 and PM10 were consistent, and because PM2.5 is of greater regulatory and health relevance, the detailed figures and statistical tables for PM10 are provided in Appendix B through Appendix D.

Chapter 7. Discussion and Conclusions

This section interprets the results of the vehicle resuspension emissions study presented in Section 6 and discusses their implications in the context of the research questions outlined in Section 1.3. The objective of this research was to evaluate how particulate matter concentrations generated by vehicle induced resuspension vary as a function of sensor mounting location, road surface type, vehicle speed, vehicle weight, and vehicle specific aerodynamic characteristics. Measurements of both fine particulate matter (PM2.5) and coarse particulate matter (PM10) were examined to capture differences in resuspension behavior across particle size classes.

The results demonstrate that resuspension emissions are not uniformly distributed around a vehicle and are strongly influenced by wake-region dynamics, surface material availability, and vehicle speed. In contrast, vehicle weight and vehicle-specific aerodynamic differences played a secondary role within the tested conditions. These findings highlight the importance of experimental design choices, particularly sensor placement and test surface selection, when characterizing non-exhaust particulate emissions.

7.1. Sensor Location and Wake Dominated Resuspension Dynamics

The first research question examined whether sensor mounting location significantly affects measured resuspension emissions. As shown in Section 6.1, sensor location emerged as one of the strongest determinants of measured PM concentrations. Rear bumper sensors consistently recorded substantially higher concentrations than front bumper and tire-adjacent sensors across vehicle, road type, speed, and loading conditions.

This consistent separation indicates that resuspended particles are concentrated within the vehicle wake rather than being evenly distributed around the vehicle body. The wake region behind the vehicle is characterized by turbulent recirculation, reduced airflow velocity, and enhanced particle residence time, all of which promote accumulation of resuspended material. In contrast, the front bumper region is dominated by incoming ambient airflow, which limits the influence of resuspended particles generated at. The tire-road interface.

Statistical analysis supports this physical interpretation. The ANOVA results in Table 8 demonstrate that locations a highly significant predictor of PM2.5 concentrations even when controlling for vehicle, road type, speed, and weight. Tukey comparisons, presented in Table 9, confirmed that rear bumper measurements were significantly higher than all other sensor locations, while differences between tire mounted sensors were smaller and often not statistically significant. Together, these findings confirm that sensor placement meaningfully alters measured PM concentrations and that rear wake measurements are essential for accurately characterizing resuspension magnitude.

This finding is important because it demonstrates that vehicle-induced resuspension cannot be accurately characterized without accounting for spatial variability within the vehicle wake. The strong and consistent influence of sensor location indicates that particulate matter generated at the tire-road interface is transported and concentrated in the rear recirculation zone, or wake zone, meaning that measurements taken outside this region may underestimate resuspension magnitude. This has direct implications for experimental design evaluation on non-exhaust emissions. Without standardized and strategically positioned sensors, comparisons across studies may be inconsistent or misleading. Establishing the rear wake as the primary measurement region improves the reliability, repeatability, and interpretability of resuspension studies.

7.2. Influence of Road Surface Type on Resuspension Emissions

The second research question addressed whether road surface type influences resuspension emissions. Results in Section 6.4 clearly demonstrate that gravel surfaces produce significantly higher PM concentrations than paved surfaces when measured at the rear bumper. This finding aligns with expectations, as gravel roads contain greater quantities of loose particulate material that can be entrained by mechanical disturbance and aerodynamic forcing.

The statistical evidence supports the visual patterns shown in Figure 11. The ANOVA model, Table 10, identified road type as a statistically significant main effect for PM2.5, while interaction terms involving road type were not significant. Tukey comparisons, presented in Table 11, quantified this difference and confirmed that PM2.5 concentrations on gravel roads were significantly higher than those on paved roads under matched conditions.

These results indicate that surface material availability is a dominant environmental driver of resuspension emissions. Even under identical vehicle, speed, and loading conditions, gravel roads consistently produced higher particulate concentrations. This finding underscores the importance of road maintenance and surface composition in managing non-exhaust emissions and suggests that mitigation strategies targeting surface conditions may be particularly effective.

This finding is important because it demonstrates that resuspension emissions are fundamentally constrained by surface material availability, independent of vehicle configuration. While vehicle speed and aerodynamics effects influence the entrainment of particles, magnitude of emissions is ultimately limited by the looseness of particulate material present on the roadway. The clear and consistent separation between gravel and paved surfaces indicates that environmental context may exert a stronger influence on resuspension and vehicle-specific characteristics under many operating conditions. From a regulatory and infrastructure perspective, this highlights road maintenance, surface treatment, and dust control practices as potentially effective mitigation strategies for reducing non-exhaust emissions. Moreover, these results reinforce the need to incorporate roadway condition and surface composition into emissions modeling frameworks rather than relying solely on vehicle-centered parameters.

7.3. Effect of Vehicle Speed on Particulate Resuspension

Vehicle speed, also part of the second research question, was evaluated to determine how increased kinetic energy and aerodynamic forcing affect resuspension emissions. As shown in Section 6.5, increasing speed from 30 to 50 mph resulted in higher PM concentrations at the rear bumper. As shown in Appendix B, this effect is particularly pronounced for PM10. This effect was visually evident in Figure 12 and Figure 17 was supported statistical analysis.

The ANOVA results, presented in Table 12, indicated that speed was statistically significant. Tukey comparisons, shown in Table 13, confirmed that higher speeds produced significantly higher particulate concentrations, especially for coarse particles.

These findings suggest that vehicle speed plays a critical role in resuspension emissions, particularly when loose surface material is available. Increased speed amplifies tire-road shear forces and wake turbulence, leading to greater entrainment and transport of coarse particles. As a result, speed management may represent and important lever for reducing resuspension-related particulate emissions, especially on unpaved or gravel surfaces.

7.4. Influence of Vehicle Weight

Vehicle weight, the last part of the second research question, was examined to determine whether increased loading leads to higher resuspension emissions through enhanced mechanical entrainment. Contrary to expectations, the results in Section 6.6 show that vehicle weight was not a statistically significant predictor of PM concentrations for PM2.5 within the tested loading range (i.e., increase of 624 lb).

Although some weighted configurations exhibited higher mean PM concentrations, these differences were inconsistent and small relative to those associated with road type and speed. The ANOVA results, presented in Table 14, indicated that weight and all weight-related interaction terms were not statistically significant. Tukey comparisons, shown in Table 15, further supported this conclusion, with confidence intervals overlapping zero for all weight contrasts.

These findings suggest that within the tested conditions, vehicle mass plays a secondary role in determining resuspension emission. While increased weight may enhance mechanical disturbance at the tire-road interface, its influence appears to be outweighed by surface material availability and aerodynamic forcing. This implies that mitigation strategies focused solely on vehicle weight may have limited effectiveness compared to those addressing road surface condition and vehicle speed.

7.5. Vehicle Aerodynamics

The final research question explored whether vehicle-specific aerodynamic and geometric differences influence resuspension emissions. Under controlled conditions designed to minimize confounding factors, paved surface, 30 mph, unweighted configuration, vehicle type was not a statistically significant predictor of PM2.5 concentrations, as shown in Section 6.5.

Figure 14 illustrates variability in mean PM concentrations across vehicles, but substantial overlap in confidence intervals was observed. ANOVA results, shown in Table 16, confirmed that vehicle type was not a significant main effect, and corresponding Tukey comparisons, presented in Table 17, indicated no statistically significant pairwise differences between vehicles.

These findings suggest that under low-resuspension conditions, such as paved roads at moderate speeds, vehicle aerodynamic differences alone do not dominate resuspension behavior. However, the observed variability across vehicles indicates that aerodynamic effects may still modulate emissions under more extreme conditions, such as gravel surfaces at higher speeds. In such cases, differences in ride height, and underbody flow may amplify or suppress resuspension when sufficient particulate material is available.

7.6. Implications and Limitations

Together, these results demonstrate that vehicle resuspension emissions are governed primarily by wake-region dynamics, road surface material, and vehicle speed. Sensor placement is critical for accurately capturing resuspension behavior, and rear wake measurements provide the most representative assessment of resuspension magnitude. Gravel surfaces and higher speeds substantially increase resuspension emissions, while vehicle weight and aerodynamic differences exert secondary but measurable influences under the tested condition.

Several limitations should be noted. The range of vehicle types and weights tested was limited, and environmental factors such as wind and surface moisture were not explicitly controlled. Future work should expand testing to heavier vehicles, additional surface types, and a wider range of environmental conditions. Further investigation into vehicle design features that influence wake turbulence may also provide insight into potential engineering-based mitigation strategies.

7.7. Conclusions

This study provides empirical evidence that non-exhaust particulate emissions from vehicle resuspension are strongly influenced by road surface type and vehicle speed. Measurements collected in the rear wake region consistently captured the highest and most sensitive PM concentrations, highlighting the importance of wake-region dynamics in characterizing resuspension behavior. Gravel surfaces and increased speed significantly elevated resuspension emissions, particularly for coarse particles, while vehicle weight and aerodynamic differences were secondary contributors under controlled conditions. These findings underscore the need to address non-exhaust emissions through integrated approaches that consider vehicle operation, road surface management, and measurement methodology as exhaust emissions continue to decline.

Chapter 8. Recommendations for Future Research

The findings of this study highlight several opportunities for expanding the understanding of vehicle-induced particulate matter resuspension. Future research should prioritize testing under a broader range of environmental and operational conditions to better characterize the variability and drivers of non-exhaust emissions.

First, additional testing should be conducted across a wider range of vehicle weights and axle loads. Although vehicle weight was not a statistically significant factor within the loading range tested in this study, heavier vehicles such as a commercial trucks, buses, and agricultural equipment may exert greater tire-road forces that could meaningfully influence resuspension emissions. Expanding the weight range would allow for improved evaluation of potential nonlinear weight effects and interactions within road surface type and speed.

Second, future studies should incorporate additional road surface types beyond gravel and paved surfaces. Surfaces such as dirt roads, chip seal, degraded asphalt, and seasonal road conditions may exhibit different resuspension characteristics due to variations in surface texture and material availability. Including surface moisture measurements and controlled wetting experiments would further improve understanding of how precipitation and humidity influence resuspension behavior.

Third, extended investigation into vehicle aerodynamic effects under high-resuspension conditions is recommended. While aerodynamic differences between vehicles were not statistically significant under low-resuspension conditions, results suggest that vehicle geometry may play a greater role on gravel surfaces and at higher speeds. Future work should include controlled wind tunnel studies or computational fluid dynamics simulations paired with field measurements to better isolate the influence of wake structure, underbody flow, and vehicle geometry on particle transport.

8.1. Measurement Methodology

This study demonstrated that sensor placement strongly influences measured resuspension emissions. As a result, several methodological recommendations are proposed for future field-based resuspension studies.

Rear bumper or rear wake sensor placement is strongly recommended as the primary measurement location for quantifying resuspension magnitude. The rear bumper consistently captured the highest PM concentrations within the test range and exhibited sensitivity to changes in speed and road surface, indicating that it effectively samples the resuspension plume. Front bumper sensors may be retained as a baseline or background reference measurements but should not be used alone to characterize resuspension emissions.

Tire-adjacent sensors, while capable of capturing localized mechanical entrainment, should be used cautiously. Their high variability and sensitivity to localized turbulence limit their usefulness for comparative analysis across vehicles and conditions. If tire-mounted sensors are employed, they should be complimented with wake-region measurements and used primarily for qualitative or exploratory analyses rather than quantitative comparisons.

Future studies should also consider increasing temporal resolution and spatial averaging in sensor data processing. Aggregating measurements over defined roadway segments, as done in this study, improves repeatability and reduces the influence of transient spikes caused by localized disturbances.

8.2. Emissions Mitigation and Policy

The results of this study suggest several practical strategies for reducing vehicle induced resuspension emissions, particularly in regions where non-exhaust emissions are a significant contributor to air quality degradation. Most notably, these strategies extend beyond naïve approaches to regulating vehicle weight to focus interventions on critical determinants of resuspension emissions.

Road surface management represents one of the most effective mitigation opportunities. Gravel roads produced substantially higher PM concentrations than paved roads, indicating that paving, surface stabilization, or regular dust suppression treatments could significantly reduce resuspension emissions. Where paving is not feasible, alternative surface treatments or binding agents should be considered to reduce loose particulate availability.

Speed management is another critical factor for controlling resuspension on all road types and across vehicles. Higher vehicle speeds significantly increased resuspension emissions, especially for coarse particulate matter. Implementing and enforcing reduced speed limits on gravel and unpaved roads may provide an effective, low-cost strategy for limiting particulate resuspension, particularly in rural or environmentally sensitive areas.

From a vehicle design perspective, these findings suggest that future emission control strategies should extend beyond exhaust systems. As exhaust-related particulate emissions continue to decline, non-exhaust sources such as resuspension will become increasingly important. Vehicle manufacturers and regulators may benefit from considering underbody design, wake control, and aerodynamic features that reduce turbulent recirculation and particle entrainment behind vehicles.

8.3. Regulatory and Inventory Applications

Current emissions inventories and regulatory frameworks often underestimate vehicle induced resuspension emissions. The results of this study demonstrate that resuspension is highly dependent on road type and speed, suggesting that inventories should incorporate surface-specific and speed-dependent emission factors.

Regulatory agencies are encouraged to incorporate field-based measurements of resuspension into air quality modeling efforts, particularly for regions with extensive unpaved road networks. Including wake-based measurements, such as those captured by rear bumper sensors, would improve the accuracy of emissions estimates and exposure assessments.

Additionally, future guidelines for non-exhaust emissions measurement should standardize sensor placement and testing protocols to ensure comparability across studies. Establishing best practices for wake-region sampling would reduce uncertainty and improve the reliability of resuspension emission estimates.

8.4. Concluding Remarks

The recommendations presented in this chapter are directly informed by the results of this study and reflect the growing importance of non-exhaust particulate emissions in transportation-related air quality research. By addressing methodological consistency, expanding research scope, and integrating findings into policy and practice, future efforts can more effectively quantify and mitigate vehicle-induced resuspension emissions.

REFERENCES

Abu-Allaban, M., Gillies, J. A., Gertler, A. W., Clayton, R., & Proffitt, D. (2003). Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles. *Atmospheric Environment*, *37*(37), 5283–5293. https://doi.org/10.1016/j.atmosenv.2003.05.005

Alfano, B., Barretta, L., Del Giudice, A., De Vito, S., Di Francia, G., Esposito, E., Formisano, F., Massera, E., Miglietta, M. L., & Polichetti, T. (2020). A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives. *Sensors*, *20*(23), 6819. https://doi.org/10.3390/s20236819

Amato, F., Cassee, F. R., Denier van der Gon, H. A. C., Gehrig, R., Gustafsson, M., Hafner, W., Harrison, R. M., Jozwicka, M., Kelly, F. J., Moreno, T., Prevot, A. S. H., Schaap, M., Sunyer, J., & Querol, X. (2014). Urban air quality: The challenge of traffic non-exhaust emissions. *Journal of Hazardous Materials*, *275*, 31–36. https://doi.org/10.1016/j.jhazmat.2014.04.053

Amato, F., Favez, O., Pandolfi, M., Alastuey, A., Querol, X., Moukhtar, S., Bruge, B., Verlhac, S., Orza, J. A. G., Bonnaire, N., Le Priol, T., Petit, J.-F., & Sciare, J. (2016). Traffic induced particle resuspension in Paris: Emission factors and source contributions. *Atmospheric Environment*, *129*, 114–124. https://doi.org/10.1016/j.atmosenv.2016.01.022

Amato, F., Pandolfi, M., Moreno, T., Furger, M., Pey, J., Alastuey, A., Bukowiecki, N., Prevot, A. S. H., Baltensperger, U., & Querol, X. (2011). Sources and variability of inhalable road dust particles in three European cities. *Atmospheric Environment*, *45*(37), 6777–6787. https://doi.org/10.1016/j.atmosenv.2011.06.003

Atkinson, R. W., Kang, S., Anderson, H. R., Mills, I. C., & Walton, H. A. (2014). Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: A systematic review and meta-analysis. *Thorax*, *69*(7), 660–665. https://doi.org/10.1136/thoraxjnl-2013-204492

Banzi, M., & Shiloh, M. (2022). *Getting Started With Arduino: The Open Source Electronics Prototyping Platform*. Make Community, LLC.

Blanchard, B. S., & Fabrycky, W. J. (2010). *Systems Engineering And Analysis* (5th ed.). Pearson. Retrieved https://testbankdeal.com/sample/systems-engineering-and-analysis-5th-edition-blanchard-solutions-manual.pdf

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., … Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/jgrd.50171

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L., & Kaufman, J. D. (2010). Particulate Matter Air Pollution and Cardiovascular Disease. *Circulation*, *121*(21), 2331–2378. https://doi.org/10.1161/CIR.0b013e3181dbece1

Brown, J. S., Gordon, T., Price, O., & Asgharian, B. (2013). Thoracic and respirable particle definitions for human health risk assessment. *Particle and Fibre Toxicology*, *10*(1), 12. https://doi.org/10.1186/1743-8977-10-12

Calderón-Garcidueñas, L., Gónzalez-Maciel, A., Reynoso-Robles, R., Delgado-Chávez, R., Mukherjee, P. S., Kulesza, R. J., Torres-Jardón, R., Ávila-Ramírez, J., & Villarreal-Ríos, R. (2018). Hallmarks of Alzheimer disease are evolving relentlessly in Metropolitan Mexico City infants, children and young adults. APOE4 carriers have higher suicide risk and higher odds of reaching NFT stage V at ≤ 40 years of age. *Environmental Research*, *164*, 475–487. https://doi.org/10.1016/j.envres.2018.03.023

Chen, G., Fu, Z., Yang, H., & Wang, J. (2020). An overview of analytical methods for detecting microplastics in the atmosphere. *TrAC Trends in Analytical Chemistry*, *130*, 115981. https://doi.org/10.1016/j.trac.2020.115981

Cleveland Clinic. (2022). *Lungs: Location, Anatomy, Function & Complications*. Cleveland Clinic. Retrieved February 9, 2026, from https://my.clevelandclinic.org/health/body/8960-lungs

Congressional Budget Office (2023) The Status of the Highway Trust Fund: 2023 Update. https://www.cbo.gov/system/files/2023-10/59634.pdf

Denby, B. R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., Kupiainen, K., Gustafsson, M., Blomqvist, G., & Omstedt, G. (2013). A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 1: Road dust loading and suspension modelling. *Atmospheric Environment*, *77*, 283–300. https://doi.org/10.1016/j.atmosenv.2013.04.069

Denier van der Gon, H. A. C., Gerlofs-Nijland, M. E., Gehrig, R., Gustafsson, M., Janssen, N., Harrison, R. M., Hulskotte, J., Johansson, C., Jozwicka, M., Keuken, M., Krijgsheld, K., Ntziachristos, L., Riediker, M., & Cassee, F. R. (2013). The Policy Relevance of Wear Emissions from Road Transport, Now and in the Future—An International Workshop

Report and Consensus Statement. *Journal of the Air & Waste Management Association*, *63*(2), 136–149. https://doi.org/10.1080/10962247.2012.741055

Fitz, D. R., Bumiller, K., Bufalino, C., & James, D. E. (2020). Real-time PM10 emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors part 1. SCAMPER method characterization. *Atmospheric Environment*, *230*, 117483. https://doi.org/10.1016/j.atmosenv.2020.117483

Fussell, J. C., Franklin, M., Green, D. C., Gustafsson, M., Harrison, R. M., Hicks, W., Kelly, F. J., Kishta, F., Miller, M. R., Mudway, I. S., Oroumiyeh, F., Selley, L., Wang, M., & Zhu, Y. (2022). A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures. *Environmental Science & Technology*, *56*(11), 6813–6835. https://doi.org/10.1021/acs.est.2c01072

Galatioto, F., Masey, N., Murrells, T., Hamilton, S., & Pommier, M. (2022). Review of Road Dust Resuspension Modelling Approaches and Comparisons Analysis for a UK Case Study. *Atmosphere*, *13*(9), 1403. https://doi.org/10.3390/atmos13091403

Good, N., Mölter, A., Ackerson, C., Bachand, A., Carpenter, T., Clark, M. L., Fedak, K. M., Kayne, A., Koehler, K., Moore, B., L'Orange, C., Quinn, C., Ugave, V., Stuart, A. L., Peel, J. L., & Volckens, J. (2016). The Fort Collins Commuter Study: Impact of route type and transport mode on personal exposure to multiple air pollutants. *Journal of Exposure Science & Environmental Epidemiology*, *26*(4), 397–404. https://doi.org/10.1038/jes.2015.68

Grigoratos, T., & Martini, G. (2014). *Non-exhaust traffic related emissions – Brake and tyre wear PM*. JRC Publications Repository. https://doi.org/10.2790/22000

Gulia, S., Goyal, P., Goyal, S. K., & Kumar, R. (2019). Re-suspension of road dust: Contribution, assessment and control through dust suppressants—a review. *International Journal of Environmental Science and Technology*, *16*(3), 1717–1728. https://doi.org/10.1007/s13762-018-2001-7

Ha, S. Y., Kim, G. B., Yim, U. H., Shim, W. J., Hong, S. H., & Han, G. M. (2012). Particle-Size Distribution of Polycyclic Aromatic Hydrocarbons in Urban Road Dust of Masan, Korea. *Archives of Environmental Contamination and Toxicology*, *63*(2), 189–198. https://doi.org/10.1007/s00244-012-9765-4

Harrison, R. M., Allan, J., Carruthers, D., Heal, M. R., Lewis, A. C., Marner, B., Murrells, T., & Williams, A. (2021). Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmospheric Environment*, *262*, 118592. https://doi.org/10.1016/j.atmosenv.2021.118592

Hoek, G., Krishnan, R. M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., & Kaufman, J. D. (2013). Long-term air pollution exposure and cardio- respiratory mortality: A review. *Environmental Health*, *12*(1), 43. https://doi.org/10.1186/1476-069X-12-43

Hooftman, N., Oliveira, L., Messagie, M., Coosemans, T., & Van Mierlo, J. (2016). Environmental Analysis of Petrol, Diesel and Electric Passenger Cars in a Belgian Urban Setting. *Energies*, *9*(2), 84. https://doi.org/10.3390/en9020084

Karagulian, F., Belis, C. A., Dora, C. F. C., Prüss-Ustün, A. M., Bonjour, S., Adair-Rohani, H., & Amann, M. (2015). Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmospheric Environment*, *120*, 475–483. https://doi.org/10.1016/j.atmosenv.2015.08.087

Kirk, R. S., & Mallett, W. J. (2015) *Funding and Financing Highways and Public Transportation*. https://nationalaglawcenter.org/wp-content/uploads/assets/crs/R42877.pdf

Kodros, J. K., Carter, E., Brauer, M., Volckens, J., Bilsback, K. R., L'Orange, C., Johnson, M., & Pierce, J. R. (2017). *Quantifying the Contribution to Uncertainty in Mortality Attributed to Household, Ambient, and Joint Exposure to PM2.5 From Residential Solid Fuel Use*. https://doi.org/10.1002/2017GH000115

Kupiainen, K. J., & Pirjola, L. (2011). Vehicle non-exhaust emissions from the tyre–road interface – effect of stud properties, traction sanding and resuspension. *Atmospheric Environment*, *45*(25), 4141–4146. https://doi.org/10.1016/j.atmosenv.2011.05.027

Lundberg, J., Gustafsson, M., Janhäll, S., Eriksson, O., Blomqvist, G., & Erlingsson, S. (2020). Temporal Variation of Road Dust Load and Its Size Distribution—A Comparative Study of a Porous and a Dense Pavement. *Water, Air, & Soil Pollution*, *231*(12), 561. https://doi.org/10.1007/s11270-020-04923-1

McKercher, G. R., Salmond, J. A., & Vanos, J. K. (2017). Characteristics and applications of small, portable gaseous air pollution monitors. *Environmental Pollution*, *223*, 102–110. https://doi.org/10.1016/j.envpol.2016.12.045

Nicholson, K. W. (1988). A review of particle resuspension. *Atmospheric Environment (1967)*, *22*(12), 2639–2651. https://doi.org/10.1016/0004-6981(88)90433-7

OECD. (2020, December 7). *Non-exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge*. OECD Publishing. OECD. https://doi.org/10.1787/4a4dc6ca-en

Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric Environment*, *77*, 78–97. https://doi.org/10.1016/j.atmosenv.2013.04.028

Pirjola, L., Kupiainen, K. J., Perhoniemi, P., Tervahattu, H., & Vesala, H. (2009). Non-exhaust emission measurement system of the mobile laboratory SNIFFER. *Atmospheric Environment, Urban Air Quality*, *43*(31), 4703–4713. https://doi.org/10.1016/j.atmosenv.2008.08.024

Piscitello, A., Bianco, C., Casasso, A., & Sethi, R. (2021). Non-exhaust traffic emissions: Sources, characterization, and mitigation measures. *Science of The Total Environment*, *766*, 144440. https://doi.org/10.1016/j.scitotenv.2020.144440

Raaschou-Nielsen, O., Andersen, Z. J., Beelen, R., Samoli, E., Stafoggia, M., Weinmayr, G., Hoffmann, B., Fischer, P., Nieuwenhuijsen, M. J., Brunekreef, B., Xun, W. W., Katsouyanni, K., Dimakopoulou, K., Sommar, J., Forsberg, B., Modig, L., Oudin, A., Oftedal, B., Schwarze, P. E., … Hoek, G. (2013). Air pollution and lung cancer incidence in 17 European cohorts: Prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). *The Lancet Oncology*, *14*(9), 813–822. https://doi.org/10.1016/S1470-2045(13)70279-1

Rienda, C. I. & Alves, C. A. (2021). Road dust resuspension: A review. *Atmospheric Research*, *261*, 105740. https://doi.org/10.1016/j.atmosres.2021.105740

Sensirion (2022) Sensirion Datasheet. https://sensirion.com/media/documents/6791EFA0/62A1F68F/Sensirion_Datasheet_Environmental_Node_SEN5x.pdf

Thorpe, A., & Harrison, R. M. (2008). Sources and properties of non-exhaust particulate matter from road traffic: A review. *Science of The Total Environment*, *400*(1), 270–282. https://doi.org/10.1016/j.scitotenv.2008.06.007

Timmers, V. R. J. H., & Achten, P. A. J. (2016). Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment*, *134*, 10–17. https://doi.org/10.1016/j.atmosenv.2016.03.017

US EPA Office of Air and Radiation. (2016, September 26). *AP-42: Compilation of Air Emissions Factors from Stationary Sources* [Other Policies and Guidance]. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources

World Health Organization (WHO). (2021) WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Retrieved February 9, 2026, from https://iris.who.int/items/5b0ca7ab-830a-44b8-b99f-4ee743b4d7b2

APPENDIX A: ARDUINO CODE

```
#include <Wire.h>
#include <SensirionI2CSen5x.h>
#include <SPI.h>
#include <SD.h>
#include <RTClib.h>

SensirionI2CSen5x sen5x;SRTC_DS3231 rtc;

const int chipSelect = 10;  // CS pin for SD card

void setup() {
 Serial.begin(115200);
 Wire.begin();

 // === Initialize sensor ===
 sen5x.begin(Wire);
 uint16_t error = sen5x.deviceReset();
 delay(500);
 error = sen5x.startMeasurement();
 if (error) {
  Serial.print("Error starting measurement: ");
  Serial.println(error);
  while (1);
 }

 // === Initialize RTC ===
 if (!rtc.begin()) {
  Serial.println("Couldn't find RTC");
  while (1);
 }

 // Set RTC time ONCE by uncommenting the line below, upload, then re-comment and reupload
//rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
```

```
  // === Initialize SD card ===
  if (!SD.begin(chipSelect)) {
    Serial.println("SD card initialization failed!");
    while (1);
  }
  Serial.println("SD card initialized.");

  // === Create log file header if needed ===
  File dataFile = SD.open("log.csv", FILE_WRITE);
  if (dataFile) {
    dataFile.println("Timestamp,PM1.0,PM2.5,PM4.0,PM10.0,VOC Index,NOx Index,Humidity (%),Temperature (°C)");
    dataFile.close();
  } else {
    Serial.println("Could not create log.csv");
  }
}

void loop() {
  delay(1000);  // Log 10x per second -- use 1000 to log once per second

  // === Get timestamp ===
  DateTime now = rtc.now();
  char timestamp[20];
  sprintf(timestamp, "%04d-%02d-%02d %02d:%02d:%02d",
          now.year(), now.month(), now.day(),
          now.hour(), now.minute(), now.second());

  // === Read sensor values ===
  float pm1p0, pm2p5, pm4p0, pm10p0;
  float voc_index, nox_index, rh, temp;

  uint16_t error = sen5x.readMeasuredValues(
    pm1p0, pm2p5, pm4p0, pm10p0,
    rh, temp, voc_index, nox_index
  );

  if (error) {
```

```
    Serial.print("Sensor read error: ");
    Serial.println(error);
    return;
  }

  // === Print to Serial Monitor ===
  Serial.print(timestamp); Serial.print(" | ");
  Serial.print("PM1.0: "); Serial.print(pm1p0); Serial.print(" µg/m³ | ");
  Serial.print("PM2.5: "); Serial.print(pm2p5); Serial.print(" µg/m³ | ");
  Serial.print("PM4.0: "); Serial.print(pm4p0); Serial.print(" µg/m³ | ");
  Serial.print("PM10.0: "); Serial.print(pm10p0); Serial.print(" µg/m³ | ");
  Serial.print("VOC: "); Serial.print(voc_index); Serial.print(" | ");
  Serial.print("NOx: "); Serial.print(nox_index); Serial.print(" | ");
  Serial.print("RH: "); Serial.print(rh); Serial.print(" % | ");
  Serial.print("Temp: "); Serial.println(temp);  // °C

  // === Write to SD card ===
  File dataFile = SD.open("log.csv", FILE_WRITE);
  if (dataFile) {
    dataFile.print(timestamp);   dataFile.print(",");
    dataFile.print(pm1p0);       dataFile.print(",");
    dataFile.print(pm2p5);       dataFile.print(",");
    dataFile.print(pm4p0);       dataFile.print(",");
    dataFile.print(pm10p0);      dataFile.print(",");
    dataFile.print(voc_index);   dataFile.print(",");
    dataFile.print(nox_index);   dataFile.print(",");
    dataFile.print(rh);          dataFile.print(",");
    dataFile.println(temp);
    dataFile.close();
    Serial.println("Data written to SD card.");
  } else {
    Serial.println("Failed to write to SD card.");
  }
}
```

APPENDIX B: PM10 VISUALIZATIONS

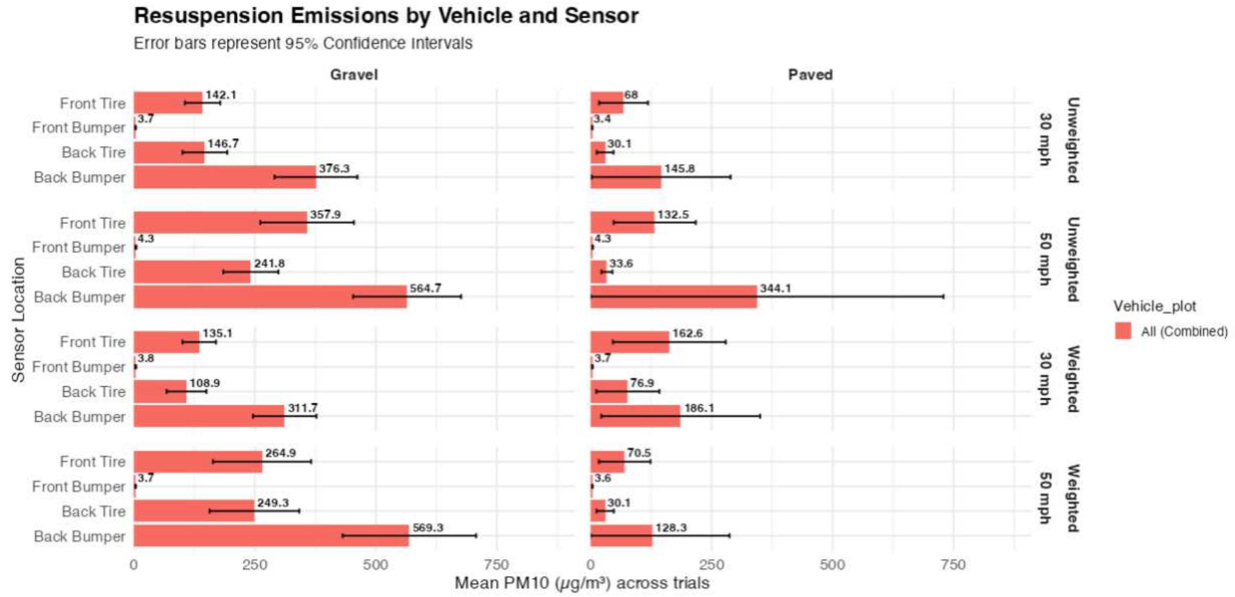

Figure 15. Comparison of Mean PM10 by Sensor Location across Conditions

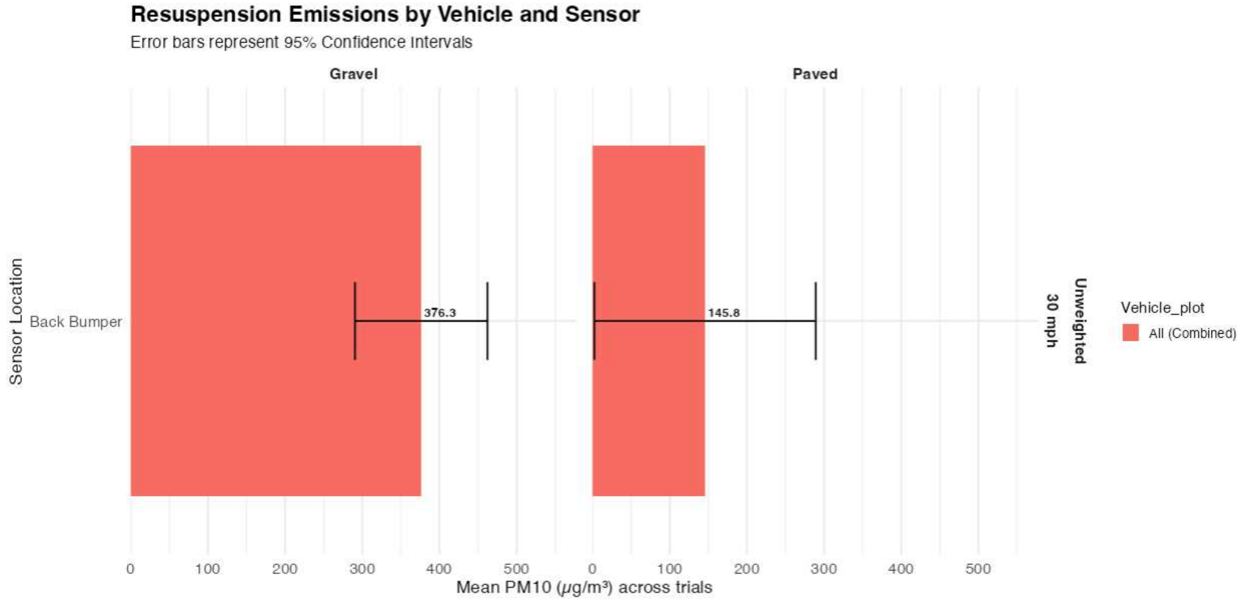

Figure 16. Comparison of Rear Bumper PM10 by Road Type

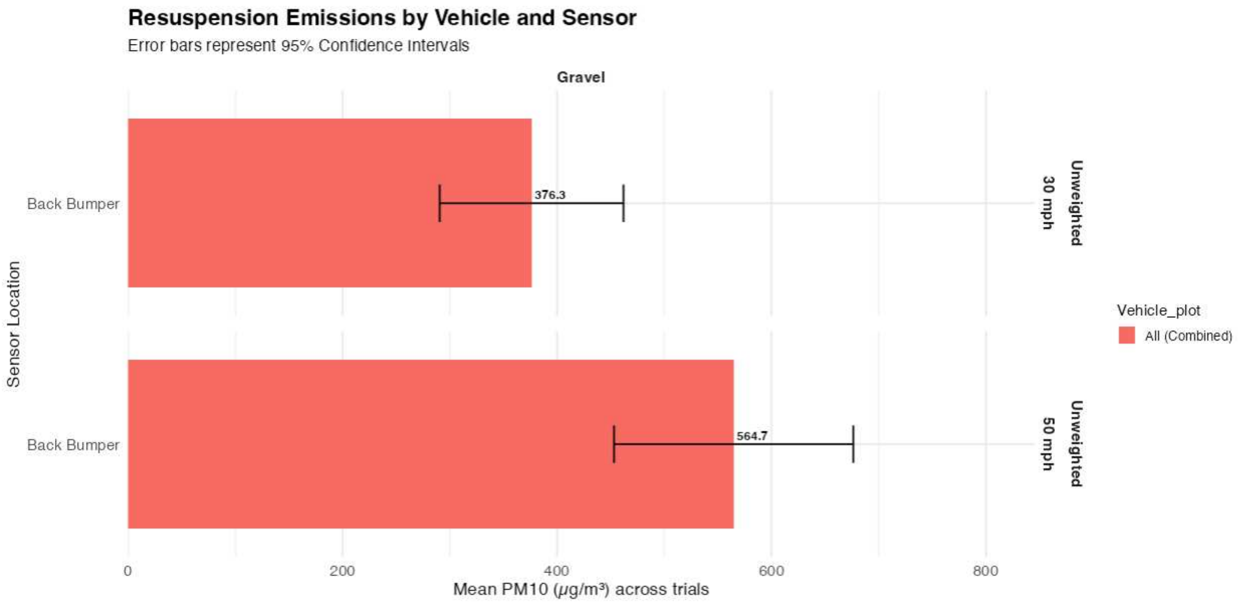

Figure 17. Comparison of Rear Bumper PM10 by Vehicle Speed

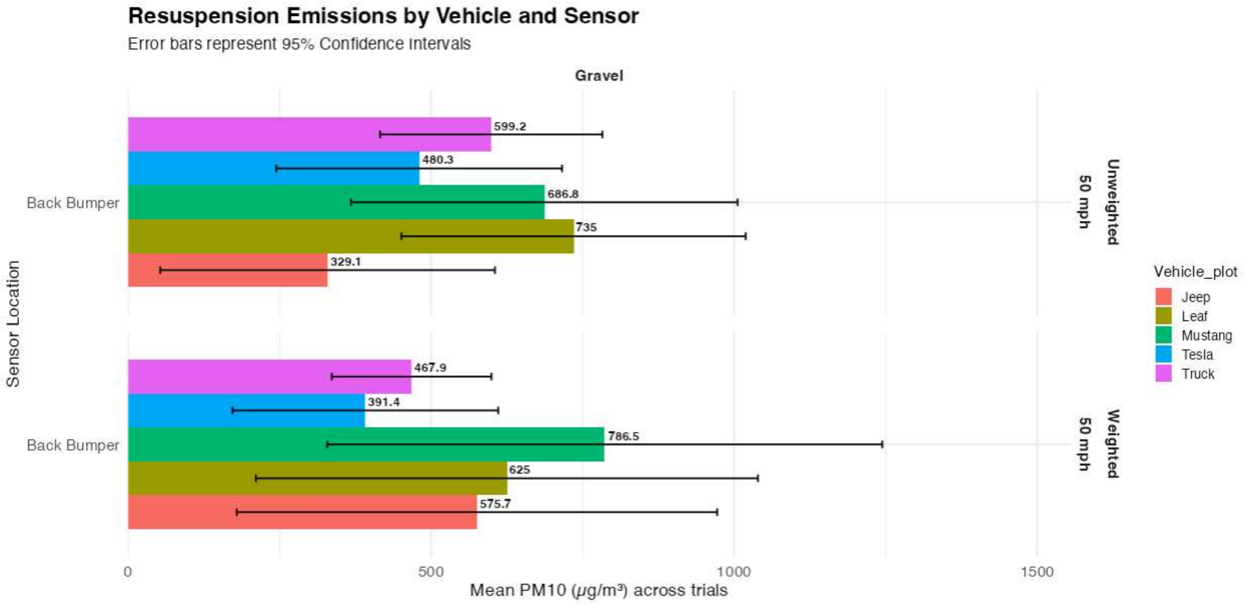

Figure 18. Comparison of Rear Bumper PM10 by Weight Condition

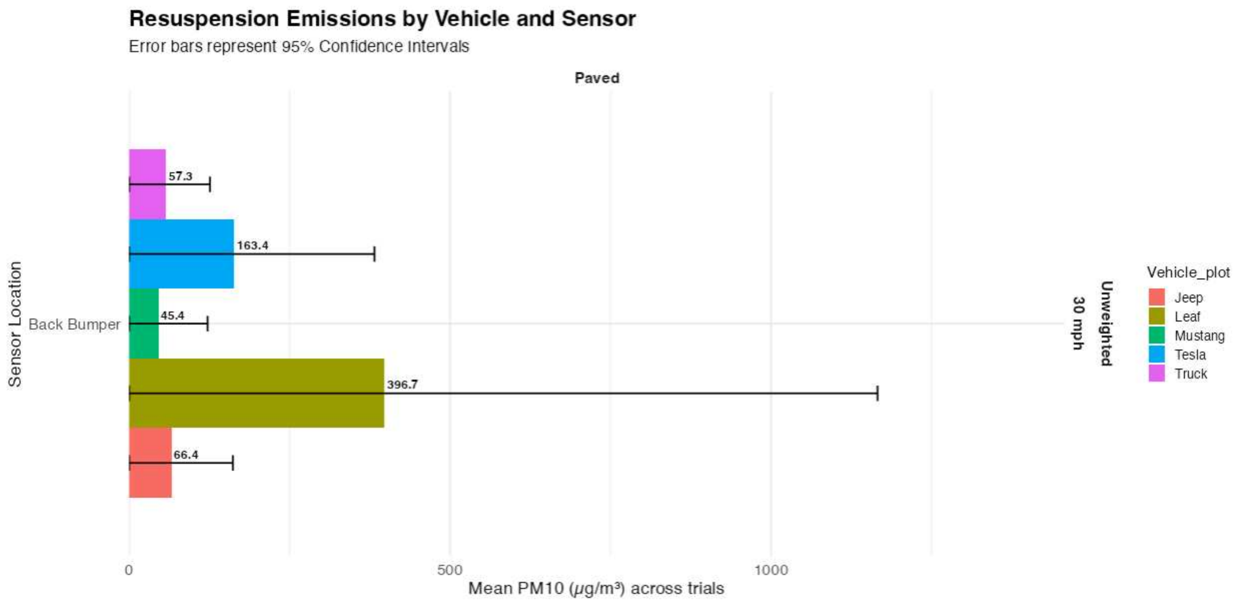

Figure 19. Comparison of Rear Bumper PM10 by Vehicle Type

APPENDIX C: PM10 ANOVA RESULTS

Table 18. ANOVA Results for Sensor Location (PM10)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Sensor Location	3	7,200,609	55.339	< 0.001
Vehicle	4	684,105	5.258	<0.001
Road Type	1	6,499,278	49.949	<0.001
Speed	1	1,814,467	13.945	<0.001
Weight	1	120,726	0.928	0.336

Table 19. ANOVA Results for Road Type (PM10)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Road Type	1	6,435,541	15.808	<0.001
Weight × Road Type	1	88,902	0.218	0.641
Speed ×Road Type	1	570,947	1.402	0.237
Weight × Speed ×Road Type	1	674,769	1.658	0.199

Table 20. ANOVA Results for Vehicle Speed (PM10)

Variable	Degrees of Freedom	Mean Square	F-statistic	p-value
Speed	1	2,098,623	5.155	0.024
Weight × Speed	1	209,605	0.515	0.474
Speed × Road Type	1	570,947	1.402	0.237
Weight × Speed × Road Type	1	674,769	1.658	0.199

Table 21. ANOVA Results for Vehicle Weight (PM10)

Variable	**Degrees of Freedom**	**Mean Square**	**F-statistic**	**p-value**
Weight	1	320,880	0.788	0.375
Weight × Speed	1	209,605	0.515	0.474
Weight × Road Type	1	88,902	0.218	0.641
Weight × Speed × Road Type	1	674,769	1.658	0.199

Table 22. ANOVA Results for Vehicle Type (PM10)

Variable	**Degrees of Freedom**	**Mean Square**	**F-statistic**	**p-value**
Vehicle	4	218,725	0.849	0.502

APPENDIX D: PM10 TUKEY POST-HOC RESULTS

Table 23. Tukey Results for Sensor Location (PM10)

Sensor Location	Mean	Front Tire	Rear Tire	Front Bumper
Front Tire	166.05	-	-	-
Rear Tire	114.39	p = 0.174	-	-
Front Bumper	4.16	p < 0.001	p < 0.001	-
Rear Bumper	327.48	p < 0.001	p < 0.001	p < 0.001

Table 24. Tukey Results for Road Type (PM10)

Road Type	Mean	Gravel
Gravel	454	-
Paved	201	p < 0.001

Table 25. Tukey Results for Vehicle Speed (PM10)

Speed	Mean	30 mph
30 mph	255	-
50 mph	401	p = 0.024

Table 26. Tukey Results for Vehicle Weight (PM10)

Weight Condition	Mean	Unweighted
Unweighted	357	-
Weighted	299	p = 0.375

Table 27. Tukey Results for Vehicle Type (PM10)

Vehicle Type	Mean	Ford	Jeep	Leaf	Mustang
Truck	57.3	-	-	-	-
Jeep	66.4	p = 1.000	-	-	-
Leaf	396.7	p = 0.570	p = 0.596	-	-
Mustang	45.4	p = 1.000	p = 1.000	p = 0.537	-
Tesla	163.4	p = 0.989	p = 0.993	p = 0.841	p = 0.985