CARB PROJECT 22RD002

Characterization of Tire-Wear and Brake-Wear PM Emissions Under On-Road Driving Conditions

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ABSTRACT

The California Air Resources Board (CARB) initiated Project 22RD002 to address the growing contribution of non-exhaust particulate matter (PM) emissions from brake and tire wear to air quality and public health concerns. The project aimed to develop robust on-vehicle systems for measuring brake and tire PM emissions under real-world driving conditions, isolate individual sources, and create a modeling framework for statewide application. A collaborative team from ERG, UCR CE-CERT, LINK Engineering, and Ricardo LLC designed two innovative sampling systems: a fully enclosed brake PM system adapted from Ricardo's concept and a semi-closed tire PM system based on Michelin's design, both integrated with gravimetric filters and real-time instruments (ELPI+, APS, DustTrak). On-road testing was conducted from March to September 2025 over city and highway routes (CA-60 concrete, I-215 asphalt) using a Chevrolet Silverado 2500. The brake test matrix included multiple friction materials (ceramic, NAO, semi-metallic) and payloads, while tire tests covered six major brands and one budget brand under varied conditions. Results showed brake emissions were strongly influenced by braking intensity and material, with ceramic pads producing the highest PM. On-road brake PM emission factors for city driving were 4–5 times higher than EMFAC estimates from dynamometer cycles. Tire emissions were higher on city routes and increased with aggressive driving and tire age, though sampling efficiency remained lower than brakes due to open geometry. Source apportionment estimated tire contributions at 4–16 percent of collected PM, and a novel Tire Wear Index (TWI) was developed to scale emissions across California's fleet. Findings indicate tire PM emissions are consistent with current inventory assumptions overall, but underscore the need for improved accounting for speed and vehicle class.

ACRONYMS

3D	three-dimensional
ADAC	Allgemeiner Deutscher Automobil-Club
AM	aftermarket
APS	Aerodynamic Particle Sizer, the TSI instrument used in Project 17RD016 to measure particle size distributions in the range from 0.5 – 20 μm
BWI	Brake wear index
CAST	Combustion Aerosol Standard
CVS	constant-volume sampling
CPC	Condensation Particle Counter
CBDC	California Brake Dynamometer Cycle – The brake dynamometer test cycle developed and used during Project 17RD016
CMB	Chemical Mass Balance
EC	elemental carbon
EEPS	Engine Exhaust Particle Sizer, the TSI instrument used to measure particle size distributions in the range from 5.6 to 560 nm in Project 17RD016
EF	Emission factor, a representative rate of emissions to the atmosphere, usually provided on a per-distance basis
ELPI	Electrical Low Pressure Impactor
EMFAC	CARB's EMission FACtor model, which inventories air pollutant emissions in support of regulatory and air quality planning efforts.
FSMI	Friction Materials Standards Institute
GPS	Global Positioning System
HDV	heavy-duty vehicle
HLW	Heavily laden weight, indicating the vehicle is tested with additional payload
JPR	Jointed Plain Concrete
LDT	Ligh-duty truck
LDV	light-duty vehicle
LM	low-metallic, a brake pad type that includes metallic fibers
lpm	liters per minute
MDV	medium-duty vehicle
MECA	Manufacturers of Emissions Controls Association
MEMA	The Motor & Equipment Manufacturers Association
mg/mi	Milligrams per mile
MPH	miles per hour

NAO	non-asbestos organic friction material
nm	nanometer
OC	organic carbon
OEM	original equipment manufacturer
OES	original equipment service
PAC	Project Advisory Committee
PCR	Pavement Condition Reports
PM	particulate matter, often classified by PM2.5, indicating particulate up to 2.5μm in diameter, and PM10, particulate up to 10μm in diamete
PMF	Positive Matrix Factorization
PN	Particle number
PSI	Pounds per square inch
PSD	Particle size distribution
SAE	Society of Automotive Engineers
SFEI	San Francisco Estuary Institute
SM	semi-metallic, a brake pad type that includes metallic fibers
SOP	State of the Pavement
TiO_2	titanium dioxide
TWI	tire wear index
μm	micrometer
USTMA	U.S. Tire Manufacturer's Association
TWRP	Tire road wear particles, particles emitted at the tire/road interface that include tire, road dust, and road materials
UCR CE-CERT	University of California Riverside's Center for Environmental Research and Technology
UTQG	Universal Tire Quality Grade
VTI	Swedish National Road and Transport Research Institute
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
XRF	X-ray fluorescence

EXECUTIVE SUMMARY

The California Air Resources Board (CARB) aims to develop robust methods for measuring and modeling real-world brake and tire wear particulate matter (PM) emissions, to address the growing contribution of non-exhaust PM emissions to ambient air quality and public health concerns. CARB Project 22RD002 set forth the ambitious aim to develop an on-vehicle system for measuring brake and tire particle emissions over typical operation in general traffic, isolate individual brake and tire emissions from these measurements, and develop a modeling framework to apply results across California's fleet. The team undertaking this effort for CARB consists of Eastern Research Group, Inc. (ERG), University of California Riverside's Center for Environmental Research and Technology (UCR CE-CERT), LINK Engineering, and Ricardo LLC. The project team designed and fabricated two innovative sampling systems to separately measure brake PM and tire PM on-road. The brake system was based on Ricardo's full enclosure concept, adapted to a Chevrolet Silverado 2500 pickup truck. It featured an inner stationary drum and outer rotating plate, with controlled airflow to maintain representative brake temperatures and minimize PM losses. The tire sampling system was inspired by a design first developed by Michelin, modified to include side panels and a single high-flow outlet to improve collection efficiency. Both systems were integrated with a common sampling tunnel equipped with gravimetric filter holders and real-time instruments (ELPI+, APS, DustTrak) for PM measurement.

Test routes were developed to capture a representative mix of driving conditions and roadway types. The Riverside City Route represented urban driving with frequent braking, while CA-60 (concrete) and I-215 (asphalt) routes represented highway conditions. The brake test matrix included variations in friction material (ceramic, NAO, semi-metallic), payload, and route type. The tire test matrix included six production tires from major brands (Michelin, Goodyear, Continental, Firestone) and one budget brand (Waterfall), tested under different payloads and pavement types. On-road testing was conducted from March to September 2025 on 37 unique brake emission tests and 58 unique tire emissions tests. Background PM measurements were also collected for city and highway routes. Results of this testing demonstrate that on-road measurement of brake and tire particulate matter (PM) emissions is feasible and provides insights not available in controlled laboratory environments. Brake emissions were strongly influenced by braking intensity and friction material, with ceramic pads producing the highest PM emissions and NAO pads the lowest. On-road brake PM emission factors for city driving were 4–5 times higher than EMFAC estimates derived from dynamometer cycles, underscoring the need to update inventories to reflect real-world conditions. For the tire samples, city routes generated higher PM mass than highways, likely due to more frequent friction events (acceleration, deceleration, cornering). However, analysis of elemental profiles derived from XRF suggests the presence of brake, crustal material, and marine (sea salt) sources in the samples, confounding results. Despite design improvements, tire sampling efficiency also remained lower than brakes due to open geometry and complex airflow, highlighting a key challenge for future work.

The study developed methods for isolating tire emissions using chemical analysis and source apportionment, estimating a range of tire contributions between 4 -16 percent of measured PM corrected for collection efficiency. The Tire Wear Index (TWI) metric was developed to scale emissions across California's fleet based on tire size and tread characteristics. EMFAC annual statewide tire PM emissions fell within the range of PM2.5 and PM10 inventories scaled up from the test data based on the 4-16 percent range and TWI, though this study suggests a need to revisit speed corrections and EF differences between vehicle classes in EMFAC. These findings, along with lessons learned on sampling efficiency and influential factors, provide a foundation for improving non-tailpipe emissions characterization and inform future research priorities.

INTRODUCTION

This report presents the methods and findings of the California Air Resources Board (CARB) Research Project 22RD002, "Characterization of Tire-Wear and Brake-Wear PM Emissions Under On-Road Driving Conditions". This ambitious project, initiated in March 2023, aims to develop an on-vehicle system for measuring brake and tire particle emissions, measure emissions with this system during a wide range of operation in general traffic, isolate individual brake and tire emissions, and develop a modeling framework to apply the data across California's fleet. The team undertaking this effort for CARB consists of Eastern Research Group, Inc. (ERG), University of California Riverside's Center for Environmental Research and Technology (UCR CE-CERT), LINK Engineering, and Ricardo LLC (referred to herein collectively as the research team). UCR and LINK led the development of the on-board measurement system, and UCR conducted on-road testing between March and September 2025 under Task 4 of the project scope. Several tasks preceding these steps helped inform the design of the sampling system and test matrices, including:

- Literature review of on-board brake and tire measurement systems and to determine factors important to account for in developing a test program (Task 1)
- Establishment of a Project Advisory Committee (Task 2a)
- Brake and Tire Market Survey (Task 2b)
- Development of Test Routes (Task 2c)
- Development of Test Matrices (Task 3)

Several analysis tasks then followed on-road testing:

- Analysis of brake and tire emissions results and chemical characterization culminating in representative emission factors for use in emissions modeling (Task 5a – 5c)
- Development of PM simulation model based on results (Task 5d)
- Compilation of remaining research questions (Task 5e)
- Comparison of on-road brake emissions data to dynamometer data collected as part of CARB Project 17RD006, which forms that basis of the EMFAC2021 and 2025 light-duty vehicle brake emissions (Task 6).

This report is laid out sequentially by task to highlight the findings and deliverables for each task. The import of Tasks 1, 2 and 3 was to develop an on-road sampling system and test plan to meet project objectives for real-world brake and tire emission factors that can be applied to better characterize non-tailpipe particulate matter in California's emissions inventory. These tasks were conducted in preparation for the on-road testing and subsequent analysis that form the body of results, and hence should be understood as preliminary efforts to plan and design what came to fruition in Tasks 4,5, and 6. The preliminary tasks reflect the perspective of the initial stages of the project, with present tense retained in this report to convey the research team's thought process at the time. The evolution of the program as tasks progressed reflect the reality that adjustments were needed to the sampling system and test plan once the project was underway. The primary adjustment to note is that although the program was initially scoped to include both light-duty and heavy-duty vehicles, the challenge of developing and testing independent measurement systems for both brake and tire emissions within the project timeframe necessitated focus on the light-duty system only. This system was tested on a larger sample of brakes and tires than initially planned to offset dropping the heavy-duty testing in this program. Discussion of Class 8 heavy-duty brake and tire system design considerations and pilot testing is included in Sections 1.0 and 2.0 although the on-road testing program did not end up including a Class 8 vehicle, as the findings may be useful for future work on heavy-duty brake and tire emissions.

1.0 TASK 1: LITERATURE REVIEW

A literature review was first conducted to understand recent developments in brake- and tire-wear PM emissions testing methods, with an emphasis on potential on-road testing configurations designed to measure brake-wear and tire-wear PM emissions separately. The objective of this review was to 1) inform the design of an on-board emissions sampling system for brake, tire, and roadway particles; and 2) to identify influential factors in brake and tire wear emission studies, to inform the experimental design for on-road testing. Broader topics relevant to brake and tire PM emissions such as their contribution to ambient PM, chemical composition, health outcomes and prior emissions studies are already well documented in the literature and were not the focus on this review.

CARB recently commissioned a significant literature review of health effects of PM emissions from brake and tire wear.[1] Emissions of $PM_{2.5}$ and PM_{10}, which are referred as particulate matter of aerodynamic diameter smaller than 2.5 micrometers (μm) and 10 μm respectively, can penetrate the respiratory system[2], while clinical data suggest that particles less than 100 nanometers (nm) are linked with chronic effects and cardiovascular diseases both chronic and acute[3,4]. Road transport is a countable contributor, with 11 percent of total $PM_{2.5}$ emissions and 28 percent of black carbon (BC).[5] With the extensive literature linking exposures to PM to a host of adverse health effects, understanding and controlling these emissions from brake- and tire-wear is an important public health measure. Many studies have linked exposure to traffic-generated pollution to adverse health effects in populations spending significant time near large roadways.[6] Moreover, recent studies have also shown that tire-wear derived chemicals such as 6PPD-quinone to be acutely toxic to aquatic habitats, thereby making the study of tire-wear particles of increasing ecological importance.

Tire and brake emission estimates underpinning current emissions inventories are based on lab studies conducted over the past three decades. Selected examples of these studies include Garg et al[7], who conducted a dynamometer study that estimated brake-wear emissions to be between 3 to 9 mg/km for light-duty spark ignition vehicles. Abu-Allaban et al. estimated real-world brake-wear emissions to be as high as 80 mg/km, although some tests were below detectable levels.[8] Another study showed that the PM concentrations varied depending on different braking conditions and type of vehicle.[9] This study also indicated that most of the particles emitted were in the ultrafine or fine range. Experiments conducted by Sanders et al. indicated that much of the brake-wear debris escapes the wheel well and enters the atmosphere.[10] More recent lab-based brake studies conducted for CARB project 17RD006 by Agudelo et al.[11] and for Caltrans project 65A0703[12] accounted for real-world driving patterns, a modern mix of brake configurations and friction material, light-duty vehicles with regenerative braking, and heavy-duty truck vocations. These latter studies formed the basis of updated brake emission rates for CARB's current vehicle emissions model, EMFAC2021.

While several studies on non-exhaust particle emissions have focused on brake-wear, fewer have studied the contributions of tire-wear to this category of emissions. Councell et al.[13] looked at the possibility of tire-wear particles being a source of zinc to the environment while Kupiainen et al.[14] looked at the effects of stud properties and resuspension on non-exhaust emissions from the tire/road interface. Sadiktsis et al.[15] found that automobile tires are a potential source of carcinogenic dibenzopyrenes to the environment. Amato et al.[16] and Han et al.[17] identified tire-wear as a source of road dust particles in three European cities as well as Beijing, China. Semi-volatile particle species were found by Dahl et al.[18] that were speculated to originate from evaporation and subsequent condensation of softening oils in the rubber mix.

Studies have also shown that 6PPD-quinone (6PPD-Q; 2-anilino-5-[(4-methylpentan-2-yl)amino]cyclohexa-2,5-diene-1,4-dione), an ozonation product of 6PPD and a causal toxicant, can cause acute mortality of coho salmon through stormwater runoff. 6PPD is an antioxidant and antiozonant that helps prevent the degradation and cracking of rubber compounds caused by exposure to oxygen, ozone and temperature fluctuation.[19,20]

Limitations of laboratory measurements of brake and tire PM have resulted in renewed interest in on-vehicle measurements of PM of vehicles operating in real-world conditions. A research team in Finland was one of the first to measure PM from brakes, tires, and resuspended road dust using mobile measurements[21], and new research from a variety of different measurement approaches for brake PM and for tire and resuspended road dust has been added to the literature since. For brake-sourced on-vehicle PM measurement, available literature is generally focused on light-duty vehicles and falls into two main categories: full enclosure systems and partial enclosure systems. In full enclosure systems, the brake rotor and caliper are completely surrounded by an enclosure with an air inlet to draw in filtered air and an outlet for collected sample to travel to the sample train. In a partial flow system, only a portion of the brake assembly is enclosed, and ambient air is drawn in at a high enough rate to ensure most emitted particles are drawn into the sampling system. There is little literature dedicated to the onboard measurement of heavy-duty vehicle brake systems; the most notable published work on heavy-duty drum brakes is the method developed by CARB that involves using the drum as an enclosure and sampling near the interface between the drum and shoes.[22]

The available literature on PM sampling from tire-wear indicates that all methods are a variation on the same concept. Most studies involve a sample probe (shapes and sizes vary significantly) placed just behind the tire/road interface. Some probe inlets are relatively large and some, as in the case of Ricardo's existing system, involve inlets that are relatively small. A key challenge for tire-wear sampling is managing the multiple sources of PM that is present in the area behind the tire/road interface. These are:

- **Ambient/background**: Airborne PM in the air around the vehicle that is present irrespective of the individual subject vehicle.
- **Road Dust:** PM that has settled on the roadway surface and is then resuspended (re-entrained) by the passing subject vehicle. It may consist of particle emitted from any and all other sources of vehicle and non-vehicle related PM.
- **Brake wear particles:** "Fresh" particles emitted from the brakes of the subject vehicle itself.
- **Road wear particles:** "Fresh" PM emitted by the roadway surface due to tire abrasion.

- **Tire wear particles: "**Fresh" PM emitted by the tire due to roadway abrasion.

The intended source of tire-wear PM for sampling and measurement varies across literature. Most references specify the measurement of tire and road wear particles (TRWP) taken together, as the abrasion of one surface generally does not occur without abrasion of the other. Other literature may include resuspended road dust and the contribution of ambient background PM. Some studies present methods to potentially resolve particles from the different sources, though that is clearly an ongoing challenge.

In accord with CARB's goals with this project, our literature review focused on newer studies which could inform the physical design of an on-vehicle brake and tire sampling system, and the experimental design of the on-road testing to be conducted in a later stage of the project. Results of this review are presented in the following sections, with discussion of sampling methods divided into lab and on-road systems.

1.1 Lab Sampling Methods

1.1.1 Brake Wear

Most literature describing laboratory measurements of PM from brake-wear involves brake dynamometer testing similar to that used during ERG's CARB Project 17RD016[23] and Caltrans Project 65A0703, both conducted at Link's brake testing facility. The brake dynamometer setup involves placing the complete brake assembly in an enclosed constant volume sampler (CVS) and sampling PM isokinetically downstream from the brake system. Alternatively, chassis dynamometer testing has also been used for brake-wear PM measurement, but this is generally subject to interference from tire-wear emitted from contact with the chassis dynamometer rolls or is only used as an intermediate step for the evaluation of mobile systems that are in development for use on the road. The enclosed nature of the brake dynamometer readily allows for downstream isokinetic measurements free of contamination by other sources. The ERG team will use the experience from past brake dynamometer projects during the development of the on-road brake wear measurement system for use in this work.

1.1.2 Tire Wear

Laboratory measurement of tire-wear PM involves rolling a test tire against pavement-simulating media in one of three general methods, a rotating drum (with the tire rolling on either the inside or the outside of the drum), rolling the tire around a circular "turntable", or rolling against a flat belt. These systems are generally housed within a controlled laboratory environment with filtered ambient air, limiting contamination from other sources. In all methods, care must be taken that the pavement simulation media is representative of the type of road surface being simulated, both in terms of the surface roughness as well as the PM emitted from the abrasive material. Each method has other potential drawbacks as described below.

Rotating Drum

The rotating drum methods involve a large (i.e. greater in diameter than a vehicle tire) circular rotating drum that has an abrasive surface that simulates roadway material on either the inside or outside of the drum. The test rig includes a mechanism to hold the tire in contact with the drum and, depending on the setup, allow for a slip angle to simulate vehicle turning. The vehicle tire can be powered, and the drum can either also be powered or be set with drag to simulate road load.

This section presents three rotating drum systems that have been recently presented in literature. The Karlsruhe Institute of Technology has a rotating drum tire test rig that is designed to have the tire rotate against actual roadway materials cast into the inside of the drum.[24] Both the drum and wheel/tire are separately driven, and the tire can be turned to simulate turning slip angles. Tire PM is sampled by means of a suction funnel placed behind the tire/drum interface. The suction flow is set at 1600 m3/h, which simulates a flow velocity of 120 km/h. The research team assumes that emitted particles are reliably extracted at any simulated vehicle speeds at or below this value. The

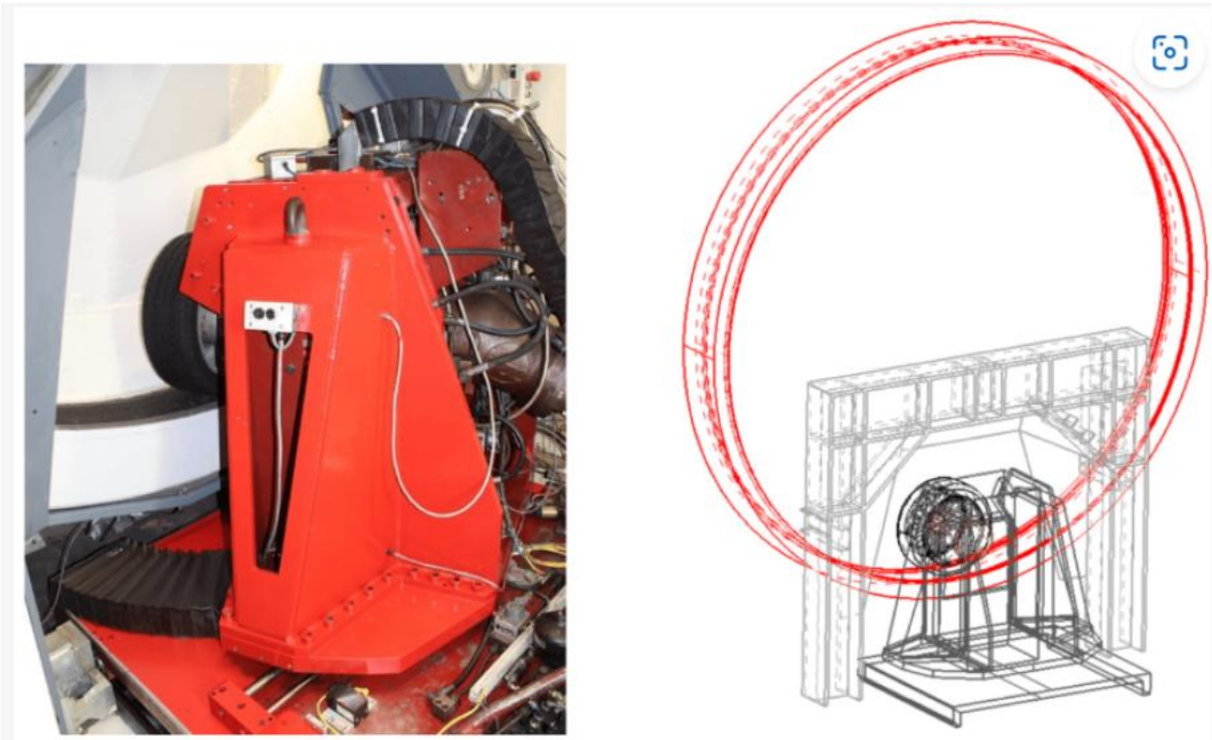

Figure 1. A photograph and diagram of the rotating drum tire test rig at the Karlsruhe Institute of Technology (Schläfle et. al., 2023).

specific orientation and layout of the sampling inlet are not described in detail in the reference. Figure 1 presents an image and schematic of the Karlsruhe system.

A recent study by the Japan Automobile Research Institute (JARI) presented the use of a rotating drum in which the tire rides against the outside of the drum.[25] The researchers created their own pavement simulation on the outside of the drum by uniformly applying a mixture of stone, sand, and gravel with epoxy resin. The test rig can control the tire's normal force, slip angle, drum speed, and tire camber angle. The emitted PM was drawn into a CVS by means of a 220 x 17.5mm suction nozzle placed behind the test tire. Figure 2 presents the JARI lab setup and a closeup of the simulated pavement surface.

Figure 2. The external rotating drum tire test rig at JARI (left) with a closeup of the epoxied roadway simulation media (right).

The Japan Automobile Standards Internationalization Center (JASIC) is developing a standard procedure for laboratory-based drum testing of tire-wear PM.[26] This work is also being conducted in part at JARI. The method being developed is based on the WLTP driving schedule, with added grade and roadway curves that will also be simulated at the interface of tire and drum.

Researchers at the Korea Institute of Machinery and Materials have also performed drum-based research into tire PM emission rates.[27] In their setup, sandpaper was used as the pavement simulation media and mounted to the outside of a rotating drum as shown in Figure 3. The tire was held in contact with the surface, and emitted PM was sampled just downstream of the tire/drum interface. The purpose of the study was not to develop realistic mass emission factors, but rather measure the amount of collected PM as a function of multiple test tires' Universal Tire Quality Grade (UTQG) wear scale. The literature indicated that some attempt was made to quantify sampling efficiency, but the details of that process were not described in the publication.

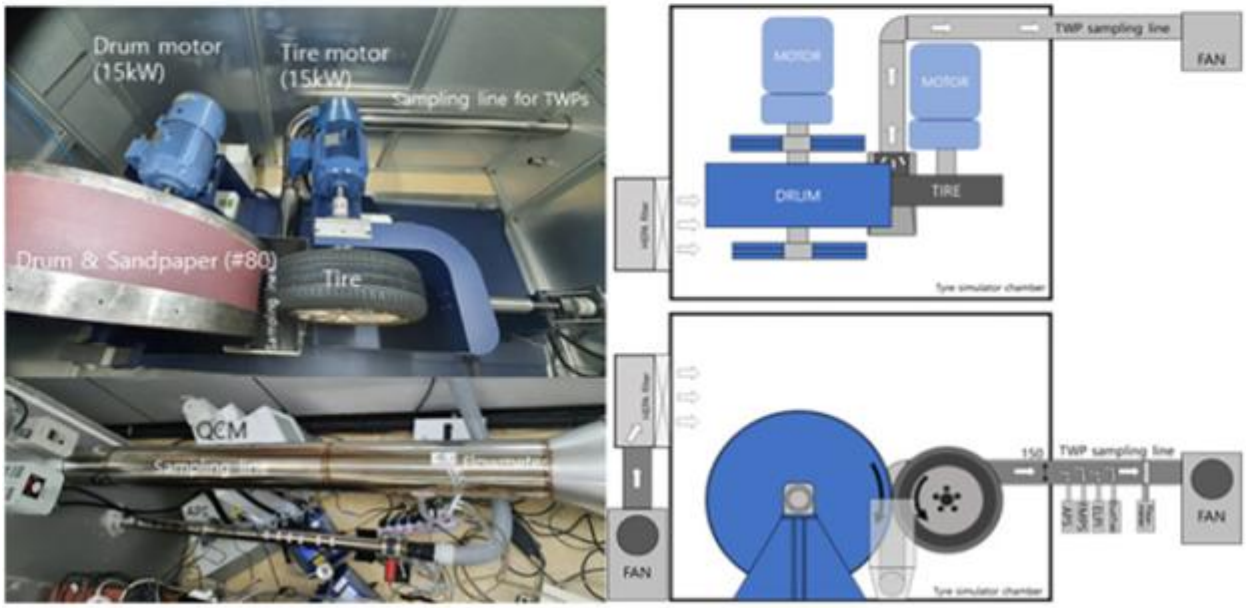

Figure 3. Diagram of a machine.

In all presented drum methods, tire PM is collected by a suction nozzle placed behind the tire/drum interface. Tests in the described facilities took place in laboratories with controlled ambient conditions such that cross-contamination is a minimal concern. Little is mentioned regarding sampling efficiency; only in the Karlsruhe study is efficiency discussed and assumed to be 100percent below a given simulated wheel speed.

Turntable

The Swedish National Road and Transport Research Institute (VTI) has a turntable road simulator that can be used for a variety of tire tests including tests of PM emissions. The simulator, depicted in Figure 4, consists of a stationary circular paved track with a central hub with arms extending in

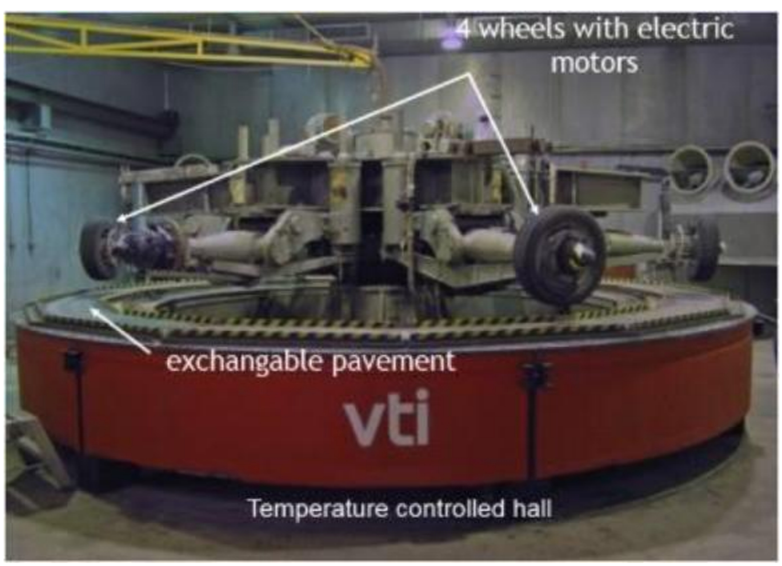

Figure 4. The VTI turntable-style roadway simulator (Grigoratos et. al., 2018).

four directions to simultaneously support four wheels and tires for testing.[28] Each wheel is motorized and the normal force and slip angles can be controlled. The system was originally constructed to test road pavement wear, but since 2005 it has also been used as a wear particle generator for tire and road interaction. The pavement consists of exchangeable tiles made from actual roadway surface material. The system is designed to operate at a constant simulated speed, however the tire slip angle can be changed during operation (though, because the track is circular, the tire can never be operating with zero slip). In this system, the room containing the simulator is closed and the air quality controlled. Researchers estimate the PM mass emissions based on the change in the PM concentrations in the room during the duration of the test.

Flat Belt

ERG did not identify any sources in literature that used a flat belt to generate tire PM emissions for measurement. However, the Smithers Group performs various tire wear and performance tests for tire manufacturers, and one test involves rolling tires against a flat belt in a laboratory to measure various parameters including those affected by tire slip angle.[29] The flat belt allows for a representative contact patch, however the rolling belt material is not made of actual roadway surface materials but rather a sandpaper-type material. Despite not performing tire PM measurements, the flat belt approach is of interest in cataloging the types of tire testing taking place in the research community. The Smithers setup is presented in Figure 5.

Figure 5. The Smithers force and moment test rig.

Laboratory-based tire-wear PM measurement systems have advantages and disadvantages that are relevant to Project 22RD002. The key advantages of these systems are they can readily prevent contamination from background and road dust and they offer a high level of control over the conditions of operation allowing for more repeatability. However, they have numerous disadvantages and challenges. The drum-based systems do not offer a realistic contact patch as compared to operating on level ground; the inside drum results in an oversized contact patch and the outside drum has an undersized contact patch. The turntable contact patch is representative, but the tire always has a slip angle against the pavement, which is not representative of typical on-road operation. Also, unlike in a brake dynamometer in which the brake system is within a CVS, the sampling system is necessarily open, which increases the complexity of estimating PM measurement efficiency. Another limitation is that, in the literature reviewed by ERG, no tire test rigs involved the use of a representative drive cycle but instead had constant speeds and/or standardized acceleration/deceleration/turning events (though this drawback is likely to be the most readily overcome). Finally, all laboratory systems researched by ERG sampled tire and simulated pavement wear together; none allowed for the sampling of only tire emissions.

1.2 On-Road Sampling

The main goal of the review is to identify test methods for the mobile on-road measurement of brake-wear and tire-wear PM in literature. Previously presented laboratory methods were included to further inform potential methods of on-road testing and illustrate any potentially relevant considerations. The most relevant literature, however, is that which includes already-implemented on-road test methods that can either be improved upon in this project or used as inputs to improve the other on-road methods being considered.

1.2.1 Brake Wear

There are a number of examples of light-duty vehicle on-road brake PM sampling system designs described in literature. In general, these systems fall into two main categories, full and partial enclosure systems. In the full enclosure, the brake system is completely encapsulated, and sample is drawn through such that all air in the enclosure is drawn through for sampling. In a partial enclosure, the system has some aspect that is completely open to the atmosphere, but the design is intended to encourage most brake PM flow to travel into the sampling system even though some may escape. Multiple examples of each type of on-road brake sampling systems for light-duty vehicles exist in literature. Conversely, there is very little published literature describing brake PM sampling systems for heavy-duty vehicles.

Full Enclosure Systems

Ricardo has recently published the results of their significant work on developing and deploying an on-road brake- and tire-wear PM sampling system design for light-duty vehicles.[30] In this approach, designed for LDVs, an enclosure was fabricated around the brake rotor and caliper of the test vehicle as presented in Figure 6. The measurement principle is based on the CVS technique in which the airflow rate through the system is held constant. Filtered air is directed into this enclosure, and an outlet allows for the suspended PM to be drawn into the onboard sampling tunnel for measurement. The airflow rate can be optimized to minimize PM losses and also to cool the brakes such that operating temperatures operate as closely as possible to unmodified conditions. In the system, the outer face of the enclosure rotates with the wheel, and the inner face does not rotate and is attached to the assembly that supports the brake caliper. A very small air gap exists between the inner and outer faces, this is addressed by maintaining a positive pressure inside the enclosure (air pumps are used upstream and downstream). The concentration of PM is measured from the enclosure and the flowrate for mass calculation is the inlet flow.

Figure 6. The Ricardo light-duty full enclosure brake PM sampling system.

Other researchers have developed similar full-enclosure systems for brake PM measurement. Those at Ilmenau Technical University developed an early brake enclosure system and conducted comparisons between brake dynamometer and on-road measurements.[31] The Ricardo system is very similar in function to the Ilmenau system. Figure 7 presents a schematic of the Ilmenau system.

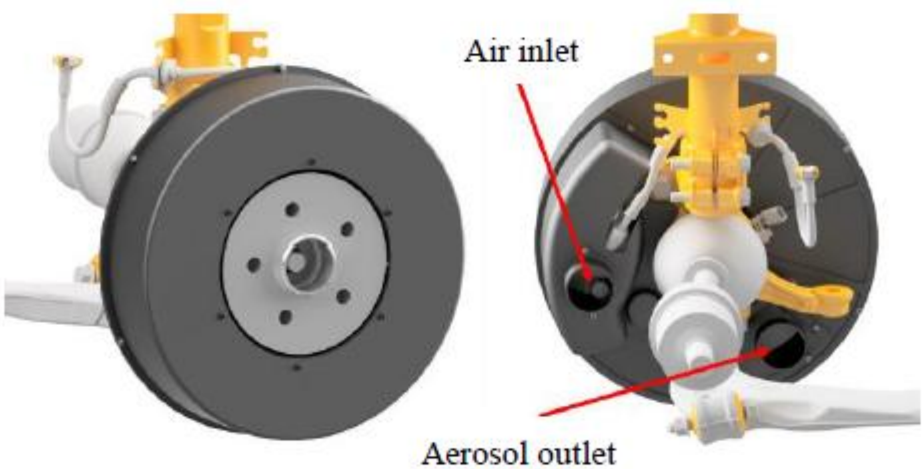

Figure 7. A graphic depicting the Ilmenau brake enclosure design (Hesse et. al. 2019).

Researchers at the Swiss Federal Laboratories have more recently developed a slightly different full enclosure system.[32] This system, presented in Figure 8, is an on-vehicle system, but is intended for use on a chassis dynamometer instead of on the road. This system is tightly sealed and the rotation of the wheel is allowed by an extended mechanical seal, which requires the wheel to be mounted outboard of its normal mounting location. The outboard mounting of the wheel is why this system must be operated on a chassis dynamometer instead of on the road.

Figure 8. The brake PM enclosure developed by the Swiss Federal Laboratories.

Partial Enclosure Systems

An early partial-enclosure method of sampling on-road brake PM emissions was performed by researchers at Ford, who used a conical sampling system mounted to the outside of the vehicle wheel to draw in and sample emitted PM.[33] In this method, a hollow sampling cone is attached to the outboard side of a single wheel as shown in Figure 9.

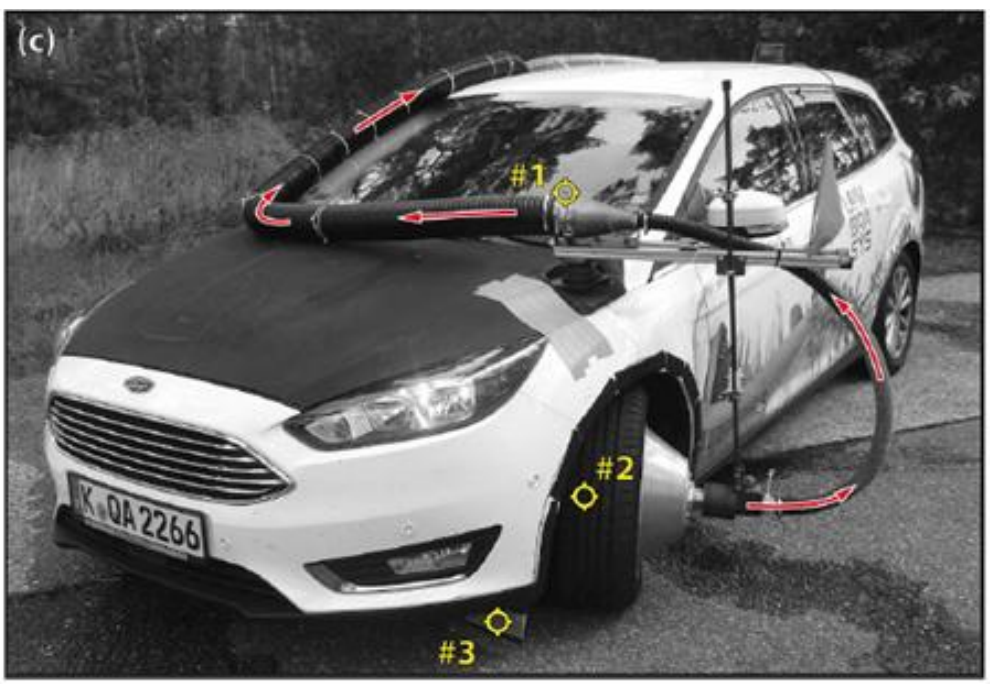

Figure 9. The sampling cone method developed by Ford.

The wheel itself serves as a partial enclosure, and the PM sample is drawn through the spokes of the wheel to the external cone. Sample is drawn through this cone, through a flexible rotating coupler, and into an onboard sampling tunnel. If the sample flow is high enough, it offers the potential to capture all PM from braking. However, the shape of the cone tends to cause adverse pressure that counters the drawn sample flow toward the center at higher vehicle speeds. The loss of sample flowrate occurring with this design has been discussed in literature and can be accounted for by continuous flowrate measurement.

Researchers at AVL have developed a different type of partial enclosure system.[34] In this method, sample is only collected from the interface between one pad and the brake rotor, and it is assumed that the other side would emit an equivalent amount. A partial enclosure surrounds the area where the rotor is exiting the caliper during rotation and directs the flow through a hole in central hub of the wheel. This flow is then directed via tubing to sampling equipment inside the vehicle. This design required manufacture of not only the partial enclosure, but also a custom central hub to direct flow from the enclosure to the opening in the wheel. This offsets the wheel outward a small distance but is not likely to affect drivability. The AVL system is presented in Figure 10.

Figure 10. The AVL partial enclosure method with center hub outlet.

The 22RD002 research team identified very little literature describing on-road testing methods to measure PM from HDV brakes. The only study found by the team was performed by Lee et. al. at CARB. CARB's work on brake emissions used a simple CO_2 tracer gas system with a symmetrical circular sampling system housed within the HDV drum brakes as shown in Figure 11. The system samples for the tracer gas and emitted PM concurrently during the entire test, and the calculated sampling efficiency is used to estimate the measured percentage of emitted PM. This system is designed to be used on the vehicle and it has a minimal effect the operation of the brake system or its temperature profile. The study only involved testing on a chassis dynamometer, however. During the study, Lee was able to demonstrate a > 90 percent collection efficiency for particles 4 µm and smaller and up to 72percent for particles up to 10 µm.

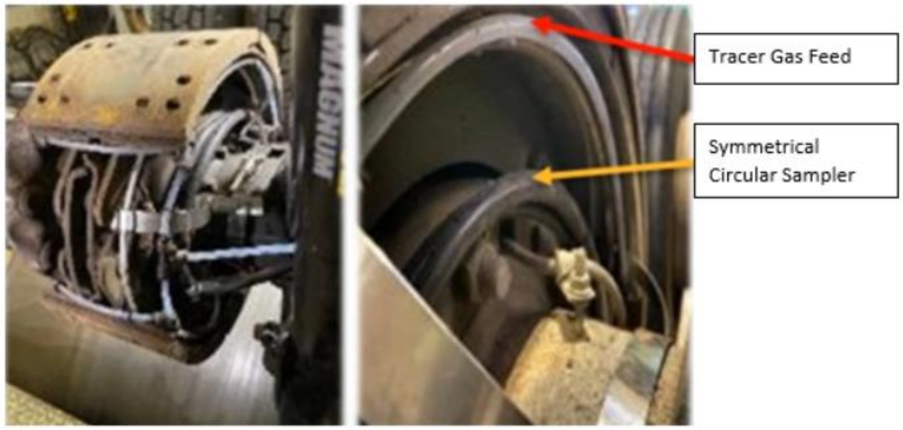

Figure 11. CARB Sampling system in HDV drum brake.

CARB sponsored another study at UC Riverside that involved logging in-use HDV brake activity.[35] The UCR research team instrumented HDV drum brakes with an in-situ temperature probe and a brake pressure transducer. During this work, the UCR team observed that HDV air brake pressure, measured at the brake pads, is fairly consistent and ranged between 135 kPa to 206 kPa, however brake temperature varied significantly and was estimated to reach as high as 260 ℃ which is much higher than the brake temperature observed during laboratory testing. Another observation from the work was that real-world testing showed an order of magnitude higher kinetic energy absorbed by the brakes when compared to chassis dyno testing. This literature is not directly informative for the development of an HDV brake PM measurement system, but the collected data and UCR's HDV instrumentation experience will be helpful in informing the design criteria of the HDV brake PM system.

The available literature will help inform the optimal way to approach the testing planned in 22RD002. For light-duty vehicle brake systems, multiple methods have been published and can be directly adapted for use in this work. The enclosure-based systems have the advantage of also preventing brake PM from contaminating tire PM measurements of the same wheel. For heavy-duty vehicle brake systems, however, no complete system exists in literature. It is likely that some combination of the enclosure approach for light-duty vehicles and the lessons learned from CARB's work on heavy-duty brake drum sampling will yield the optimal approach.

1.2.2 Tire Wear

The measurement of tire wear PM, especially mass measurement, is more complex and technically challenging than measurement of brake wear PM. In part, this is because there are multiple sources of the PM present in the airborne region near the tire/road interface. So, to measure PM emitted at this interface, it is important to clearly define what sources are to be measured and what other sources may contaminate those measurements. Much of the recent literature around tire wear PM discusses tire and road wear together as tire and road wear particles (TRWP), because these particles are emitted together and one does not occur without the other; the tire abrades the road surface and the road surface abrades the tire.

In addition to effects of contamination, tire/road interface sampling is subject to a similar consideration for collection efficiency as sampling from the braking friction couple. Because the airflow around the tire is generally complex and unsteady, it is not straightforward to develop a system with a known collection efficiency. Very little literature exists presenting methods that directly allow for the calculation of sampling efficiency. Similarly, because, at least in current literature, it is not practical to completely enclose the tire/road interface, sampling must take place from a probe open to ambient air and the unsteady flow behind the tire renders it impossible to continuously draw in this sample isokinetically.

One of the earliest research projects into sampling tire wear PM was in Norway and was motivated by the heavier PM emission rates from studded snow tires.[21] This study involved sampling from a large inlet mounted behind the rear wheel of a van as shown in Figure 12. Sample was drawn through this inlet and measured by instrumentation within the van. Researchers generated flow maps of the area behind the tire to estimate the sampling efficiency of the system. The purpose of the testing was to measure and evaluate all PM emitted by the tire/road interface; no attempt was made to isolate only PM from tire wear. This system has also been used in other more recent research projects.[14]

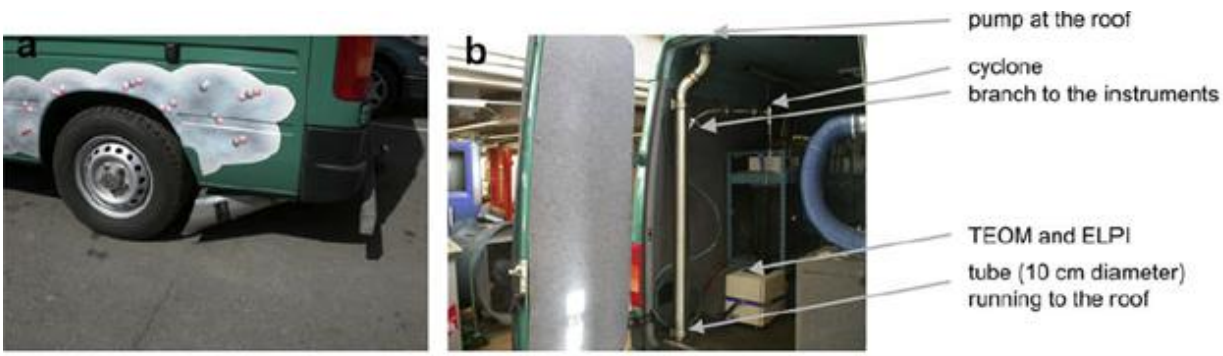

Figure 12. One of the initial TWRP research methods at Metropolia University.

More recently, Ricardo presented recent research in the development of an on-road tire/road interface PM sampling system.[30] The general concept is similar to the previous study, with an inlet placed just behind the wheel to be sampled. Ricardo found that, when operating on-road, the vast majority of collected sample was resuspended road dust, which significantly contaminated the small fraction of TRWP, rendering any analyses difficult. Figure 13 presents pictures of the Ricardo system.

Figure 13. The Ricardo-developed tire sampling system utilized for characterization of PM emitted from the tire/road interface.

Other published on-road tire/road interface sampling has had the intent only to determine particle characteristics and morphology, not specifically mass emission rate factors. By not prioritizing mass emission estimates, it is possible to avoid the requirement of estimating the sampling efficiency. Emissions Analytics has conducted research into sampling tire/road interface wear for the purposes of determining particle characteristics, chemical analyses, and identifying various compounds to use as markers for the chemical determination of the proportion of PM emitted by each source.[36] Similarly, the Korea Institute of Machinery and Materials has done similar research.[27] Both teams deployed similar simple PM samplers behind the tire/road interface; each is presented in Figure 14.

Figure 14. Sample probes used in tire/road interface PM sampling for the intention of studying particle characteristics but not estimating mass emission factors.

Researchers at Gustave Eiffel University have published findings from research into comparing rear of wheel particle (RoW) concentration, i.e. PM emitted just behind the tire road interface, to particles found at the backspace of the wheel, which they define as inside of the wheel near the axle and brakes.[37] The study concept is that the RoW includes TRWP, re-entrained road dust and ambient PM, and the backspace includes only the ambient and road dust PM. The approach is that subtracting the ambient and background (at the backspace) from the tire/road interface (RoW) will isolate only the TRWP from the test vehicle. The study makes the assumption that the amount of road dust at the RoW is equivalent to that airborne behind the tire due to aerodynamic disturbance from the vehicle passing over the road; this assumption is not found or corroborated in other literature. Figure 16 presents a picture of the test vehicle and a schematic of the sampling locations.

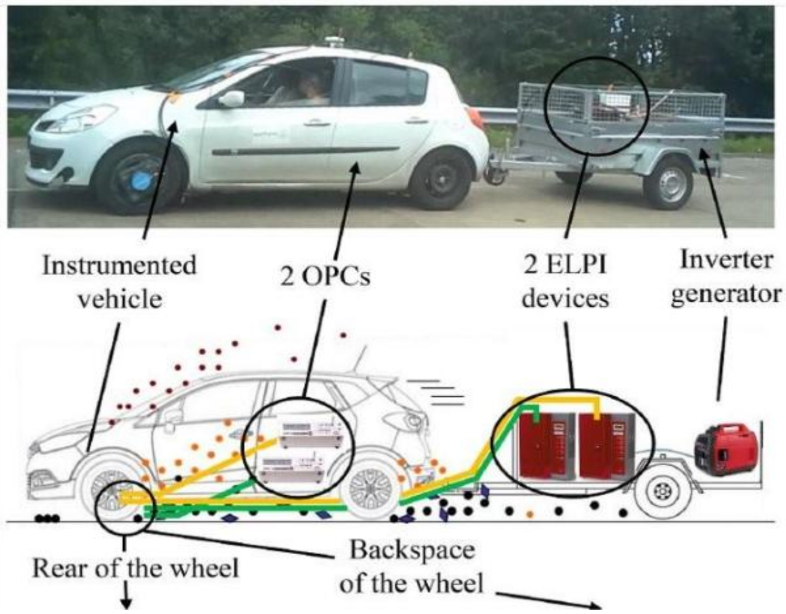

Figure 16. The dual sampling system developed at Gustave Eiffel University, depicting RoW and wheel backspace sampling locations.

Researchers at Michelin have presented results of a study involving on-vehicle testing of tire PM emissions. In this study, multiple iterations of close-coupled intake nozzles were placed at the rear of the tire/road interface and their performance evaluated.[38] Figure 15 presents schematics of the different nozzle designs evaluated. Emitted particles were measured during vehicle operation on a test track. The researchers also determined that the majority of collected media was due to particle re-suspension. To mitigate this, they then cleaned the test track during the night before each test. This significantly reduced the collection of road dust, but the collected particles still contained road surface media. The project involved two multi-inlet design iterations; the latter was more successful and involved three inlets arranged circumferentially, covering more than 90° of the tire. Each of the three inlets in each configuration was sampled one at a time due to instrument limitations. Findings were presented as the PM emission rate as a percentage of the measured tire weight loss over the test; researchers did not specifically estimate PM collection efficiency. The

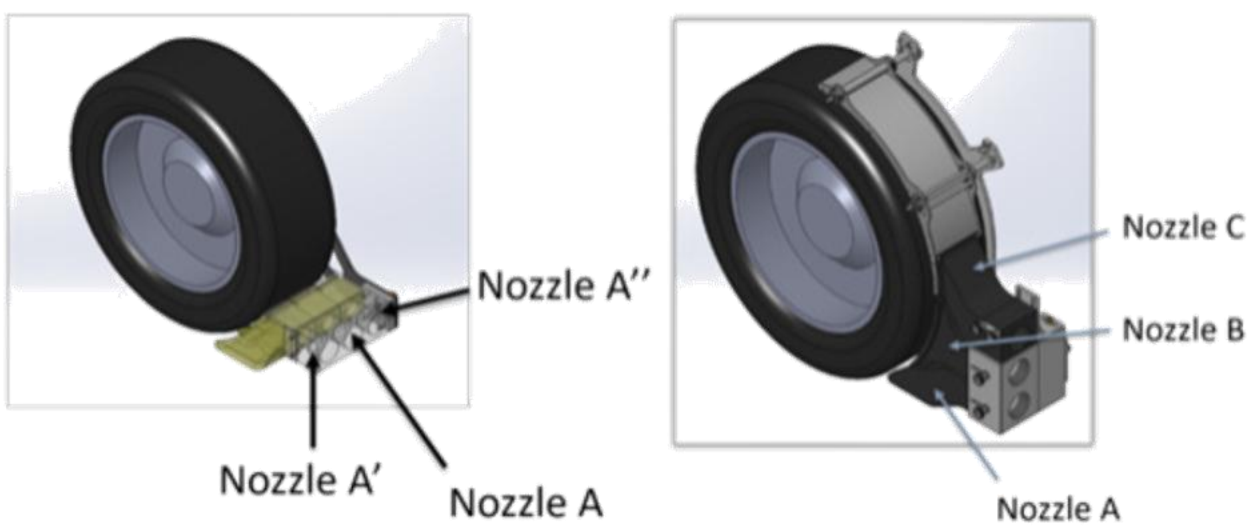

Figure 15. Schematics presenting the initial (left) and improved (right) sampling inlet layouts for tire PM emissions testing performed by Michelin.

study determined that PM2.5 emission mass ranged from 0.1 percent to 0.2 percent of tire mass loss and that PM10 emissions ranged from 1.1 percent to 4.1 percent. The study found that it was crucial to clean the test track to prevent non-tire debris from dominating the sample and, despite cleaning the test track, there were still non-TRWP materials found in samples.

Continental Tire has also recently presented research into PM emissions from tires. In this study, a wide nozzle was used to draw sample in from behind the tire/wheel interface.[39] The nozzle was mounted by a sprung arm to the vehicle's rear axle, and the mounting was equipped with wheels such that if the system were to strike the roadway in a bump, the springs would flex and the wheels would prevent damage to the nozzle. Sample was drawn by a commercial vacuum cleaner and collected on a HEPA filter (as the analyses were primarily morphological and chemical). A bespoke tire was fabricated for use in this work with its tread doped with titanium dioxide (TiO_2) at 6 percent, which would serve as a chemical marker not otherwise present in the tire. As a result, the researchers could determine the amount of collected material that came from the test tire as compared to background. TiO_2 does exist in the roadway environment (such as in roadway paint markings), so repeated tests without the TiO_2-doped tire were conducted to establish an expected level of TiO_2 in the background. In the introduction to the study, the researchers indicated that they estimated TRWP to consist of approximately 50 percent tire and 50 percent roadway material. The results of the research indicated that about 5 percent of collected media came from the test tire, though it was not clear if the 5 percent was of the collected rubber or the entire TRWP sample. In this study, no attempt was made to determine the system's sampling efficiency or mass emission rates from the tires. Figure 17 presents a picture of the sampling system as well as the collection nozzle and filter for the capture of particles.

Figure 17. The sampling setup used by Continental Tire, in which a tire doped with TiO2 was used as a marker to determine the tire-sourced percentage of collected TRWP.

For tire testing, it is unlikely that a different design concept will be necessary for light- and heavy-duty vehicle testing. However, no on-road method has been demonstrated that can generate mass emission factors for the tire portion of TRWP. Most notably, ERG found no reference that presents a direct method of estimating collection efficiency irrespective of method. However, it may be possible to bring the methods attempted in various literature together to develop this estimate. The key issues to resolve are the unknown collection efficiency (and the related challenge that isokinetic sampling in the wake of the tire isn't feasible) and the challenge in determining the proportion of tire-source PM in any collected sample by utilizing source apportionment techniques.

The literature review of on-road systems informed several key factors and conclusions for consideration in the development of measurement systems in 22RD002.

- There are a variety of viable designs in use for the on-road measurement of brake PM. The existing tire PM measurement systems are much less developed and have more measurement error and challenges.
- Brake PM Measurement
    - Designs that allow brake enclosures to operate more like a brake dynamometer/CVS measurement will likely result in the lowest measurement error for brake PM.
    - Maintaining representative brake temperatures within the enclosure is a key concern. The sample flowrate may need to be very high to do this, resulting in a high power requirement. Little data exists for how an enclosure would affect HDV drum heat rejection.
    - In most brake PM enclosure designs, PM loss to the atmosphere is minimal or can be quantified. However, the complex geometry may cause relatively high amounts of particle settling, the rate of which could be speed dependent.
- Tire Sampling
    - Almost all tire PM design possibilities fundamentally involve some type of sample intake port mounted behind the tire/road interface.
    - Roadway debris and dust is far more prevalent than tire emissions in the area behind a rolling tire. Operating on a cleaned surface can reduce but not eliminate the effect of this on measurement.
    - Even if the roadway surface is perfectly clean, the emissions at the tire/road interface consist of both tire and roadway particles.
        - The use of chemical markers may facilitate resolving the percentage of collected emissions from the tire.
    - Estimating the tire PM sampling efficiency is an exceptionally difficult engineering challenge.

1.3 Influential Factors in Brake and Tire Emissions

A secondary focus of our literature review was to identify factors found to influence brake and tire wear emissions. Understanding these factors is important in supporting two objectives of this project:

1. Assessing what factors should be accounted for in the experimental design, specifically with the selection of vehicles, components, and test routes.

2. Identifying factors to be accounted for in developing a statewide brake and tire emissions inventory, given that the scope of this project cannot control for every influential factor.

1.3.1 Brake Wear

The CARB and Caltrans Brake PM studies conducted by ERG and LINK identified several influential factors for brake PM emissions[11,12,23], many of which were confirmed in Ricardo's recent work for the UK Government[30]. The overall factors can be divided into two categories: those intrinsic to the vehicle or brake systems, and those related to usage at a given time. Factors affecting brake PM emissions that are intrinsic to the vehicle or brake system include vehicle class and weight, brake type, friction material composition, and regenerative braking. Vehicle weight is a key determinant of brake emissions as greater vehicle weight requires more braking force to slow at a given deceleration rate, resulting in greater energy transfer through the system. Brake type (disc or drum) and form of actuation (hydraulic or air) also affect PM emission rates, especially for light-duty vehicles in which the brake backing plate largely encloses the friction surface. For light-duty vehicles, installed brake friction material composition was found to affect PM emissions, as well as whether the material was original equipment (OEM) or aftermarket. OEM vs. aftermarket was not a significant factor for heavy trucks however, since aftermarket friction material is more similar to original equipment for this class. Although non-exhaust emissions for electric buses with regenerative braking system have been estimated from conventional vehicle emission factors based on vehicle mass[40], we are not aware of studies that directly measured brake emissions from heavy trucks or buses with regenerative braking.

The ERG/LINK and Ricardo studies confirm that operational parameters also affect the PM emission rate from braking. Factors such as deceleration rate and vehicle speed both affect the energy being absorbed and converted by the braking system; higher values of these generally result in higher brake emissions. Likewise, the duty cycle or percentage of time spent braking affect the PM emissions on a distance or time basis. Finally, the temperature of the brakes is likely to affect the PM emission rate (though elevated temperatures generally require higher braking energy events, so the temperature may not be causal to the elevated emission rate). For the CARB and Caltrans studies these factors were characterized as "braking intensity", defined as the combination of braking frequency, duration and power of braking events. This is captured by the duty cycles used for testing and is well correlated with average cycle speed. For example, for HD trucks, the duty cycle with the highest emissions on a gram/mile basis was the drayage truck cycle, which has the lowest average speed of all duty cycles tested and consists mainly of stop-and-go operation representative of trucks operating in port terminals.

1.3.2 Tire Wear

Our literature review found several peer-reviewed research papers that identify and quantify factors that influence tire PM emissions. Among these papers, influencing factors such as tire characteristics (e.g., composition, construction, studs), road surface characteristics (e.g., surface roughness, material), vehicle operation characteristics (e.g., speed, cornering, weight, power, braking intensity), and temperature were among the most common. Vehicle type and use also play significant roles in tire emissions as tire compositions vary depending on end use.

The UK NAEI reported an average tire wear $PM_{2.5}$ and PM_{10} emissions factors of 5 mg per km per vehicle and 7 mg per km per vehicle. The EMFAC base rate for tire wear $PM_{2.5}$ ranges from 0.002 to 0.009 grams per mile, or 1.24 mg per km to 5.59 mg per km, and PM_{10} ranges from 0.008 to 0.036 grams per mile, or 4.96 mg per kg and 22.36 mg per km.[41] It is estimated that approximately 10-30 percent of a light duty vehicle's tire tread rubber mass is emitted in the form of wear particles throughout its typical life of 40-50 thousand kilometers. The wear rate depends on tire type, vehicle configuration, and driving dynamic properties. Higher vehicle speeds, longitudinal and lateral acceleration are also linked to increased tire emissions. These driving behaviors increase the amount of frictional power transmitted between the tire and road surface which transforms into thermal energy that further degrades tires and increases emissions. However, thermal energy is not directly proportional to frictional factors and is highly subjectable to road temperatures, air-cooling as a function of vehicle speed, and heating due to hysteresis (system lag) losses.[42]

In a study conducted in Boston, MA, tire emissions at the interface of road and tire abrasion were strongly correlated with temperature, time of day, and the number of vehicles on the road.[43] Humidity levels were also considered to play a significant role in tire emissions as drier conditions were typically associated with warmer conditions which promotes more tire wear.

Electric vehicles have also been identified as contributors to increased tire emissions. As a result of light-duty electric vehicles being, on average, 24 percent heavier than their gasoline counterparts, light-duty electric vehicles are responsible for an approximate 20 percent increase in tire wear PM_{10} and a 30 percent increase in tire wear $PM_{2.5}$.[44] Tire composition plays a significant role in tire emissions. As shear and friction forces originating at the tire-road interface are the main cause of abrasion TWPs, tires with stronger tear resistance tend to produce less TWPs. Since natural rubber has a high tear resistance, tires that contain higher percentages of natural rubbers than styrene butadiene rubber or butadiene rubber will produce less TWPs through shear and friction forces. Heavy-duty vehicle tires, for example, contain approximately 80 percent natural rubber whereas passenger car tires contain only 15 percent.[45]

Tire composition and construction vary widely by tire brand, which has been identified as a large source of emissions variability. Emissions Analytics tested a single Mercedes C-Class vehicle with multiple payloads on ten different tire brands and found that emissions more than doubled between the lowest-emitting premium brand and highest-emitting budget brand.[36] This study also found that increasing payload by 500 kg increased emissions by 21 percent. Allgemeiner Deutscher Automobil-Club (ADAC), Europe's largest automobile association, conducted a study to compare tire emissions across 15 tire manufacturers evaluated by type of tire (all-seasonal, summer, winter) and size.[46] This study found a variation of over 40 percent from the lowest emitting (Michelin) to the highest emitting (Pirelli). Although there was no conclusive evidence to suggest there are fundamental differences in tire emissions between summer, winter, and all-season tires, a strong correlation can be made between tire emissions and the width of the tire. Except for a few outliers, tire emissions increase with tire width when under the same weight loading, indicating that tire emissions are directly related to the size of the road-tire interface.

Road surface roughness is also a significant variable that contributes to tire emissions. Variations in road surface roughness can alter the shape and size of TWPs as well as the total emissions. Contact with rougher road surfaces lead to a larger total number of TWPs but a reduction in concentrations of fine TWPs, further indicating rougher road surfaces lead to an increase in concentration of coarse TWPs.[44]

A study by Arizona State University tested and compared tire emission rates for vehicles driving on asphalt and concrete road surfaces.[47] The experiment compared tire emission data against the International Roughness Index (IRI) of the Deck Park Tunnel Highway before and after the concrete road surface was repaved with an asphalt rubber surface. The experiment showed that the IRI of the road surface decreased by over 50 percent when repaved with the asphalt rubber overlay. The decrease in the IRI of the road surface was then correlated with a 25 percent to 50 percent decrease in tire emissions. Although this experiment does not confirm that all concrete road surfaces are rougher than asphalt surfaces, it does confirm the notion that rougher road surfaces are a leading contributor to increased tire emissions.

An overall summary of influential factors identified for brake and tire emissions is shown in Table 1. Factors including vehicle weight, vehicle class, and vehicle operation are shared as the physical mechanisms of emission formation from both brakes and tires are dictated by the kinetic forces the vehicles are subjected during normal operation.

Table 1. Influential Factors Identified for Brake and Tire Emissions

Brake	Tire
Braking intensity Vehicle weight & class (car, lt truck, delivery etc.) Friction material (e.g.,semi-metallic, NAO) Powertrain (e.g., ICE, HEV, BEV) Original equipment (OEM) vs. aftermarket Axle	Vehicle class (car, light truck, delivery etc.) Vehicle operation Ambient temperature Tire size Tire pressure Season (summer, winter, all season) Tire age Pavement type Road condition

1.4 Summary of Literature Review Findings

The literature describing methods of brake- and tire-wear PM measurement varies greatly in terms of the level of development, ranging from proven methods for brake PM measurements to exploratory and incomplete methods of tire PM estimation. For brake PM measurement, laboratory methods in literature are generally similar to the methods employed by ERG and LINK during projects 17RD016 and 65A0703. These brake dynamometer methods are relatively well proven, but are of limited applicability for on-vehicle measurement. The available literature does include a variety of on-road light-duty vehicle brake enclosures to choose from for this project. Unfortunately, there is very little literature describing sampling methods for on-road heavy-duty vehicle brake PM. The key concerns for brake PM measurement will be the development of a system that has a minimal effect on brake operating temperature, minimized PM losses, and generally operates as similarly as possible to a brake dynamometer CVS system. This said, the Ricardo system for brake measurements emerges as the leading candidate for 22RD002 as has been testing successfully on-road already and is design to maximize sample capture while minimizing contamination.

Methods of measurement of tire-wear PM are less proven than for brake-wear PM. There are two key challenges to tire PM measurement, the presence of PM from multiple sources at the tire/road interface, and the challenge of estimating PM collection efficiency at that interface. Available literature suggests that the only way to separate tire and road wear is chemically, otherwise they can and must occur together and are otherwise indistinguishable. Of all the literature reviewed by the project team, only the Continental Tire study presents a complete process to estimate the tire fraction of collected PM by chemical means, and this study does not attempt to make any estimate of collection efficiency or overall mass emissions. Most successful on-vehicle studies included vehicle operation on a cleaned test track. Since 22RD002 will be conducted on the open road in the midst of real traffic, a method which brings as much enclosure to the wheel as practical on-road is desired.

The literature documents a number of influential factors for both brake and tire emissions, beyond what can be controlled for in this project. Several major factors can be addressed, however, with deliberate selection of test routes to cover a range of driving and road conditions; and with selection of test vehicles, brake components and tires with consideration for both market representation and emissions variability. These factors informed the development of the on-road test matrix discussed in Sections 3.0 and 4.0.

2.0 TASK 2: DEVELOP ON-ROAD EMISSIONS SAMPLING SYSTEM AND MEASUREMENT APPROACH

Task 2 consisted of four subtasks which provide a foundation for on-road testing and analysis in later tasks. Task 2a convened a Project Advisory Committee (PAC) to provide input on the sample system design, market survey, and test route development addressed in the other elements of the task. Task 2b conducted a market survey of brake and tire use in California to inform selections for testing and provide a basis for applying test results from Project 22RD002 to the broader California fleet. Task 2c developed test routes for on-road brake and tire testing to account of vehicle operation and road properties of interest for brake and tire emissions identified in Task 1. Finally, Task 2d encompassed a major effort to design, fabricate, and evaluate individual on-board measurement systems for brake and tire particulate matter (PM) collection with a common system of sampling and measurement of both filter-based and real-time PM. The approach and results of each of these tasks is addressed in the following sections.

2.1 Task 2a: Project Advisory Committee

The project team assembled a PAC to participate in CARB monthly status calls to provide ongoing input on Task 2 of Project RD22002. Per CARB direction, panel members were recruited to ensure representation from U.S EPA, state agency stakeholders, local air districts, tire and brake manufacturers, automotive research consortia, and independent experts in particulate matter (PM) measurement. PAC members attended two virtual meetings where the project team provided status updates and proposed methods related to three specific elements::

- The design of on-road testing and emission sampling methods.
- The market survey of California brake friction and tire materials.
- Fleet-representative vehicle types.

PAC members were encouraged to provide feedback during the calls, and were then sent a follow-up survey to provide written responses as well. Meeting summaries and comments received are presented in Sections 2.2-2.4.

Table 2 shows a complete list of PAC members for Project RD22002. Cells with multiple members are listed indicate where new representatives were appointed during the project.

Table 2. CARB Project RD22002 PAC members and their organizations

Member	Organization
Chad Bailey	U.S. EPA Office of Transportation & Air Quality
Rich Baldauf	U.S. EPA Office of Research & Development
Sam Cao	South Coast Air Quality Management District
Nico Shulte	South Coast Air Quality Management District
Daisy Laurino	CA Dept. of Transportation (Caltrans)
Jonathan Goodman	CA Dept. of Transportation (Caltrans)

Member	Organization
Hannah Schoolmeester	CA Dept. Toxic Substances Control
Kaitlyn Kalua	CA Ocean Protection Council
Kelly Moran	San Francisco Estuary Institute
Phil Wetzel, Mahmoud Yassine	Coordinating Research Council (CRC)
Theo Grigaratos	European Commission Joint Research Center – Particle Measurement Programme
Matti Maricq	Independent Consultant
Tracey Norburg	U.S. Tire Manufacturers Association (USTMA)
Alex Boesenberg, Emily Sobel, Ana Meuwissen	Motor & Equipment Manf. Association (MEMA)- Brake Manufacturers Council

2.1.1 PAC Meeting Summaries

The first PAC meeting took place on December 19, 2023 followed by the second meeting on October 31, 2024. ERG led presentations for both virtual meetings with support from larger project team of Ricardo, Link, and UCR. Throughout the meeting presentations, the project team encouraged members to engage in the content by using the raise-hand feature or typing questions in the meeting chat. ERG concluded both meetings asking PAC members to share feedback on various project objectives and processes through a post-meeting survey (see Section 2.3). See the appendix for the full meeting slides presented at each meeting.

Meeting #1

The first PAC meeting began with introductions from the research team and PAC members, followed by a description of the PAC charge and process. The research team provided a brief overview of the project motivation, background, objectives, and schedule. Next, ERG reviewed several brake and tire on-road methods, then opened the discussion to members for feedback on the methods discussed.

After reviewing background information, discussions shifted to the factors that influence both brake and tire emissions and how those factors should be considered when designing the on-road sample system and sample method. Specific factors influencing brake emissions include brake intensity, vehicle weight, and brake type, among others. For tire emissions, specific factors include tire width, seasonality, and composition.

During the review of the design concept in development, Ricardo shared their "Design C" as the leading candidate for light-duty vehicle (LDV) and heavy-duty vehicle (HDV) sampling. ERG also reviewed the constant-volume sampling (CVS) design concept for brake and tire sampling tests. Lessons learned from Ricardo's brake and tire PM testing will be considered in finalizing the design concept for this project. After discussing how to best address tire measurement issues and gathering live feedback from PAC members, the project team planned to rethink the best path forward for appropriately calculating tire measurements. The design and pilot study portion of the meeting also included vehicle selection considerations for LDVs and HDVs.

Before concluding the meeting, ERG reviewed the market survey (Task 2b), noting the two main purposes: informing friction material and tire selection for test vehicles and informing statewide inventory of brake and tire wear emissions. For brake emissions, the project team proposed starting with prior work but updating to account for LDV registration data and electric vehicle growth over time. For tire emissions, ERG noted U.S. Tire Manufacturer's Association (USTMA) sales data as a key resource as well as the importance of considering tire size, replacement, and brand.

Meeting #2

The second PAC Meeting began with a review of the topics discussed during the first meeting, along with a summary of key PAC member recommendations submitted through the first post-meeting survey (see Section 2.4). Then, the ERG team presented on the exploratory experiments happening at UCR CE-CERT. After a brief overview of the preliminary sampling system, ERG described the particle losses evaluation based on a mini-cast evaluation (under zero miles per hour (MPH), 30 MPH, and 60 MPH). The results showed high particle losses due to impaction at the funnel inlet, with higher particle losses in the sub two µm range.

Next, ERG presented findings on the aggregated emissions levels of the Old and New tires. Although the findings showed no clear trend appeared between the two under the PN spectrum, the Old tire showed higher PM emissions. Alternatively, measurement findings based on the New tire showed a higher nucleation mode under US06 compare to the less aggressive UDDS, with high PN and PM emissions under US06. The preliminary sampling system also showed wheel alignment to affect tire temperature, with minimal variation between acceleration and deceleration.

During discussions on the design and fabrication of the overall sampling system, ERG shared the project team's focus on the LDV and noted they will shift attention to HDV based on lessons learned. The research also noted their plans to use a CVS Sampling system. ERG shared that the brake and tire sampling will be conducted separately to maintain unique point of sample systems and different configurations for brake and tire.

ERG presented the finalized configurations for the brake and tire systems, along with the finalized brake enclosure design, tire point of sample design, and test route selection. The project team selected a roadway on California Interstate-60, a main highway that is primarily concrete.

Last, ERG shared how the market survey will guide the project team's choice of tire and brake selections, brake wear index (BWI), and tire ware index (TWI). The project team's recommendation for HDV is to perform testing on Class 8 drum NAO friction material to capture the largest heavy-duty brake source and allow a direct comparison with Caltrans program. The recommendation for LDV is to perform testing on non-asbestos organic friction material (NAO) and aftermarket (AM) metallic friction material to capture the largest light-duty brake sources and allow direct comparison with CARB dynamometer program. ERG noted that available TWI data differs from the brake market due to tire size and milage being the primary known variables. To account for these variables, the project team's recommendation is to test high sales brands with a range of tire wear per Allgemeiner Deutscher Automobil-Club (ADAC) study[46], mileage ratings.

2.1.2 Survey Questions

Table 3 and Table 4 display the survey questions distributed to PAC members following the first and second PAC meetings. Section 2.1.3 summarizes participant responses.

Table 3. Survey questions for PAC members following PAC meeting #1

Topic	Survey Question
On-Vehicle Sampling System	1. Please provide your comments on the overall approach. 2. Are there studies not mentioned in the literature review that you believe should be considered? 3. What are your thoughts on the separation of tire emissions from road/background dust particles in the sample?
Market Survey	1. Please provide your comments on the overall approach. 2. Please provide your comments on the data sources for brake/tire sales and use in California. 3. What are your California-specific considerations for the brake/tire market?
Fleet Representation	1. Please provide your comments on the rationale. 2. How can we maximize representation of California brake/tire "fleet"? 3. What are your California-specific considerations for the vehicle fleet?
Additional Feedback	1. Please provide any additional comments below.

Table 4. Survey questions for PAC members following PAC meeting #2

Question Number	Survey Question
1.	Do you know of any relevant ongoing work, research, or publications that could be useful to the project team?

Question Number	Survey Question
2.	What techniques would you suggest for validation and shakedown of the measurement system during Pilot Testing?
3.	Do you have any comments on our plans for development of test routes?
4.	Do you have any comments on our plan to select candidate brake components and tires?
5.	Please provide any additional comments you may have in the space below.

2.1.3 Summary of PAC Recommendations

Following each PAC meeting, ERG distributed a survey for PAC members to submit feedback on the research process. This section summarizes the main themes that emerged from PAC member responses, followed by how the project team has addressed PAC comments.

Importance of correlation with lab/dynamometer testing

Several members suggested the study would benefit from noting the importance of the correlation between lab and dynamometer testing. This would allow for additional lab testing to fill in the matrix of condition combinations. Brake dynamometers have the capability to run real-world brake cycles and control brake temperature. Additionally, members suggested CE-CERT could conduct chassis dynamometer tests during exploratory investigation and pilot testing. Comparing road to brake dynamometer measurements could provide insights into assessing future brake emission laboratory studies.

How Addressed: *Pilot testing will be conducted on chassis dynamometer to provide a direct comparison between controlled lab results and on-road testing. Brake emissions will also be compared to brake dynamometer results from the CARB 17RD016 program in Task 6.*

Brake temperature representativeness

Members suggested the project team review brake temperature representativeness during pilot testing. Unlike the non-enclosed wheel, the on-road test is unable to control brake temperature deviations. Additionally, if the on-board brake emissions measurements do not differ from the lab testing, some members suggest using a brake dynamometer as it can act as a real-world example. Temperature can provide a more complete understanding of brake and tire PM emissions.

How Addressed: *Brake temperatures will be measured during on-road and can be compared to brake temperatures from a test track measured during the CARB 17RD016 project, and from brake dynamometer testing from the same project.*

Separating tire percent of the total collected sample

Members noted that it is important to note the differences in tire PM emissions from brake and tailpipe emissions. Since both the vehicle and the environment create tire emissions, members also suggested it may be unnecessary to distinguish between the following emissions factors: tire wear, road wear and resuspended road dust, as all are necessary to understand the impacts of airborne particles on the environmental and human health. However, a chemical analysis could identify the particles from tires in the experiment and can be measured using a small sample of the tread material.

How Addressed: *per CARB's direction for the program, brake and tire emissions will be measured separately. The separation of tire particles from road dust will rely on source apportionment based on chemical characterization of tires from dynamometer testing.*

PM sampling recommendations

Members advised the project team to define the connection between the two sampling systems described in the presentation, as the system geometries differ and therefore losses will differ. Additionally, using CAST soot particles can be problematic for measuring brake and tire PM because the characteristics of the soot particles are not a good match for the brake and tire particles. Using Electrical Low Pressure Impactor (ELPI) with CAST soot can also impair the loss function. To ensure reporting accuracy, it is also important to state whether the results are mass or number weighted. A way to account for this is to use a loss function that is size dependent or use separate loss functions for sub-micron and super-micron modes. Ultimately, distinguishing between the two modes of brake and tire PM as well as mass and weight numbering is relevant to discussing temperature effects. To get a holistic understanding of brake and tire PM emissions, it is important to consider the effects of temperature, along with other variables such as tire age on each PM mode.

How Addressed: *Findings in this work will be explicit on particle mass versus count. We understand that the loss functions may be different for the separate testing of brake and tire. Have minimized length and radius of bends to the extent possible with our test vehicle. Our team decided not to use CAST soot particles during pilot testing but may consider two loss functions for the size ranges of interest after the completion of testing.*

Input on the project team's recommended test routes and brake and tire candidates

Members recommended choosing brakes that use the most fuel by type, including gasoline, diesel, hybrid or zero-emission. Suggestions for recommended test routes include a route subject to variable road conditions (rain/surface wetness), road grade and elevation change, road roughness, and material (concrete, asphalt, rubberized asphalt). Additional recommendations include using a route that allows for repeatable driving and variable braking events. Repeatable driving can be used to discover error bounds but should be done on the road or at time with minimal traffic as to reduce PM from other vehicle brakes and tires as much as possible.

How Addressed: *As discussed under Task 2b, brake selection will be driven by the market shares of brake material from CARB 17RD016 study along with data provided by brake manufacturers during the PAC meetings. The project team has largely adopted test route suggestions, although some are beyond the scope of testing for this project (e.g. dry/wet surface).*

2.2 Task 2b: Market Survey

The objective of the market survey under Task 2b was twofold. The first objective was to select brake configurations, friction material, and tires to test that would represent the California fleet as much as possible given limited sample size. The second objective was to develop metrics which will enable the transformation of this project's emissions data to a representative fleet-wide California emissions inventory. Although Task 2b was initially supposed to inform the choice of test vehicles, the project team made the ultimate choice of a Chevrolet Silverado 2500 owned by UCR out of the necessity to have a vehicle with ample space to accommodate the sampling and measurement system, and to provide a low-cost and readily-accessible option to the UCR team for ongoing design, fabrication, and pilot testing.

2.2.1 Brake Market

The project team conducted a brake market survey for LDVs for CARB Project 17RD016 to inform the choice of vehicles and brake friction materials tested in that program. The survey found that the majority of light-duty cars and trucks use NAO, though the prevalence of low-metallic (LM) or semi-metallic (SM) increases with vehicle age due to use in the AM as a lower-cost alternative to NAO material (Figure 18. LD brake market survey from 17RD016. Informed by this survey, 17RD016 project tested both NAO and LM friction material on most vehicles, including a Ford F-150.

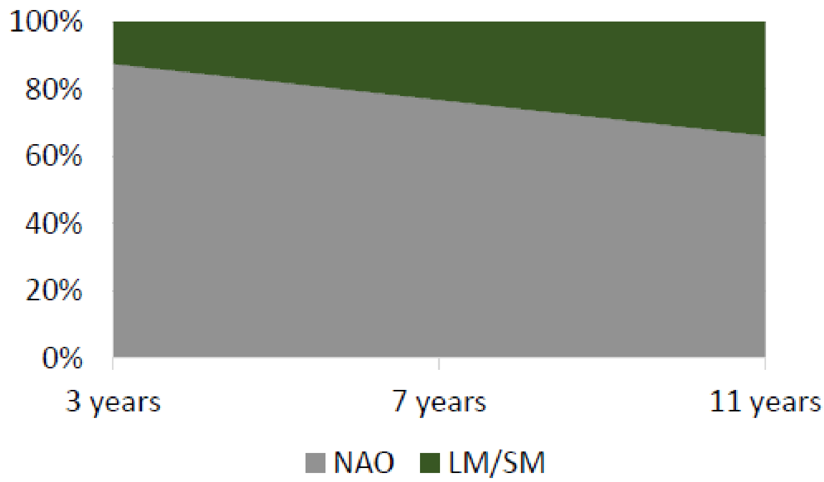

Figure 18. LD brake market survey from 17RD016.

To update the brake market survey, The Motor & Equipment Manufacturers Association (MEMA) provided results from a survey of brake manufacturers as part of the PAC process (Table 5). The results for LDVs corroborate the findings of 17RD016, with original equipment manufacturer (OEM) material predominantly NAO, and AM majority ceramic (similar to NAO) but with a larger prevalence of metallic. However, light HDVs like the Silverado 2500 are shown to use 90-95 percent metallic. In order to represent materials tested in 17RD016 and the friction material used on the majority of LDVs, light-HDVs and medium-duty vehicles according to MEMA, the project team plans to test NAO, Ceramic, and LM friction material for on-road testing.

Table 5. Brake market survey results provided by MEMA

Vehicle Class	OE Usage	AM Usage
Light Vehicle (1500 and below)	95 percent NAO, 5 percent LS	75 percent Ceramic, 25

Vehicle Class	OE Usage	AM Usage
HD Light Truck (2500-4500)	10 percent NAO, 90 percent SM	95 percentSM, 5 percent NAO
Medium Duty (hydraulic)	95 percent SM, 5 percent NAO	95 percent SM, 5 percent NAO
Class 8 (Disc Brake)	95 percent LS, 5 percent SM	50 percent LS, 50 percent SM
Class 8 (Drum Brake)	95 percent NAO, 5 percent SM	95 percent NAO, 5 percent SM

2.2.2 Tire Market

The project team's assessment of the tire focused on identifying high sales brands to select for testing, and developing a tire wear "index" to scale emissions data collected in the project (and others eventually) to the broader California fleet. Assessment of the tire market focused on publicly available U.S. data. The project team explored the purchase of California-specific data from S&P Globa Mobility, which could provide a dataset of OEM tires equipped on new vehicles sold in California down to the county level. However, this dataset would not address replacement tires, which accounts for the majority of the tire market, so the project team decided the purchase was not justified.

A tire emissions study published by the San Francisco Estuary Institute (SFEI), represented on the PAC, provided valuable insight for this task.[48] SFEI obtained a tire market analysis from the Berkeley Bay Area Environmentally Aware Consulting Network, which reported that replacement tires make up over 75 percent of the tire market. The analysis also found that although over 400 tire brands are sold in the U.S., three major U.S. brands – Bridgestone, Goodyear, and Michelin – sell tires under a variety of different brand names which may have similar formulations (Table 6).

Table 6. Brands within top three manufacturers (Source: SFEI)

Top Tire Manufacturer	Example of Brands Owned
Bridgestone	Firestone, Bandang, Tires Plus, Wheel Works, Azuga, and GCR Tires
Michelin	BF Godrich, Kleber, Casmo, Siamtyre, Riken, Kormoran, Levorin, Uniroyal, Tigar, and Taurus
Goodyear	Cooper, Dunlop, Kelly, Debica, Sava, Fulda, various Goodyear-owned house brands and customer private-label brands

The SFEI report recommended that sample selection for tire studies account for major tire market segments and manufacturers, a range of price points, and tires intended for high-sales vehicles. These recommendations were considered along with the factors determined in Task 1 to be influential for tire emissions to develop the tire sample selection outlined in Task 3. This sample selection includes a representative of the three major brand families from Table 6, a range of price points, new and aged tires, and varying inflation levels.

2.2.3 Brake & Tire Wear Indices

As a second objective of Task 2a, the project team developed metrics to apply emission results from this program to the broader California fleet for emissions inventory purposes. These metrics are termed “wear index” to represent the wear rate of a given brake pad or tire based on wearable mass and mileage rating. Wear index provides a means to linearly scale emission results from this program to a range of brake pad and tire sizes.

Brake Wear Index (BWI) was first developed in the CARB 17RD016 and Caltrans heavy-duty brake programs. For this project CARB provided 2024 vehicle registration data in order to update BWI. Using these data the project team estimated BWI for the top-owned vehicles in California, spanning 10 different vehicle manufacturers, 20 different vehicle models, and 23 different years (2000 – 2023). For each vehicle, data for disk drum brake information was collected using the Friction Materials Standards Institute (FMSI) catalog and ATE Disc Brake catalog. Wearable mass for each pad was calculated from pad area and thickness; the wear index estimates a wear rate assuming the wearable mass is lost over the mileage rating of the pad. Pad area calculations were done using an online area calculations tool sketchandcalc.com (Figure 19). The resulting database includes FMSI datasheet for friction material wear, wear volume for front and rear axles, and wear calculations based on input friction material specifications.

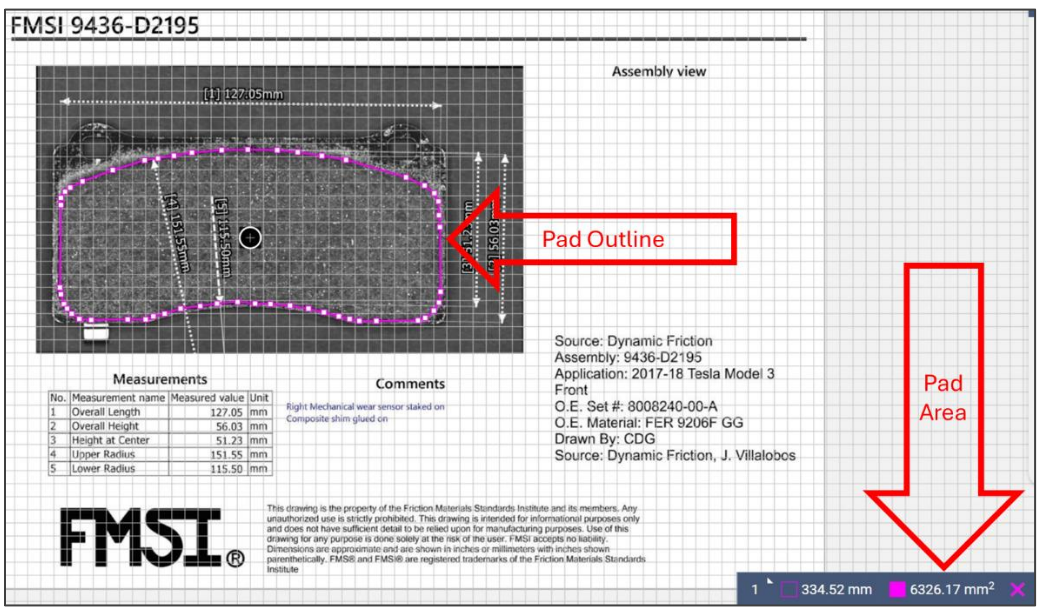

Figure 19. Brake pad area calculation used for BWI.

Our team applied a similar process to develop TWI, a new metric to scale emission results from this program to the range of tire sizes in California's fleet. Our team compiled the most prevalent tire sizes in California's fleet based on tire market data for the top 94 vehicles in operation in California defined for the BWI calculation, and the U.S. Tire Manufacturer's Association (USTMA) Factbook.[49] Wearable mass was estimate based on tire width, tread depth and void volume, the latter of which was estimated using a Python script to analyze tire face images. TWI was then calculated as an estimated wear rate assuming wearable mass is lost over the mileage rating of the tire, expressed as grams of total tire mass loss (not just PM2.5 or PM10) per kilometer of travel (Figure 22). As discussed in Section 5.0, TWI was used to scale PM emissions across tire sizes for use in calculating a comprehensive emissions inventory, assuming that tire emission rates are proportional to TWI. SEFI took a similar approach for scaling emissions from a small sample of tires to a California statewide inventory, but using tire width only.

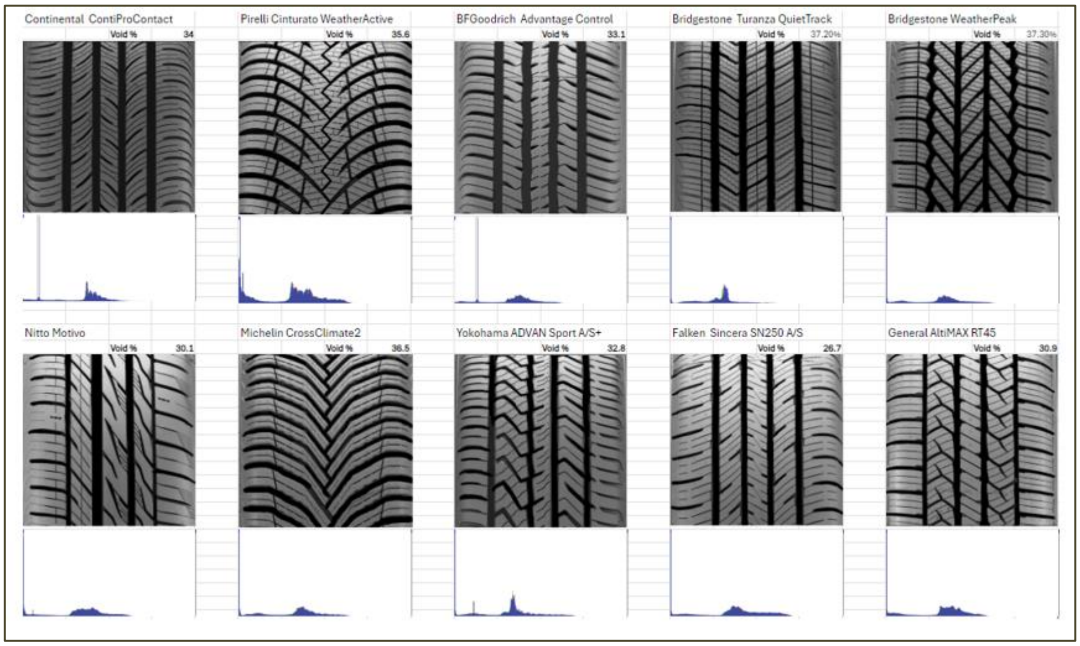

Figure 20. Void volume estimate with Python code and physical tire validation.

2.3 Task 2c: Identify Test Routes

Under this task the project team developed on-road test routes in and around Riverside, California. The team selected test routes to provide a representative mix of driving, with a focus on vehicle operation modes deemed important to evaluate for influence on brake and tire emissions. The development of test routes followed from the identification in Task 1 of factors important to capture for brake and tire emissions measurement and inventory development, shown in Table 7.

Table 7. Influential Factors Identified for Brake & Tire Emissions

Brake Factors	Tire Factors
• Braking intensity • Vehicle weight & class (car, light truck, delivery etc.) • Friction material (e.g., metallic, semi-metallic, NAO)	• Vehicle class (car, light truck, delivery etc.) • Vehicle operation • Ambient temperature • Tire size

Brake Factors	Tire Factors
• Powertrain (e.g., ICE, HEV, BEV) • Original equipment (OEM) vs. aftermarket • Axle	• Tire pressure • Season (summer, winter, all season) • Tire age • Pavement type • Road condition

For brake emissions, braking intensity is the one influential factor associated with vehicle operation. With regard to test route selection, this translates to braking frequency, braking force (i.e. gentle vs. aggressive braking), brake event duration (encompassing whether braking is to reduce speed in traffic or come to a complete stop), and speed of initial braking.

Test routes are a combination of geographic routes and traffic conditions. To capture a range of representative braking intensities, UCR developed the "Riverside Route" to represent typical near-urban driving (Section 4.0) – this is referred to interchangeably herein as the "City" route. It begins and ends at the CE-CERT facility and contains about 70 percent operation on urban and suburban surface streets, and 30 percent highway driving in the urban setting. The city driving component includes local, minor arterial, and major arterials with intersections requiring full stops. Though the Riverside Route includes some highway driving on a restricted access divided highways (CA-91 and Interstate-215), unique routes will also be developed to provide an extended drive under highway conditions.

For tire emissions testing, factors influencing test routes include vehicle operation, pavement type, and road condition. Vehicle operation needs to capture a representative range of acceleration, cruise, deceleration in city and highway conditions, as well as turning events. The Riverside Route provides urban operation and will be used for tire testing as well as brake testing. Use of the same route for brake and tire introduces the ability for direct comparison of the two sources.

As highlighted in the Task 1 literature review, high speed operation is expected to generate more tire PM emissions than low speed operation. The project team will test extended highway routes to ensure sufficient measurement at high speeds.

Controlling for pavement type and condition presents a unique challenge for tire sampling test routes. Caltrans monitors and reports on these factors for California's major roadways in the State of Pavement report. A state-wide summary of major road pavement type and condition from Caltrans State of the Pavement (SOP) 2020 report[50] is shown in Figure 21; 2020 was the latest version published by Caltrans at the time of this analysis, but significant differences in the current overall mix are not expected. Road material on California's network is roughly ¼ concrete and ¾ asphalt. Road conditions are "Good" for roughly half the network, "Fair" for much of the remainder, and "Poor" for a small percentage.

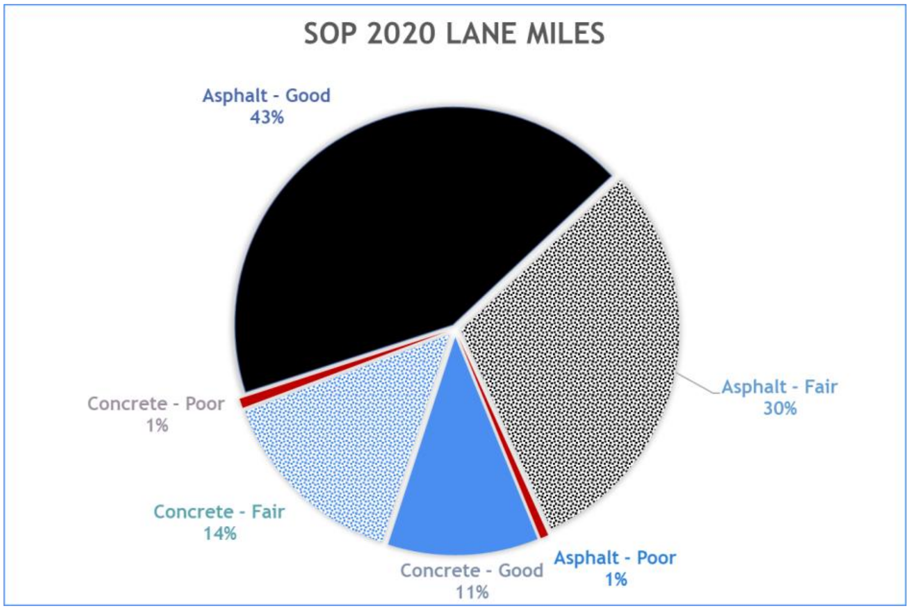

Figure 21. Material and condition of state and interstate highways.

Caltrans publishes Pavement Condition Reports (PCR) for California's highways which provide the pavement material and road condition by lane and direction for each lane-mile of road. These data were used to assess potential routes originating from near the UCR campus. After reviewing PCRs, the project team concluded that it would be possible to define highway routes with different pavement types, as major routes near Riverside are constructed with primarily Jointed Plain Concrete (JPC) or Flexible material (asphalt). However, the team concluded it would not be possible to control for pavement condition, as roadways are generally a mix of good, fair, and poor conditions. Therefore, the objective was to define highway routes with primarily concrete or asphalt material, each with a representative mix of condition according to statewide road conditions report in SOP. The project team assessed three candidate highway routes near Riverside: CA-60 between Riverside and CA-91 (Ontario); I-15 between CA-60 (Ontario) and I-215 (Murietta); and I-215 between Riverside and Murietta. Figure 22, Figure 23, and Figure 24 show PRC data for these routes. "L" and "R" refer to highway direction (L is Southbound, R is Northbound), shown for two lanes.

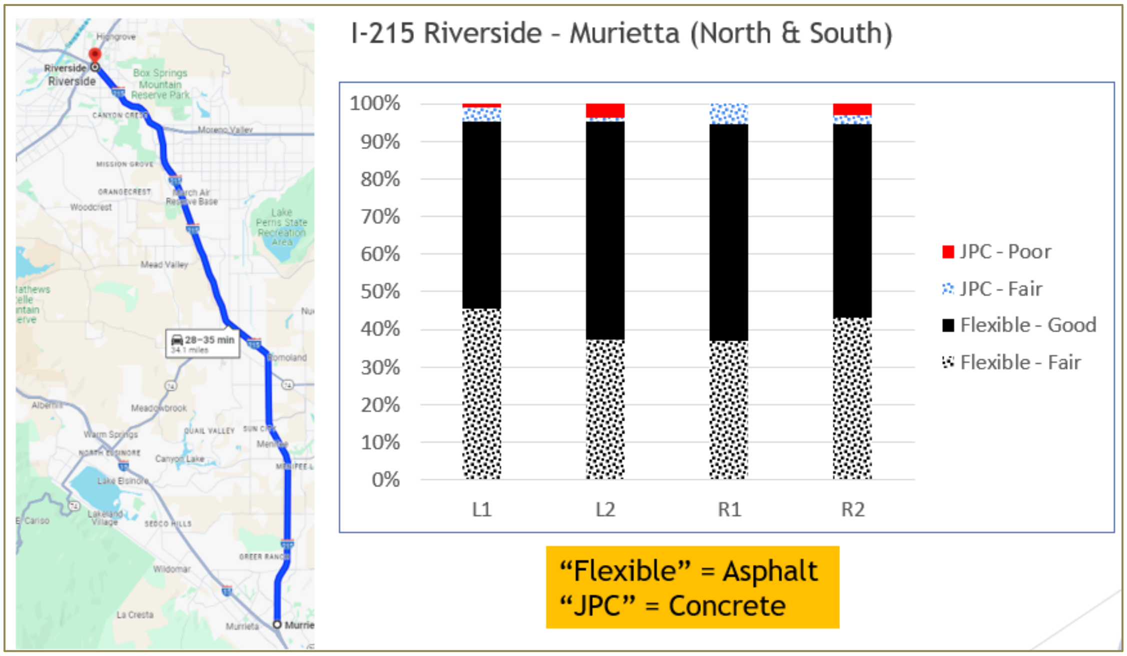

Figure 22. I-215 route.

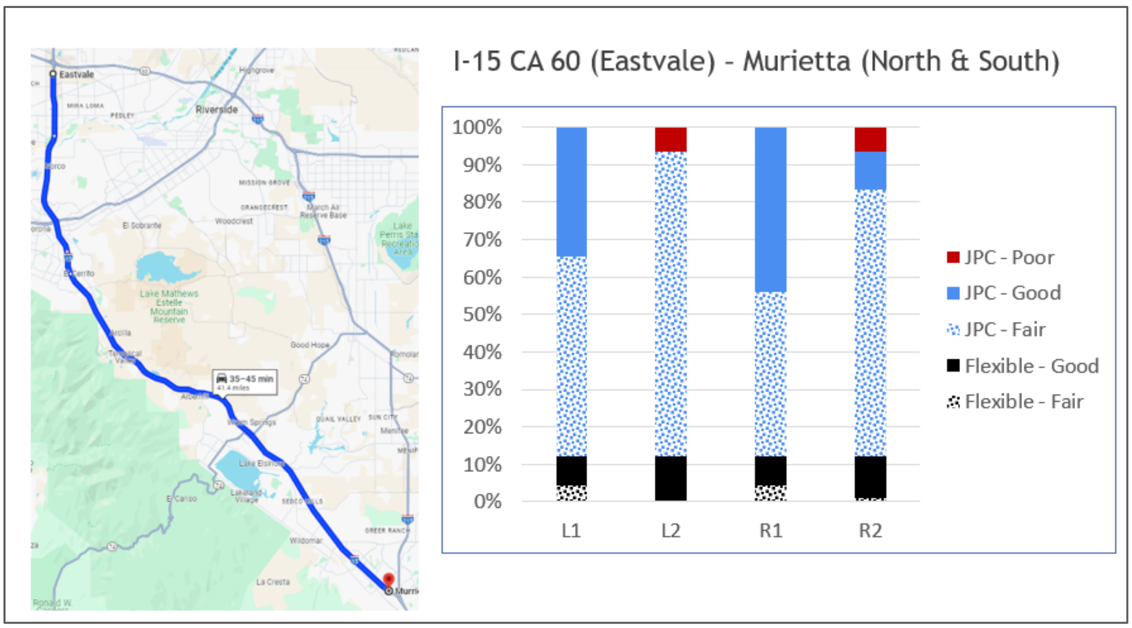

Figure 23. I-15 route.

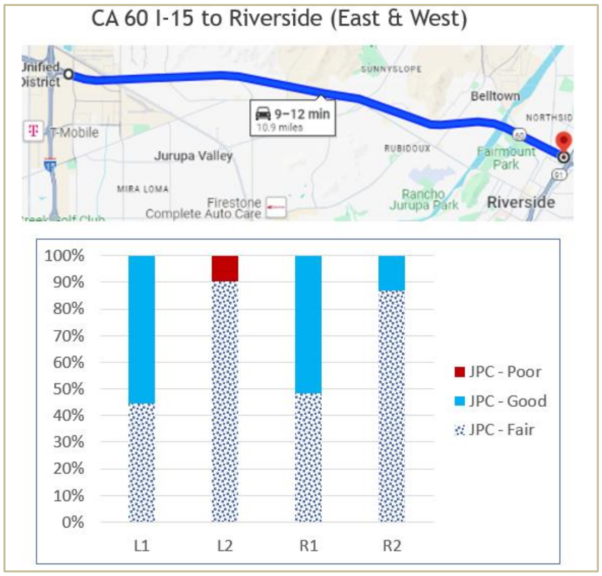

Figure 24. CA-60 route.

As shown, the CA-60 and I-15 routes are primarily concrete, while the I-215 route is primarily asphalt. Road conditions are comparable for both directions of each highway, and mirror the statewide distribution of majority "good" and "fair", with a small portion of "poor". Differences exist lane-to-lane, but controlling for lane on a test route is not feasible for safety reasons. An analysis of the overall mix of road conditions across different combinations of route found that the I-215 and CA-60 routes together produce a similar distribution of pavement material and road condition as the California statewide distribution. Figure 25 shows the combined attributes of the I-215 and CA-60 routes. The purpose of combining for analysis is to confirm that these routes will provide a mix of pavement material and condition representative of California's roadways. However, the two highways will be run as separate routes for a subset of tires to determine how pavement material influences tire emissions.

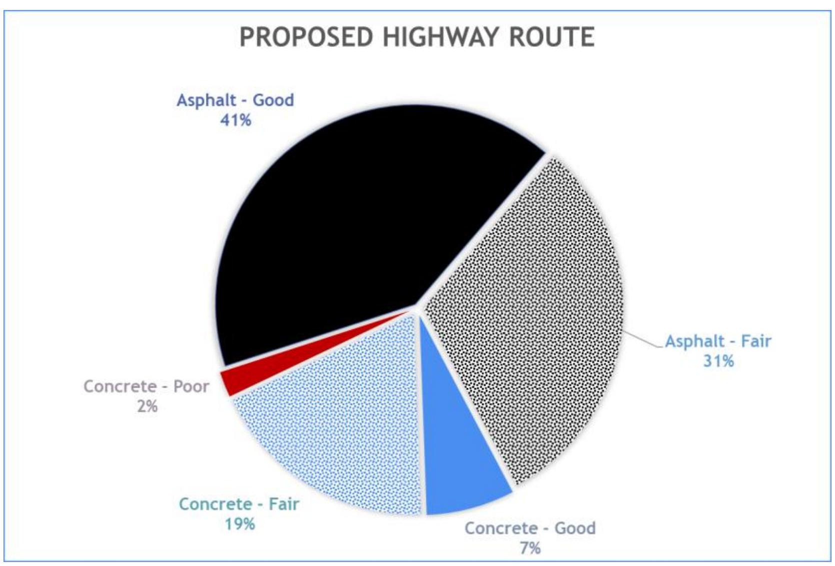

Figure 25. Road material and condition mix of combined I-215/CA-60 highway routes

Unlike the Caltrans data on California highways, comprehensive data on arterials, collectors, and local roads is not readily available at the local level, preventing a similar analysis to support a city driving route. CARB subsequently indicated to the project team that pavement material and condition were not important for defining a city route, relative to representing a range of vehicle operation. The Riverside Route will be used for city driving on tires as well as brakes, since the route includes a range of driving conditions and road types (e.g. residential to major arterials).

2.4 Task 2d: Design On-Road Sampling Method and Conduct Pilot Tests

Under this task, the project team designed and fabricated brake and tire emissions sampling systems from scratch, and conducted a variety of investigatory testing to help inform the design and ensure safety and functionality on the road. This section discusses the design and development process for brake and tire systems separately, the PM sampling system designed to measure gravimetric filter and real-time emissions, and emissions testing conducted to support these efforts.

2.4.1 Brake System Design

To develop an on-road system to sample brake PM emissions, the project team conducted literature research to understand what systems have already been developed for collecting and analyzing brake PM emissions. The team also conducted research on vehicle, operation, and brake characteristics that largely influence the creation of brake emissions for both LDVs and HDVs. Studies concluded the following characteristics were most influential:

- Braking intensity
- Vehicle weight
- Original vs. aftermarket equipment
- Friction material
- Brake Type
- Regenerative Braking; and
- Axle

Based on the information collected during the literature review, the project team determined that a fully enclosed system that encapsulates the caliper and brake rotor would be preferable to a partially enclosed system, as it would reduce the uncertainty in PM collection efficiency. The Ford[51] and AVL[52] partial enclosure systems showed promise for this work, but the project team was concerned about having external piping extend outward from the vehicle axle for safety and durability reasons. Of the full enclosure systems, the Swiss Federal Labs[53] system was intended for chassis dynamometer usage, leaving the very similar Ricardo and Ilmenau systems. The project team concluded that Ricardo’s Design A enclosure would be the best system to use as a basis for the design of our brake emissions collection device and had the benefit of having their staff on the project team to draw from that experience.

Ricardo's Design A is a fully enclosed system that includes an outer plate that rotates with the wheel and an inner drum that is stationary around the caliper. There is a single inlet and outlet to allow for introducing clean air and extracting the sample-carrying flow. To recreate this design for our test vehicle, the project team first took detailed measurements of the test vehicle brakes using

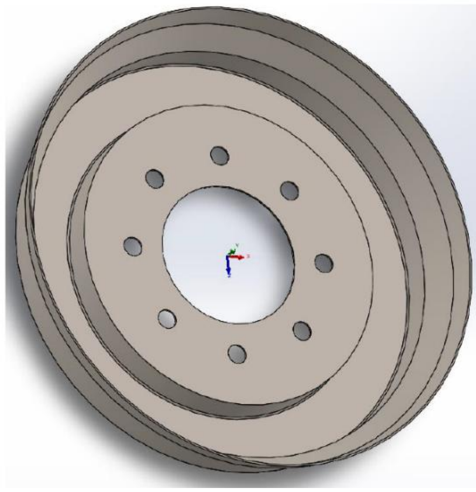

Figure 27. Rendering of the brake sampling system design (outer plate).

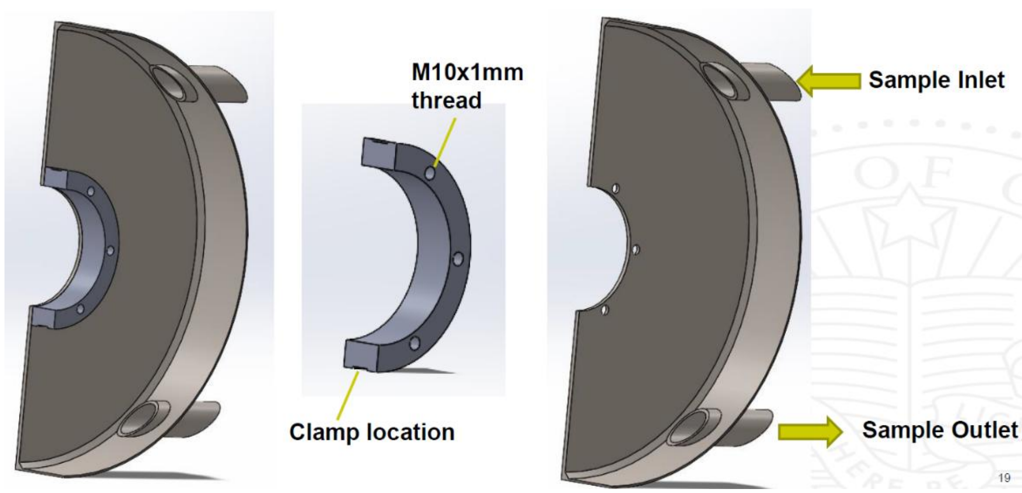

Figure 26. Renderings of the brake sampling system design (inner plate).

a three-dimensional (3D) scanner. The team then generated a design using computer-aided design and 3D printed a protype of the enclosure design to test the fitting and assembly. Once the prototype was fitted to the brake, the brake enclosure designs were simulated for static loading stress and then sent to be manufactured by a metal fabricator. Figure 26 presents a rendering of the finalized inner plate, and Figure 27 presents a rendering of the outer plate.

After fabrication, the project team installed the completed assembly onto the test vehicle. Initial shakedowns were conducted both on the chassis dynamometer and in low-speed driving in the parking lot of CE-CERT. During these evaluations, the project team observed for any interference or potential damage from taking turns or from driving over uneven surfaces. The design showed no apparent problems and was then deemed ready for pilot testing. Figure 28, Figure 29, and Figure 30 show the completed brake enclosure installed on the test vehicle.

Figure 28. Final fabricated brake enclosure system.

Figure 29. Final fabricated brake enclosure system.

Figure 30. Final fabricated brake enclosure system.

2.4.2 Tire System Design

As with the development of the brake sampling system, the literature review informed our approach to the existing tire emission sampling system concepts, the pros and cons of each system, and the factors that are important to consider when designing such a sampling system.

Through our research, our team found that there were two main sampling techniques used to analyze tire PM emissions. The first type of system collects samples of PM emissions to determine the physical and chemical characteristics of the particles using chemical analysis irrespective of sampling efficiency, while the second type of system aims to collect all (or a large majority of) the PM emissions from the tire and then uses a mass balance estimation to determine the total quantity of PM emissions.

While there are multiple systems that have been developed to utilize the mass balance technique, the team concluded that the Michelin design[54] was best suited for use as a starting point to this project's tire sampler design. Initially, our team considered a low, wide probe of the type used in the Ricardo design, but that design has a relatively low sampling efficiency, with high uncertainty in its estimate. Our team also considered the Continental method[55], which required doping the test tires with tracer chemicals. Upon further consideration, the project team determined this method was not feasible for this project, as our project focuses on testing multiple tires that are representative of those in use by the on-road fleet (and, even if doping tires were feasible, it would introduce uncertainty in the tire wear rate). As a result, the Michelin design with its relatively high sampling efficiency served as a basis for the new design developed in this work.

The Michelin design utilizes three vacuums to catch all a high percentage of wear particles, Global Positioning System (GPS) + X/Y acceleration data loggers, an aspiration nozzle to induce airflow, and an ELPI+ device for real-time particle measurements ranging between six nm and 10 µm. During review of the design and initial tests, our team determined that the sampling efficiency could be improved by adding side walls and side panels to partially cover the sides of the tire. The project team also determined that, for this project, the multiple vacuum/nozzle aspect of the Michelin system would not be needed and that the new design would include only a single flow path. Another key change was the specification of a higher flowrate than used by Michelin, with the goal of maximizing sampling efficiency. Figure 31 shows the project team's improved design with added side walls and single sample outlet and Figure 32 presents the Michelin system.

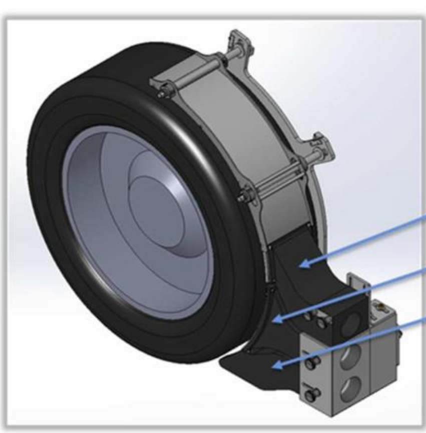

Figure 32. Michelin tire sampler design

Figure 31. Final project design with single outlet port and added side walls.

After computer designs were complete, our team then fabricated the tire emissions collection system. This semi-closed system covers almost half of the tire (designed for 245/75R17 tires) and is designed for a total flow collection in the range of 700-1,000 lpm. During fabrication, the project team took steps to file surfaces and connections make the inner surface as smooth as possible to minimize PM losses. Figure 33 shows the fully fabricated tire emissions sampling system.

Figure 33. Fabricated tire emissions collection system.

The system was mounted to the Chevrolet Silverado using a custom-designed and fabricated mounting bracket (Figure 35 and Figure 36) affixed to the rear axle to allow movement of the sampling system along with the wheel over bumps in the road. The final installation is shown in Figure 34.

Figure 34.Tire system installed on test vehicle

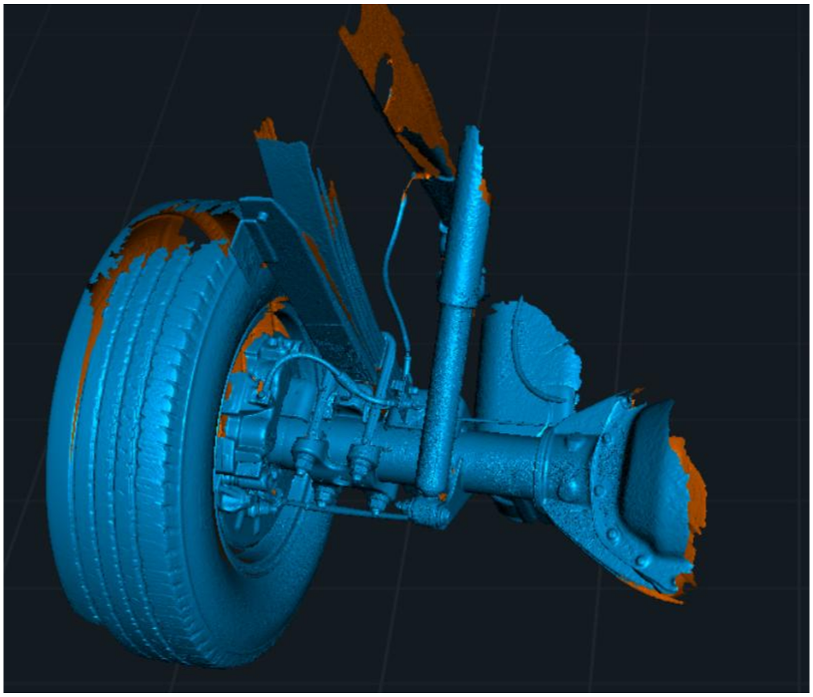

Figure 35. Tire mounting bracket fixture point.

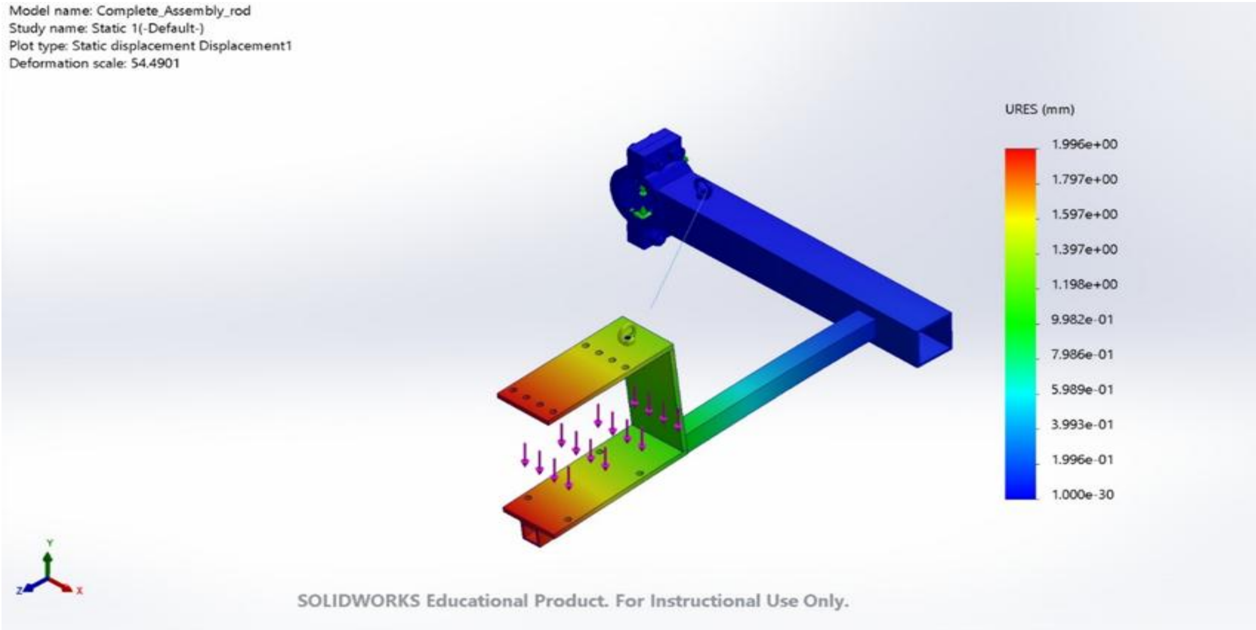

Figure 36. Tire mounting bracket design.

2.4.3 PM Sampling System

To collect and analyze emissions collected from both the brake and tire collection systems, our team developed a sampling system that transports the collected PM to the point of analysis. To accomplish this goal, our team designed and fabricated a sampling tunnel that could be connected to both the tire and brake collection systems. This sampling system, shown in Figure 37, can be attached to both the brake and tire collection system. When connected to the brake system, the sampling system introduces clean air through a blower to induce airflow across the brake enclosures, which then pushes the emissions to a sampling tunnel where various data loggers are connected to analyze the PM emissions. The clean air blower is not required when connected to the tire sampling system. The measurement devices include an APS, TSI DustTrack, ELP+PN/PM 6nm, and both PM10 and PM2.5 filter holders for gravimetric and chemical analysis. The total sample draw for filters and analyzers is in the range of 300-600 lpm.

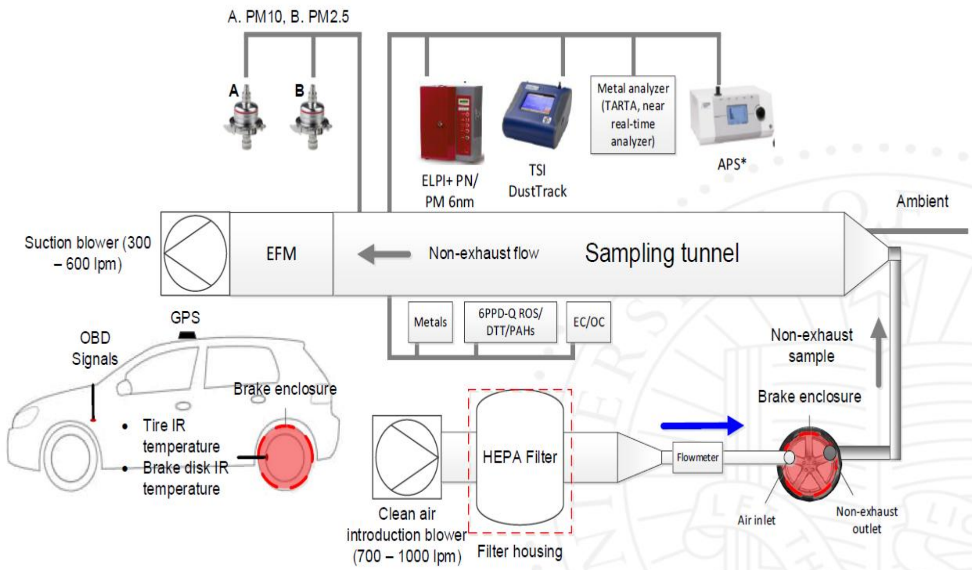

Figure 37. Schematic of the PM emissions sampling system.

Figure 38 presents a schematic of the major components that will be used during testing. This includes the emission analyzers, the tunnel and blower layout, the batteries, and the electronics such as the pressure, temperature, onboard diagnostic and GPS sensors and dataloggers.

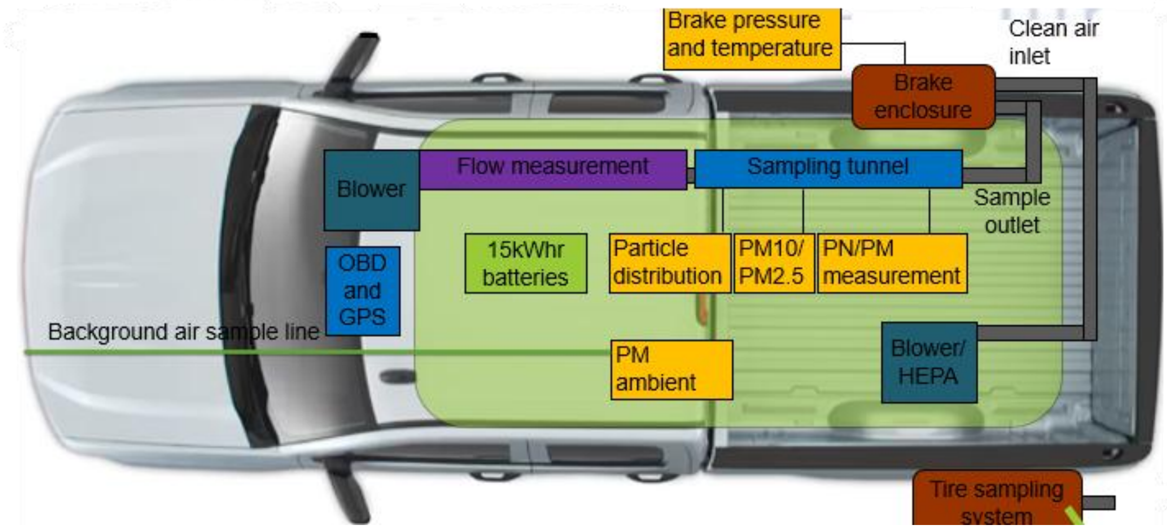

Figure 38. Brake and tire sampling system diagram.

2.4.4 Pilot Testing

To provide an initial evaluation of the brake and tire sampling systems, the project team conducted pilot testing consisting of chassis dynamometer measurements of the PM emissions from the brakes and tires. Pilot testing took place in two phases. the initial evaluation of only the PM sampling system (see Section 2.4.3), and the second evaluation of the complete system including the point of sample components. The initial phase of pilot testing involved chassis dynamometer operation of both a LDV and HDV to better understand the tire and brake parameters (i.e. temperature) during operation, to evaluate the responsiveness of the sampling system to different vehicles and modes of operation, and to inform any potential changes to the planned system designs. For the LDV evaluation, the project team ran 30 tests with three different vehicles (including the vehicle eventually used for on-road testing), and varied vehicle loads, sampling systems, tire conditions, measurement type, temperature states, and test cycles to collect and aggregate emission levels. These tests were run primarily using a simple funnel for tire sampling, to confirm that tire PM could be measured even with a simple system and a chassis dynamometer, but concluded with dynamometer tests using the final brake and tire sampling systems installed on the vehicle. Result confirmed ample tire PM, and provided insight into the influence of operation and tire condition on emissions. Through the tests, the project team determined that there were likely two main PN/PM generation regimes, which incorporated the mixing of aged and fresh-formed particles during accelerating and braking. During this testing, specific tires seemed to have different temperature thresholds where particle volatility is potentially higher than anticipated.

Analysis of the results revealed that the age of the tire and tire temperature were the most prevalent differences in tire emissions. While there was no clear trend in the number of emission particles between old and new tires, a clear trend did emerge showing higher emissions in older tires (Figure 39).

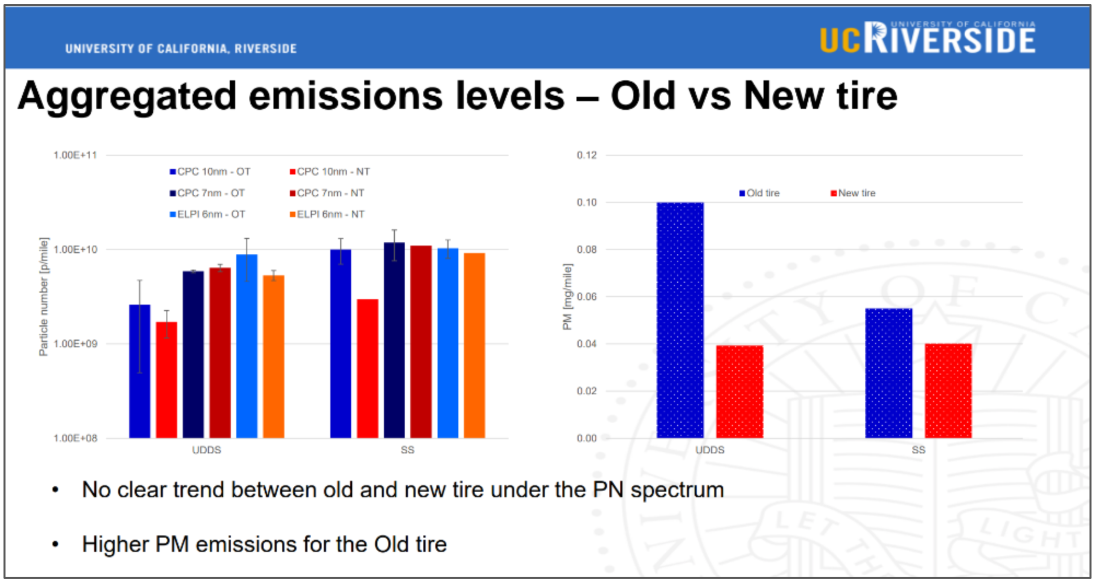

Figure 39. Old (Aged) vs. New Tire Emissions

More aggressive driving (US06 cycle) showed higher particle number and mass emissions, but a more particles of smaller size distribution (Figure 40).

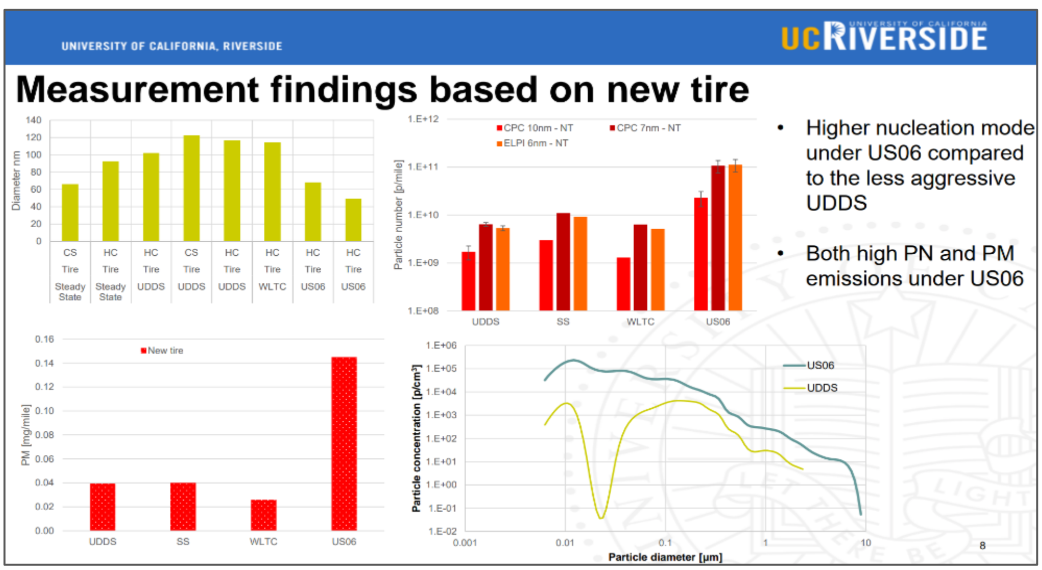

Figure 40. Effect of Aggressive Driving on Tire Emissions.

Our team also observed similar results when altering the temperature of the tires by increasing or decreasing the speed of the vehicles. Faster vehicle speeds and higher tire temperatures led to higher concentrations of particles. This trend was more prevalent for particle sizes between 10 nm and 310 nm and tended to be less impactful for particle sizes between 310 nm and 7,235 nm. Figure 41 presents the graphical results of the dyno tests with varying vehicle speeds and tire temperatures.

The project team also evaluated the operation of a HDV on the chassis dynamometer during the initial round of pilot testing. To better understand the release of PM from tires, a PM sample probe

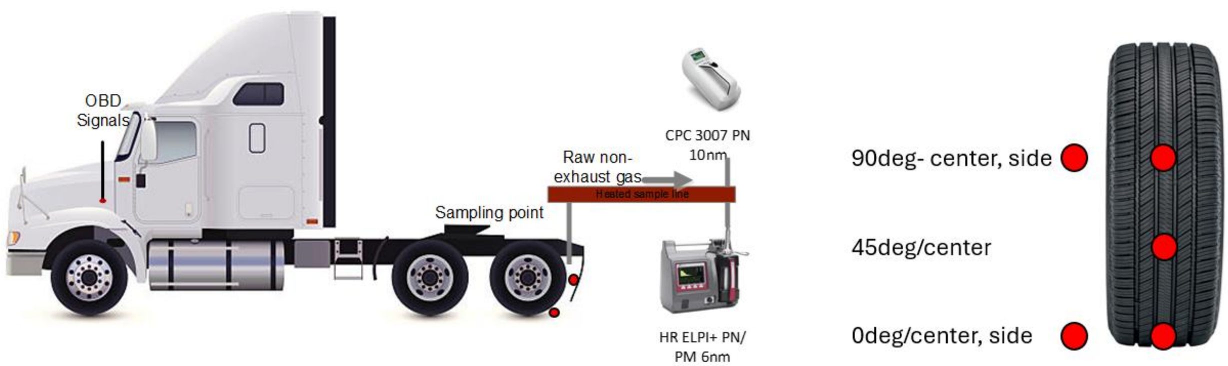

Figure 42. Schematic of HDV sample probe locations.

was placed at various locations behind one of the drive tires, and trends in collected PM were

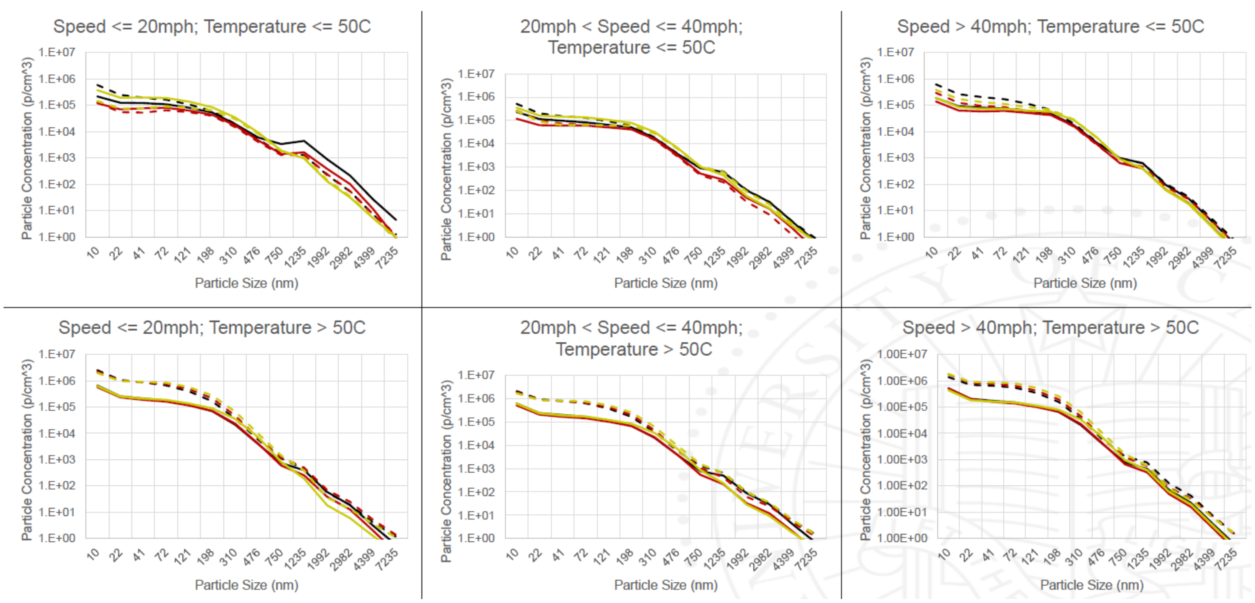

Figure 41. Particle size concentrations for varying vehicle speeds and tire temperatures.

compared. The HDV tractor was a useful test platform for this experience due to the open nature of the rear drive wheels. Figure 42 presents the probe locations.

The HDV testing helped inform the design of the tire sampler by indicating the relative prevalence of PM traveling upwards with the tire tread behind the contact patch. Figure 41 presents the observed PM concentrations for the various locations. Though Project 22RD002 will not test a HDV, this element of the pilot testing verified that tire sample can be collected from operation on a chassis dynamometer roll and that tire particles do emerge from different parts of the tire. This information helped inform the need for a tire sample design which captures PM emissions along the vertical face of the tire, along with the sides.

The project team conducted the second phase of pilot testing prior to the commencement of the main test matrix in Task 4. During this phase, the brake system and tire system were installed on the test vehicle, and the project team operated the vehicle over multiple chassis dynamometer test cycles with all emissions analyzers and sample collection systems in operation. The systems did not experience any functional problems and no damage to the test vehicle or equipment took place. The emissions analyzers were responsive to the PM collected, and the filter system collected measurable amount of sample. Figure 44 shows the test vehicle operating on the chassis dynameter during the second phase of pilot testing.

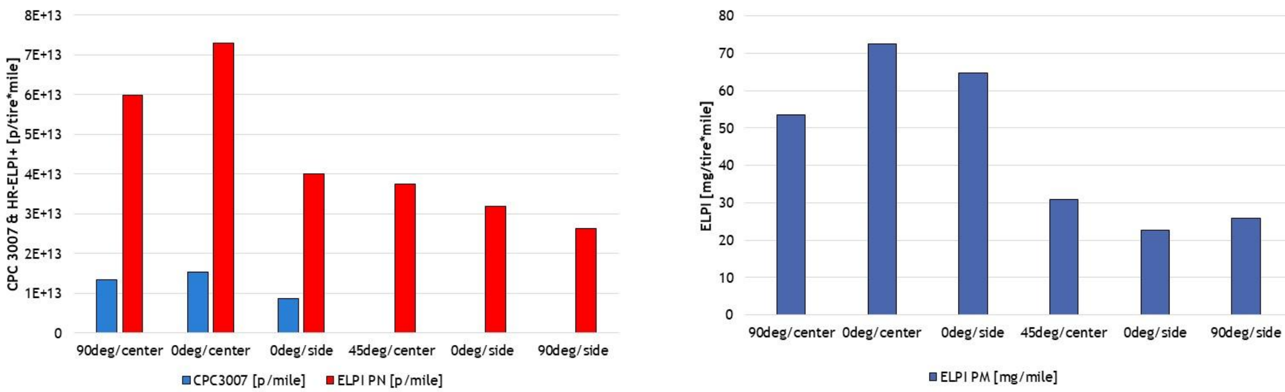

Figure 43. PM emission concentrations observed at various probe locations behind the HDV tire.

Figure 44. The fully instrumented test vehicle operating on a chassis dynamometer during the second phase of pilot testing.

3.0 TASK 3: ON-ROAD TEST PLAN

Under Task 3 an on-road test plan was developed based on the findings of prior tasks. The Literature review informed the project team's approach to the system design. The disc brake enclosure developed in this work in Task 2c is a refinement of on-vehicle braking enclosures previously described in literature. The tire sampling system represents a more innovative design development over existing tire sampling systems, with a more complex collector design and a higher planned flowrate than comparable systems described in literature. The findings of the Task 2a Project Advisory Committee (PAC) meetings, the Task 2b Market surveys, and the Task 2c California Roadway Data and Test Routes all inform the development of the test matrices for brake and tire testing. This plan will first introduce the possible test factors that can be varied for each test and possible test levels within each.

This project will include non-exhaust PM testing of a light-duty vehicle (LDV). Because brake-PM testing will not be conducted at the same time as tire-PM testing, this test plan has a separate text matrix for brake and tire testing. In conjunction with CARB project staff and the PAC, the project team chose a 2012 Chevrolet Silverado 2500 as the test vehicle, a rear-wheel drive vehicle. This test vehicle was selected in part due to being readily able to accommodate the size and weight of all necessary test equipment. This vehicle belongs to CE-CERT and was available throughout the project for measurement, initial component fit testing, and emissions testing. Brake and tire testing were conducted on the driver side rear brake/tire of the test vehicle to reduce the complexity caused by the steering function of the front wheels. The test vehicle is equipped with front and rear disc brakes. The specified tire size for the vehicle is 245/75-R17.

3.1 Brake and Tire Test Matrix Development

The project team began the development of the test matrix by identifying potential test factors to investigate, along with their respective test levels.

3.1.1 Brake-Wear PM Test Matrix Levels

The following are the factors for the test matrix and their respective test levels considered by the project team for brake testing in this work:

Brake Pad Material

Project 17RD016, which involved testing of LDV brake components on a brake-dynamometer, identified the two main materials used in LDV brake pads, non-asbestos organic (NAO) and low metallic (LM). Project 17RD016 further divided the pad materials into original-equipment service (OES), indicating the single formulation that would be provided during dealer service of a given vehicle, and aftermarket (AM), indicating the range of materials available from auto parts suppliers. Modern OES materials are almost always NAO formulations, whereas AM parts could use either of the major material types. Ceramic and semi-metallic (SM) friction material will also be included for market share coverage, and to allow a comparison of new and aged material (ceramic only), since the test vehicle's as-received condition includes aged ceramic pads. Past research indicated that the effect of the rotor material is minimal; in this work, only the pad material will be considered as test levels, the rotors will be left unchanged.

Payload

The weight of a vehicle is proportional to the energy required for deceleration, so it may be of interest to evaluate the effect of vehicle weight on brake emissions. For the test LDV, the range of equipment that will be utilized in this work is likely to add significant weight during operation. However, additional weight could be added for the purpose of determining the effect of vehicle weight on measured brake emissions.

Roadway Type

The types of roads that are driven during testing can be further divided to better understand PM emission rates on different roadways. In this work, roadway type will be separated into representative mixed suburban driving and driving on highways that are entered and exited only from ramps. CE-CERT has developed the Riverside (aka City) Route, which consists of approximately 70 percent urban and suburban driving, and 30 percent highway driving in the immediate area around Riverside, CA to represent mixed driving. The UC-Riverside campus is close to two different restricted-access highways which will be used to represent highway driving; highway tests will include only minimal driving on surface streets before entering the highway's on-ramp.

Time of Day/Week

The time of day or week that testing is conducted will affect the likelihood of encountering heavy traffic. Testing will occur on weekdays, and since traffic cannot be strictly controlled for this will be treated as a random factor with test times spaced to include a mix of heavy traffic and free-flow traffic.

Repeats

Repeats of a given combination of test levels may be present in the matrix to improve the statistical significance of observed trends.

3.1.2 Tire-Wear PM Test Matrix Levels

The test factors and levels of the tire matrix will have some overlap with the brake test matrix, but the project team has considered more options for tire testing as follows:

Test Tires

Unlike with brake pad materials, there is no major material category available for the selection of test tires. The project team will consider other possible characteristics for selection of test tires, based in large part on the findings of the survey in Task 2b. Tire characteristics to vary in the selection of test tires can include:

- Cost
- Length of warranty - Time or mileage
- Intended season – All-season, summer, or winter

- Uniform Tire Quality Grading (UTQG) – Manufacturer-given values of treadwear life, traction, and temperature resistance
- Speed rating – The letter indicating the maximum speed for which a tire is rated
- Load rating – The letter indicating the maximum rated load of a tire; could additionally include "Light Truck" (LT) tires vs. other passenger tires
- Tread void volume – The percentage of a tire's tread area that is void, i.e. does not contact the pavement, as opposed to the percentage of tread area that contacts pavement
- Brand – It may be possible that the tire brand may trend with PM emission rates.[1]

Not all of these factors can be controlled for given the project scope. Some of these variables are well-correlated and can be represented by one variable (e.g. cost, warranty, and quality can be represented by cost). Other variables can be addressed by choosing the most representative option, e.g. all-season tires. In order to generate data which is representative of California vehicles and a range of PM-related emission rates, tire selection and testing protocol will account for the following factors:

Brand

Tires will be chosen across three top-selling brand "families" (Goodyear, Michelin, Bridgestone) plus an additional low-cost "off-brand".

Tire Cost

Tires will be selected across the low-, moderate- and high-cost ranges.

Tire Age

To evaluate whether emissions from tires change as they age and wear down, at least one tire pair will be a new and aged version of the same tire.

Payload

As with brake-wear PM, tests will be conducted with additional payload added.

Tire Pressure

The primary test level will be to inflate tires to the vehicle manufacturer's specified pressure. Though tire pressure may be influential per Task 1 findings, the test matrix scope is not large enough to have separate levels of tire pressure.

Roadway Type

As with braking, the project team will select routes from restricted-access highways or unrestricted access city routes.

Roadway Material

This may affect the PM emission rates from tires. The two main roadway materials considered in this work are asphalt- or concrete-based. For city routes, the project team does not expect to be able to select routes consisting largely of one type or another as surface materials can vary frequently in the urban environment. However, for restricted-access highways, our team has identified routes near Riverside that consist primarily of asphalt (I-215) or concrete (CA-60) surfaces, with pavement conditions representative of statewide conditions per the Caltrans State of the Pavement report.

Time of Day/Time of Week/Season

As with brake testing, all tests will be conducted on weekdays with test times varied to ensure a mix of traffic conditions. For tire testing, however, it may also be of benefit to conduct testing both cold start and warm start conditions to determine the impact on emission rates.

Repeats

As with brake testing, repeating test level combinations in the matrix will improve statistical significance.

Testing will also include provision for measurement of ambient PM and/or airborne road dust. For logistical, space, and budget reasons, the project team expects to drive the test vehicle separately for city and highway test routes sampling only for ambient PM sampled through the same inlet tube used for brake and tire sampling but exposed to to ambient air.

Table 8 presents the overall factors available for consideration in the development of the brake and tire testing matrices. The table shows that there are more factors relevant to tire testing; it is likely that there will be more tire tests than brake tests in this program because of this. Also, given the limited project scope, not all combinations of factors will be tested. All matrix combinations will be repeated at least once to improve statistical uncertainties.

Table 8. Master Test Matrix Factors for Brake and Tire Testing

	Test Comp-onent	Roadway Type	Roadway Material	Payload	Age (one pair)
Brake	OES-NAO AM-LM	City Highway	--	Normal Loaded	New Aged
Tire	A B C D E F	City Highway	Asphalt Concrete	Normal Loaded	New Aged

4.0 TASK 4: ON-ROAD TESTING

On-road testing was conducted from March through September 2025. Brake and tire testing were done sequentially, with brake emissions testing conducted initially followed by tire emissions testing. Background tests were conducted in the midst of brake testing. The same driver was used for all tests.

Instrumentation was identical for all tests, as detailed in Section 4.1.

4.1 Instrumentation

The instrumentation used in this work supported the measurement and collection of PM and PN, both continuously and in batch on filters.

- PM2.5 & PM 10 Filters: PM2.5 and PM10 mass emissions were collected onto 47 mm Teflon filters using stainless steel single stage filter holders (URG-2000-30FX-QCF). PM2.5 and PM10 emissions were sampled concurrently with stainless steel PM2.5 (URG-2000-30EHS-2) and PM10 (URG-2000-30EX) cyclones. Prior to testing, the 47 mm diameter 2 µm pore Teflon filters (Whatman brand) were stored in a climate-controlled space and were allowed to stabilize before pre- and post-test weighing. The filters were measured for net gains using a UMX2 ultra precision microbalance with buoyancy correction in accordance with the weighing procedure guidelines set forth in 40 Code of Federal Regulations (CFR) 1065.

- The DEKATI high-resolution ELPI+ was used for measurement of PN and particle size distributions (PSD). The ELPI+ has a measurement range of 6 nm to 10 µm. The instrument functions by charging particles in a corona charger, then size classifying them according to their aerodynamic diameter. Electrometers measure the charge at each impactor stage. A picture of the ELPI+ is presented in Figure 45.

- Real-time PM2.5 emissions were monitored with a TSI DustTrak DRX 8533. The DustTrak measures the particle mass concentrations at 1 Hz frequency using a light-scattering laser photometer technique.

Figure 45. The DEKATI ELPI+

Additional instrumentation measured brake temperature, flow rate, speed, and altitude. Brake thermocouples were placed through the rear of the brake pad approximately 2mm from the brake pad surface. Thermocouple measurements were recorded through the ELPI+. Efm (Flow Measurements) : The Dwyer Omega stainless steel pitot tube was used for measurement of flow. The pitot tube measures total pressure and static pressure of the sampling tunnel. Pressures are converted to flow measurements through a Sensors Inc. exhaust flow meter EFM2. Matlab Mobile (GPS): GPS is monitored through the position sensor of the Matlab Mobile app. The position sensor provides latitude °, longitude°, speed (m/s), and altitude (m).

Metals and trace elements were analyzed on a subset of PM2.5 and PM10 samples in duplicate using the XRF (X-ray fluorescence) technique, following EPA Method IO-3.3. The XRF method analysis included the quantification of sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), germanium (Ge), arsenic (As), selenium (Se), bromine (Br), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), molybdenum (Mo), palladium (Pd), silver (Ag), cadmium (Cd), indium (In), tin (Sn), antimony (Sb), barium (Ba), lanthanum (La), mercury (Hg), lead (Pb), and ruthenium (Ru).

4.2 Brake Emissions Testing

On-road testing for brake emissions was conducted over March and April 2025, according to the test matrix. The full brake emission test log is shows in the Appendix. The test matrix expanded on the factors detailed in Task 3 to include an additional set of brake friction material: a new version of the ceramic friction material initially installed on the truck. This provided a direct comparison of new and original (“aged”) friction material components that were otherwise identical.

Test matrix factors discussed in Section 3.0 were implemented as follows:

- **Brake Friction Material (Disc):** New Ceramic (Brembo P10072N), Aged Ceramic, Non-Asbestos Organic (NAPA Silent Guard), Semi-Metallic (Brake Best M1411).
- **Payload:** "loaded" routes added 850 pounds in the cab of the truck.
- **Test Routes**:
    - ***City Route*** is the Riverside Route discussed in Section 3.0, repeated two times per test for 25 miles of driving.
    - ***Highway Route*** is repeated runs of CA-60 between Exit 39 (Haven Ave.) and Exit 52B (Main St.). The route begins and ends at the UC Riverside campus with approximately one mile of urban driving before entering and after exiting CA-60.

Day and time were not controlled for during testing. Repeat runs were made for a subset of tests, in some cases multiple repeats were conducted.

With the exception of Aged Ceramic, all brake pads were purchased new and installed on the test vehicle "out of the box" without burnishing (break-in) procedures. This differed from the 17RD006 test protocol which burnished friction material for several hours prior to conducting emissions tests.

4.3 Tire Emissions Testing

On-road tire testing took place from June through September 2025. Test routes were the City and Highway (CA-60) routes used for brake testing for concrete, and a second Highway route on I-215 between Riverside and Murietta for asphalt. Test routes and statistics are shown in Figure 46 through Figure 48.

As described in Section 3.0, the test matrix design involved testing six production tires for the Chevrolet Silverado 2500 of size 245/75-R17. The tires included a new version of Firestone already equipped on the vehicle, providing a direct comparison of the same tire at different age intervals. Three tires were chosen from the other top-selling brand families in California: Michelin, Goodyear, and Continental. The final tire was chosen to represent a "budget" brand, and was selected from among the lowest cost options available Walmart (Waterfall). Details on the test tires are shown in Table 9. All tires listed have a width of 245 millimeters, aspect ratio of 75, rim diameter of 17 inches. Tire manufacturer "Tiers" are subjective measures of tire quality by brand from expert elicitation, with Tier 1 being the highest.

Table 9. Test Tires

Test Tire	Condition	Tier	Tread Depth (mm)	Estimated Void (%)	Mileage Rating (mi)	Tire Wear Index
Firestone Transforce HT	Aged	2	11	34.4	65,000	0.20
Firestone Transforce HT	New	2	11	34.4	65,000	0.20
Michelin LTX M/S2	New	1	10	30.1	70,000	0.17
Goodyear Wrangler Territory HT	New	1	9.5	26.7	60,000	0.20
Continental Terrain Contact HT	New	1	11	29.2	70,000	0.20
Waterfall Terra X H/T	New	3	11	39.6	45,000	0.27

The tire testing matrix is shown in the Appendix. Each tire was run over the Riverside (City), CA-60 (Concrete Highway) and I-215 (Asphalt Highway) routes. An additional run was conducted on the CA-60 route with 850 added pounds of payload. The original tire was tested in “as received” condition as it was already installed on the vehicle at the outside of testing. The other test tires were all purchased new and underwent a break-in period installed on the non-sampled rear tire of the test vehicle. The break-in period was nominally 100 miles for each tire. Tires were filled to standard pressure of 80 PSI before each test. All tests received at least one repeat, and in some cases two repeats.

Background tests were run for the City and CA-60 Highway Route. Emissions were sampled from the inlet to the PM sampling system at the bed height of the test vehicle.

- Average speed: 25mph
- Elevation: 254 – 468m
- Test Duration: 65 -80 minutes
- Distance: ~26 miles
- Max acceleration: 12.8 mph/s
- Max deceleration: - 11.4 mph/s
- Urban driving: 88% (22.7miles)
- Highway driving: 12% (3.1 miles)
- Road Type: 12% concrete; 88% asphalt

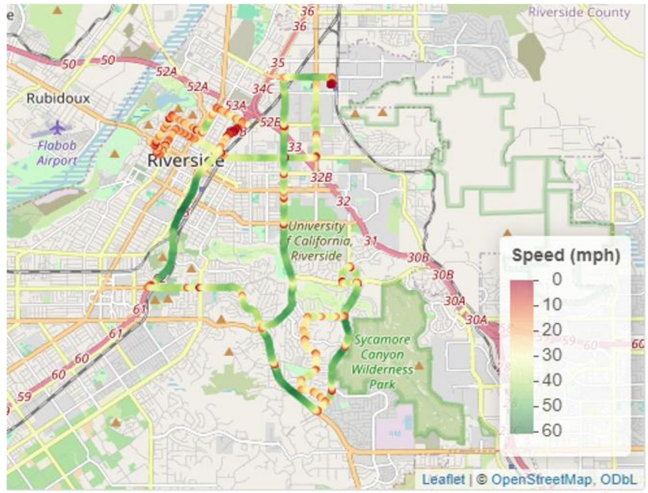

Figure 46. Test Route: City.

- Average speed: 47mph
- Elevation: 238 – 291m
- Test Duration: 70 -90 minutes
- Distance: ~ 56 miles
- Max acceleration: 14.7 mph/s
- Max deceleration: - 14.0 mph/s
- Road Type: Concrete

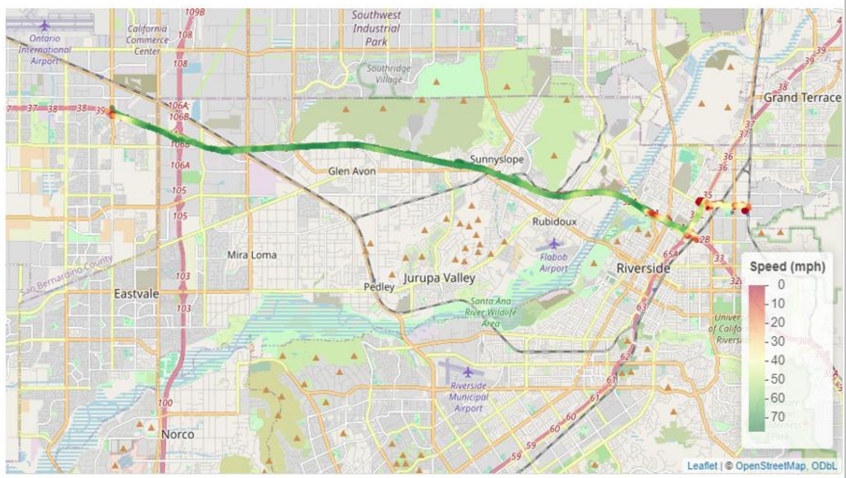

Figure 48. Test Route: highway CA-60.

- Average speed: 45mph
- Elevation: 281 – 474m
- Test Duration: 70 -90 minutes
- Distance: ~ 56 miles
- Max acceleration: 6.6 mph/s
- Max deceleration: - 8.22mph/s
- Road type: Asphalt

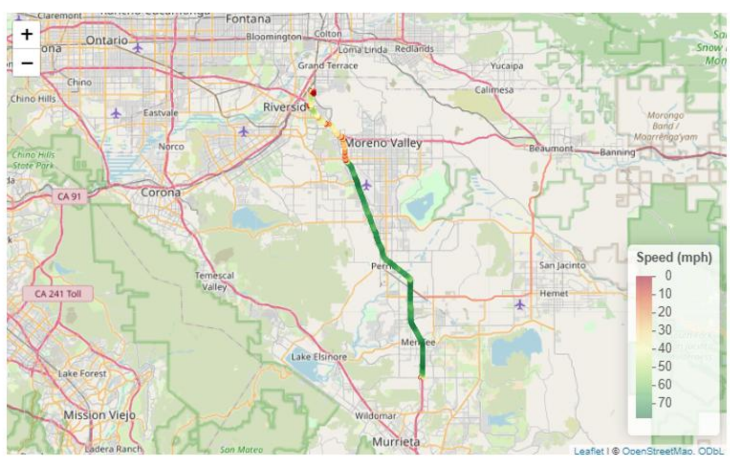

Figure 47. Test Route: Highway I-215

5.0 TASK 5: ANALYSIS

Task 5 encompassed summarizing raw measurement results, quantifying the collection efficiency (sample and transport) of the brake and tire measurement systems, conducting chemical characterization of PM filter results, performing source apportionment of on-road tire measurements to estimate the tire-only contribution, and applying these findings to estimate on-road brake and tire emission factors. The task concludes with a description of the open questions that remain after the completion of testing and analysis.

5.1 Task 5a: Raw PM and PN Measurements

Gravimetric PM results were calculated by weighing filters before and after each test. This section presents the raw values prior to correction for dilution, sampling efficiency, and collection efficiency (i.e. they are not emission factors). PM2.5 and PM10 filters were weighed and reported separately and reflect only the raw mass accumulated on the filter from each test. Corrections for sample dilution, collection efficiency, etc. are described in Section 5.1.3 with tire samples undergoing further analysis to determine the contribution of tire and other sources to the raw sample. Fully corrected emissions factors are presented in Section 5.4.

5.1.1 Raw Brake Testing Measurements

Figure 49 presents real time results from an example brake test on the Riverside route of the new ceramic pad. The measured brake disc temperature reached a maximum of approximately 200°C near the end of the test. In contrast, a typical maximum temperature reached on a highway test was approximately 105 degrees Celsius. The real time PN and PM traces indicate the nature of particulate emission over a test and the individual peaks show that most PM mass accumulates in individual high-emission brake events.

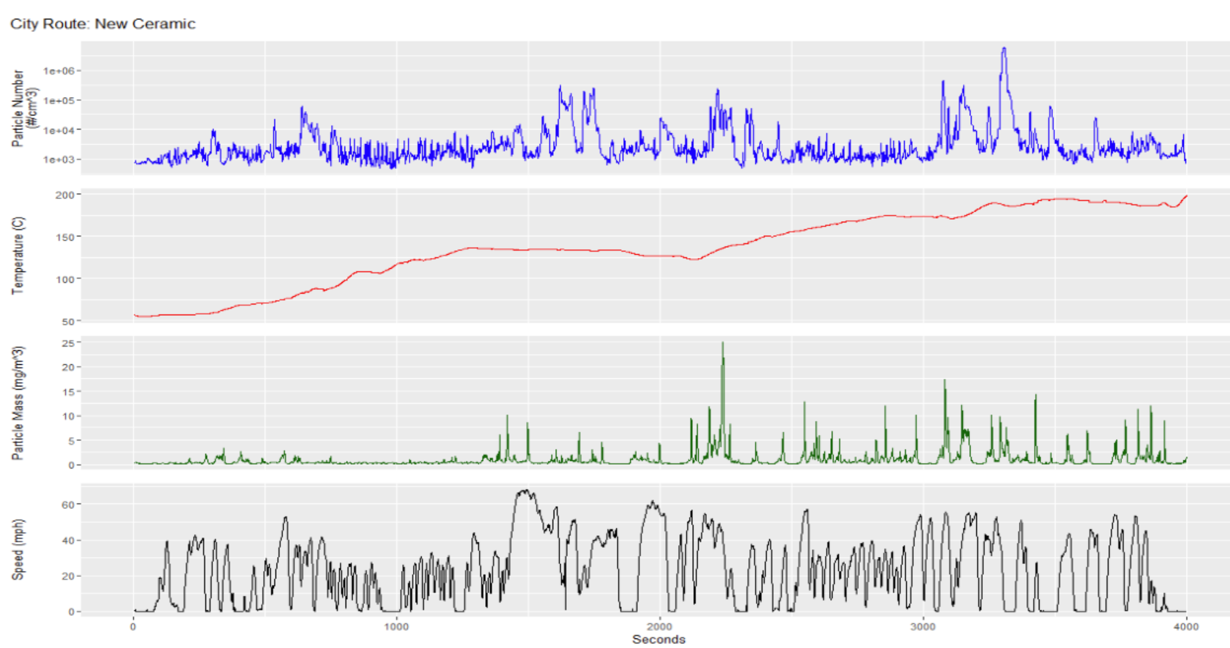

Figure 49. Selected real-time measurements from an example brake test of the new ceramic pad.

Each test included the sampling of PM2.5 and PM10 on separate filters for gravimetric analysis. Each filter was stabilized and then weighed three times before and after each test. Table 10 presents statistics on measured filter weight gains. The unloaded filters weighed approximately 123 mg. No brake filters experienced negative weight gain.

Table 10. Statistics on Brake PM Filters

Statistic	PM 2.5 Measurement (mg)	PM10 Measurement (mg)
Mean filter weight gain	2.495	4.898
Maximum filter weight gain	10.053	15.197
Minimum filter weight gain	0.053	0.757

Figure 50 presents the raw, uncorrected total PN measurements from the brake tests, average by route and pad type. Error bars present the standard deviation across tests. The total per-mile emissions averaged around 7.8x10[12] across tests. Particle counts are presented as measured by the ELPI+, and cover an aerodynamic diameter range of approximately 6 nm to 10 µm. Total particle number concentrations were obtained by summing counts in all impactor stages. The ELPI+ formed the basis for the sample and transport efficiency calculations, presented in Section 5.1.3, so further EPLI findings are presented in that and later sections.

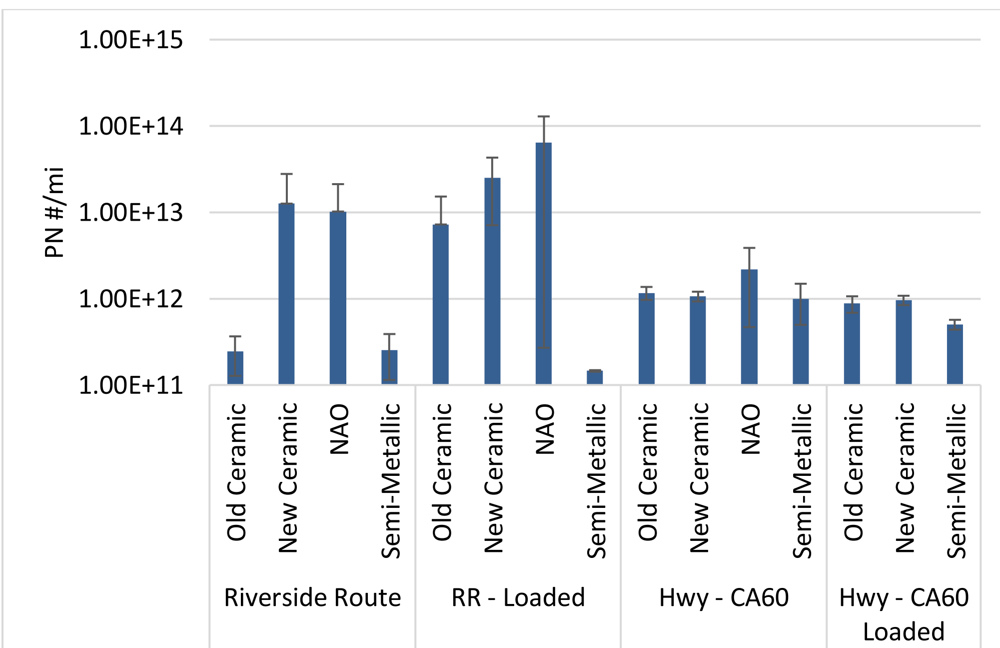

Figure 50. Raw total PN measurements for brake testing.

5.1.2 Raw Tire Testing Measurements

A summary of raw filter mass results by tire and route is shown in Figure 51. These are the direct results observed on the PM filter without correction for collection efficiency or separation of tire-

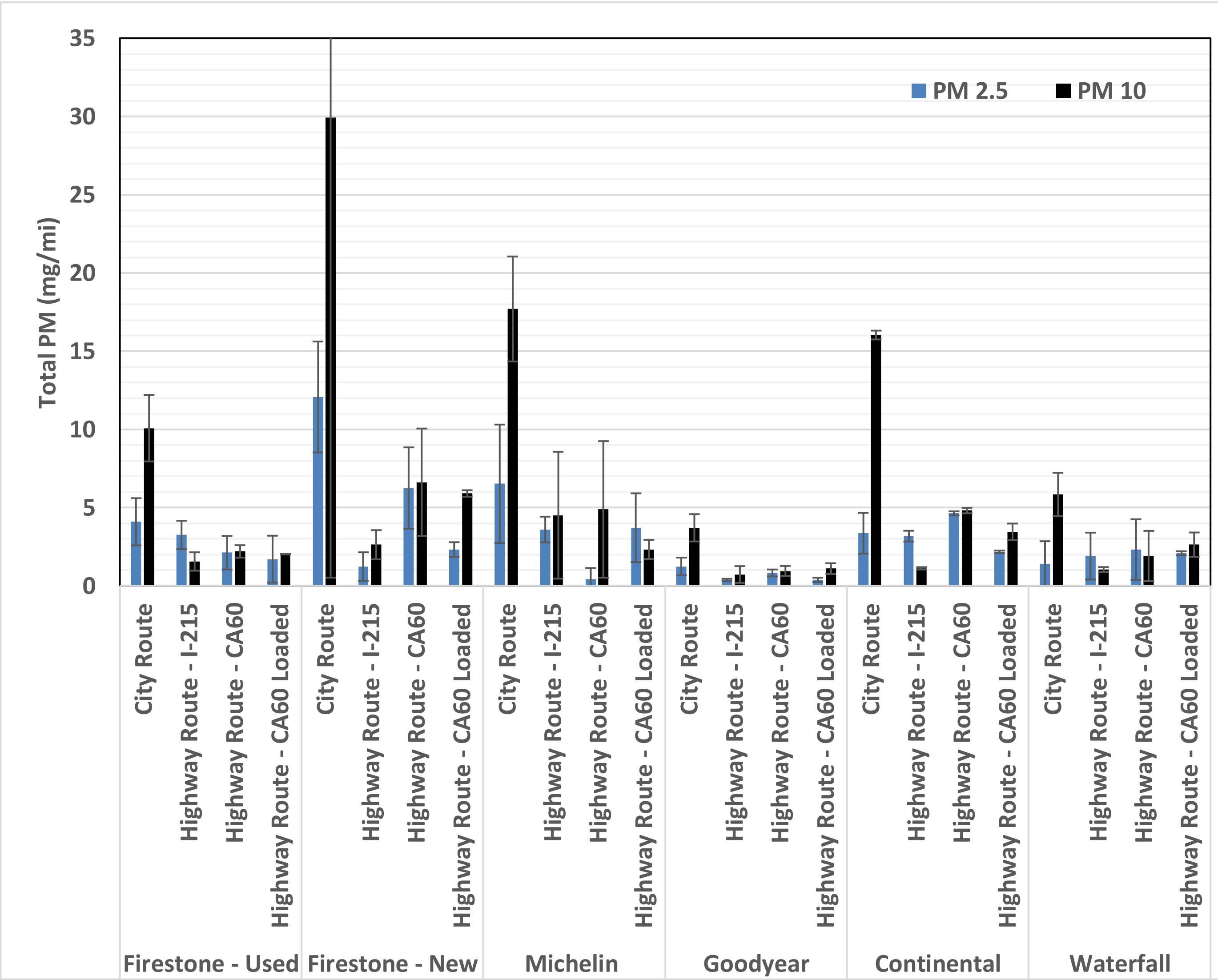

Figure 51. Raw PM Mass from On-Road Tire Tests (Error Bar = Std Dev)

only emissions from other potential sources on the road – e.g. entrained dust, road particles, exhaust etc. Key observations from the raw data include:

- PM mass from the city route is generally higher than highway routes, especially for PM_{10}.
- Tests with the new Firestone tire display the highest results for the city tests, but mixed results for the highway test.

Statistical analysis of tire results are discussed in the context of corrected emissions in Section 5.3

Table 11 presents statistics on measured filter weight gains. The unloaded filters weighed approximately 124 mg on average. Of the 108 filters deployed in tire testing, one experienced a negative weight gain (shown in the table).

Table 11. Statistics on Tire PM Filters

Statistic	PM 2.5 Measurement (mg)	PM10 Measurement (mg)
Mean filter weight gain	1.04	2.67
Maximum filter weight gain	4.75	18.42
Minimum filter weight gain	0.11	-0.16

Raw, uncorrected PN counts from tire testing are shown in Figure 52. Measurements are averaged across combinations of tire and route, and error bars depict the standard deviation across tests. Measured particle numbers averaged approximately 7.3×10^{10} and ranged from approximately 3.2×10^{10} to 2.1×10^{11}. As with the brake results, the ELPI+ measurements of the tire PM served as the basis for correction for collection and transport efficiency as described in the next section.

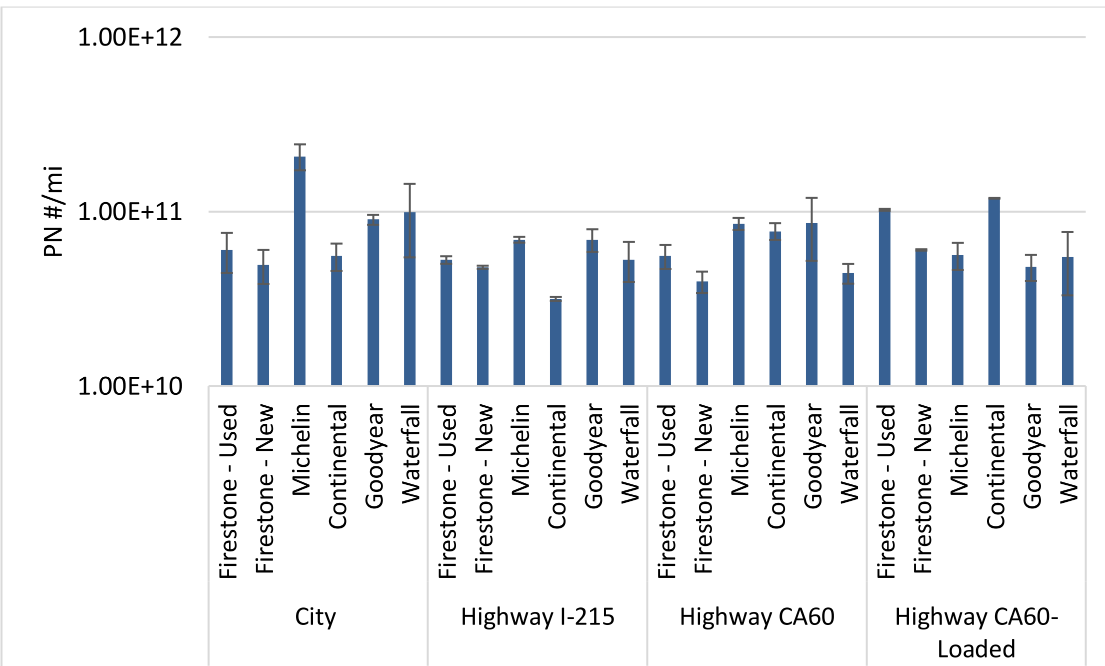

Figure 52. Raw total PN measurements from tire testing

5.1.3 Collection Efficiency Analysis and Corrections

The raw PM observations presented in the previous section were "as measured" by the instruments sampling from the system's main tunnel. This section describes the experiments and calculations used to estimate collection and transport efficiencies so that emission rates can be estimated at the point of the friction interfaces. In this project, the collection efficiency is relevant primarily to the tire sampling system and represents the fraction of total emitted particles that enter the inlet of the sample collector probe. The transport efficiency accounts for the particle loss rate from the point of initial entry to sampler through the transfer tubing and downstream through the tunnel to the system's point of sample feeding the instruments and filters.

To estimate collection and transport efficiencies, the project team developed an experiment using particle generators emitting near the friction interface and measured the recovery rate in the tunnel's sampling point. For most experiments, a miniCAST 5201 soot generator was used to generate the particles used in the recovery experiment. In a subset of experiments of the tire system, a novel fluidized bed generator (FBG) was used to generate particles. The particle generators were used to inject stable and reproducible (in terms of rate and size distribution) PM aerosol upstream in the sampling system. Experiments were conducted separately for the brake system and tire system and generally took place in two stages. First, the ELPI+ was set up to measure directly at the outlet of the particle generator, which would serve as a baseline for the measurement of what was being injected upstream. Then, without changing the settings of the particle generator, the ELPI+ was set up to measure at its actual tunnel measurement location in the on-board test location. Finally, the ELPI+ was moved back to the original baseline location to verify drift. The difference between what was injected and what was recovered informed the sample and transport efficiencies.

Brake System

Because the brake system is closed to ambient air and all inlet air is assumed to convey the particles into the sample tunnel, the collection efficiency of the brake system is assumed to be unity and only the transport efficiency is applicable to these measurements. The project team conducted the miniCAST recovery experiment by injecting the generated soot into the brake enclosure and measuring the recovery in the tunnel's point of sample. The experiment was conducted with the test vehicle operating on a chassis dynamometer at wheel speeds of 25 mph, 45 mph, and 65 mph. As an example of the findings, Figure 53 presents the experimental efficiency data for 25 mph. The ratio of the recovered particle counts to the injected particle counts represents the overall transport efficiency at that size range and wheel speed.

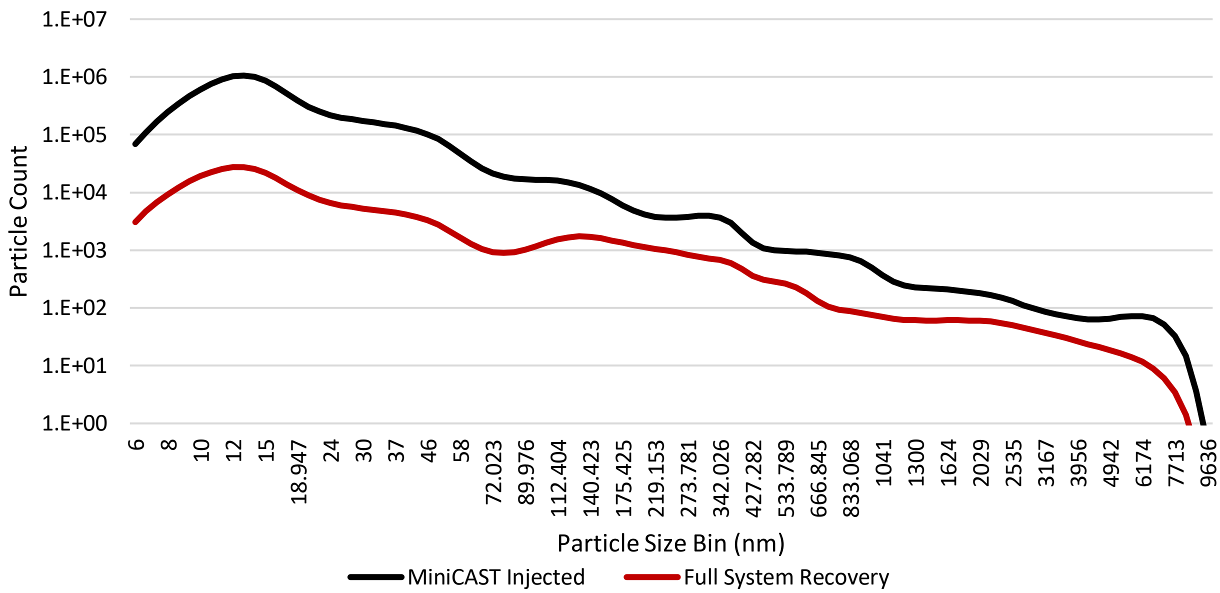

Figure 53. Injected and recovered particle counts during brake efficiency testing at wheel speed of 25 mph

Figure 54 presents the calculated transport efficiencies at 25 mph, 45 mph, and 65 mph, along with the average size distribution of the injected PM.

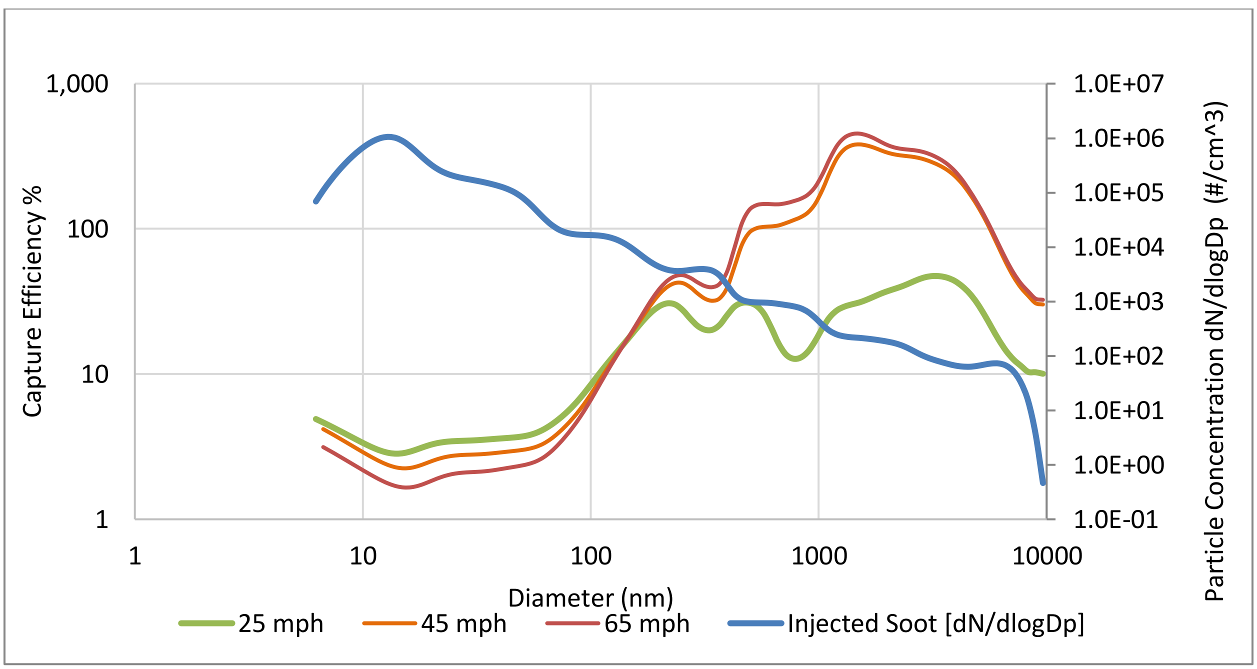

Figure 54. Size distribution of injected particles and brake system transport efficiency at various speeds.

Tire System

Evaluating the overall sample efficiency of the tire sampling system is more complicated than for the brake system because the tire sampler is open to the atmosphere. Because of this, the collection efficiency is less than 1, though downstream of the sample inlet, the transport efficiency is likely to be very similar to that of the brake system. However, to manage the complexity of the efficiency evaluation, the experiments were designed to estimate the collection and transport efficiency together, not individually.

The project team evaluated the tire system collection and transport efficiency together in a two-part experiment. The tire system included the use of an FBG, in which clean air is forced upward through a small hopper of fine particulate[56]. The FBG, if loaded with a consistent particulate powder, results in a relatively steady flow with consistent particle concentration and size distribution. In this work, the project team loaded the FBG with A4 coarse test dust meeting the ISO 12103-1 standard. By using this material, the FBG could complement the size distribution of the miniCAST; with most miniCAT particles smaller than approximately 1 micron and most FGB particles larger than 1 micron.

The efficiency evaluation experiments were conducted by injecting the particle generator flows just behind the tire/dynamometer roll interface with the vehicle installed on the chassis dynamometer. These experiments were conducted at zero wheel speed to prevent contamination from tire wear. The experiments were calculated similarly to the brake calculations, with the ELPI+ used to measure the characteristics of the generated particulate flows and then the downstream recovered flow. Efficiency calculations were then performed similarly to those for the brake system by determining the differences in collected particulate across the size range. However, due to the complimentary nature of the two particle generators, the efficiency curves were then calculated piece-wise across the size distribution, with the miniCAST used at the small end and the FBG at the larger end. Figure 55 presents the calculated overall sample and transport efficiencies. It can be seen that the two systems tend to agree in the location where they overlap around 750 to 1000 nm. The overall efficiency tends to be lower for the tire system than the brake system at most size ranges, primarily due to the open nature of the sample probe.

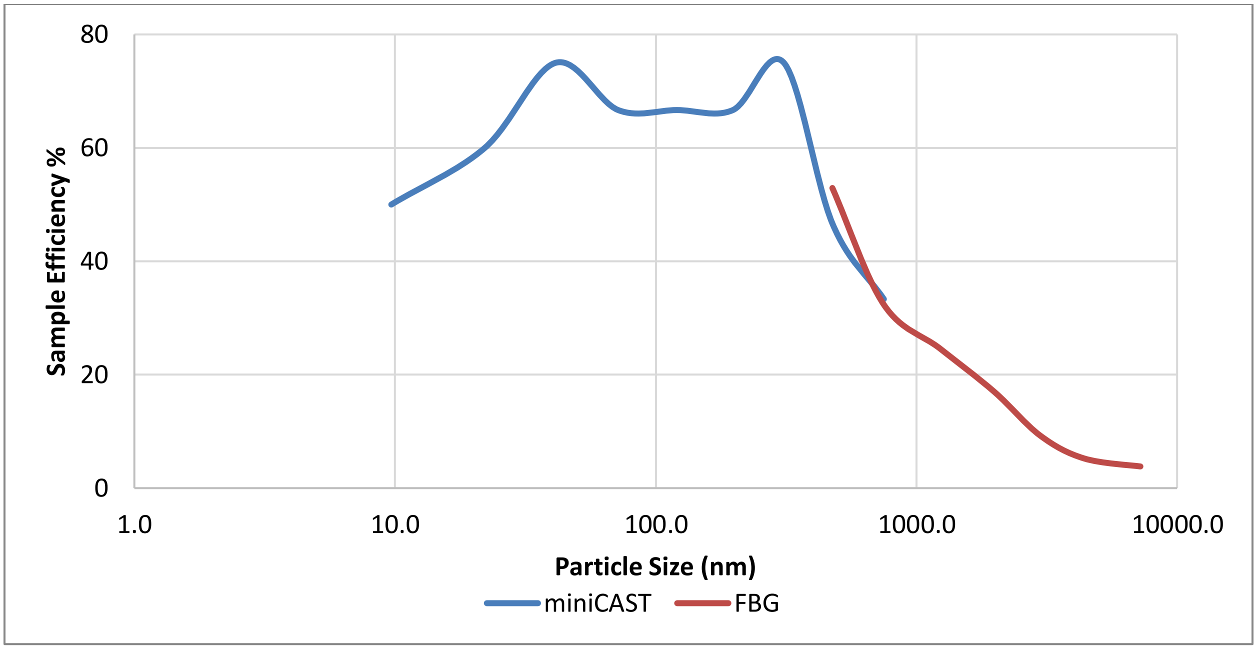

Figure 55. Size distribution of injected particles and tire system transport efficiency at various speeds.

The overall sampling efficiency curves for each of the two systems then formed the basis for corrections. The project team applied the calculated efficiencies differently for various measurements:

- Brake mass – Not corrected as efficiency is relatively high and very dependent on specific speed. Emission factors presented in 5.4.1.
- Brake PN and PSD – Both corrected on a 1s basis based on binned vehicle speed. Speed was binned into the three bins corresponding to each experimental wheel speed.
- Tire mass, PN, and PSD – Corrected by an average efficiency level taken across the size distribution ranges separately for PM2.5 and PM10.

5.1.4 Processed Brake Emission Measurements

This section presents the single-wheel brake emission rates, adjusted where applicable for the system's transport efficiency. Figure 56 presents the average rear-wheel PM emission rate, averaged for combinations of pad material, test weight, and test route. Error bars represent the standard deviation in results across all tests of the given combination. Emission rates are presented on a per-mile basis and directly represent total measured emissions divided by total distance traveled. In general, the Riverside routes, for both standard test weight and loaded, have the highest emission rates. The new ceramic material tended to have the highest emissions as measured, and the NAO material tended to have the lowest emission rates.

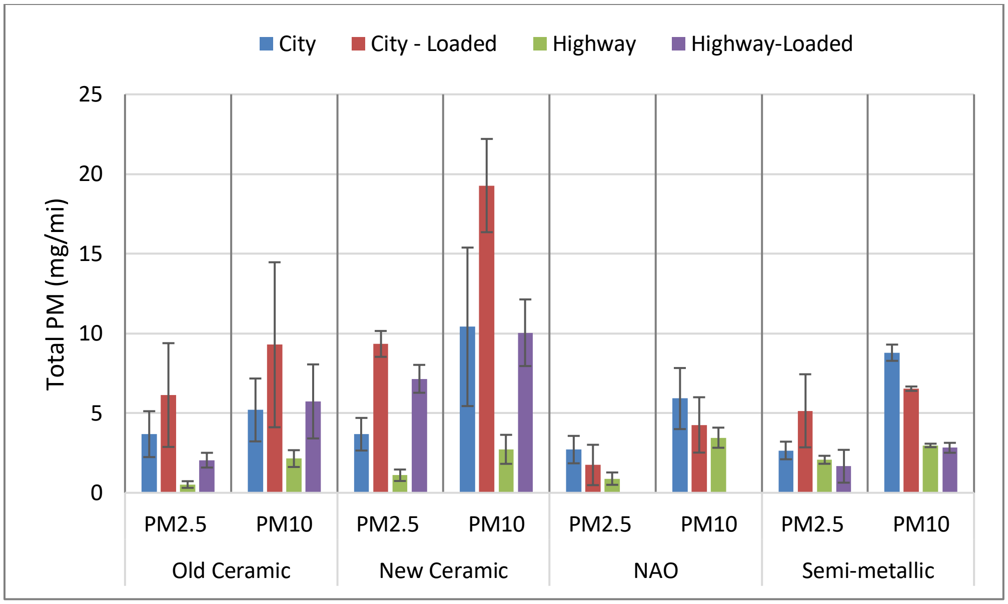

Figure 56. Average rear-wheel PM emission rates by pad material, test weight, and test route

Figure 57 presents the total PN emission rates for the single measured rear brake of the test vehicle, corrected for transport efficiency in the brake system. Emissions are averaged within each group by pad material, test route, and weight loading. Error bars represent the standard deviation in the results across tests. As described previously, counted particles cover an aerodynamic particle size range of approximately 6 nm to 10 µm. The average calculated emission rate in this size range is approximately 3.1 x 10^{14} per mile.

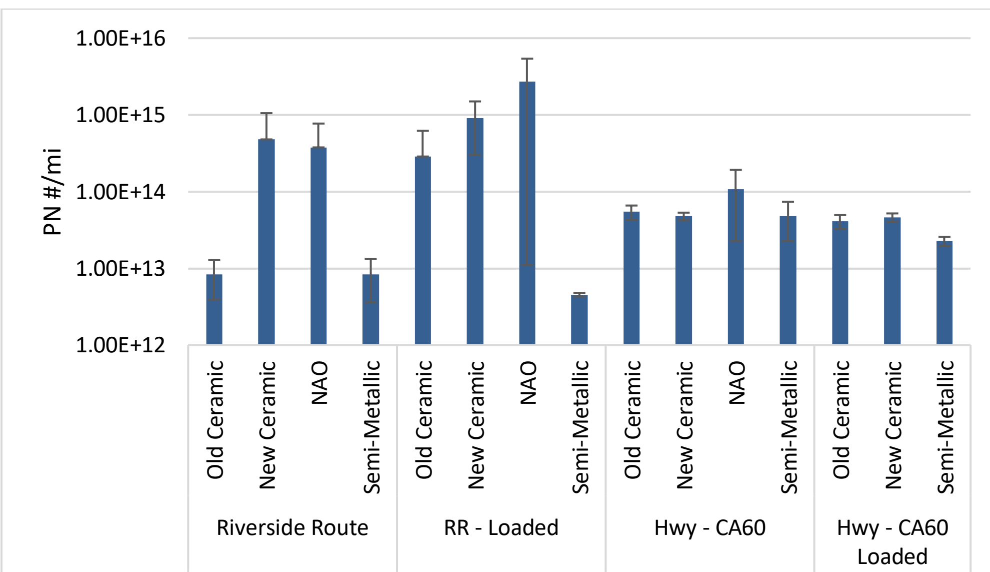

Figure 57. Corrected total PN emission rates from brake tests, averaged by pad material and route.

Brake particle size distributions are presented by test route and vehicle loading. Figure 58 presents the corrected particle size distribution for standard-weight tests over the Riverside route. The size distributions are corrected based on the observed transport efficiency described in the previous section. Particle counts are normalized to sum to unity. The maximum counts occur around 7 nm in size, with a secondary peak around 40-50 nm. Peaks are also observed at about 350 nm and 0.5-1 µm. The semi-metallic distribution is shifted more towards larger particles, whereas the NAO tends to have the lowest count of particles in the 1-10 µm range.

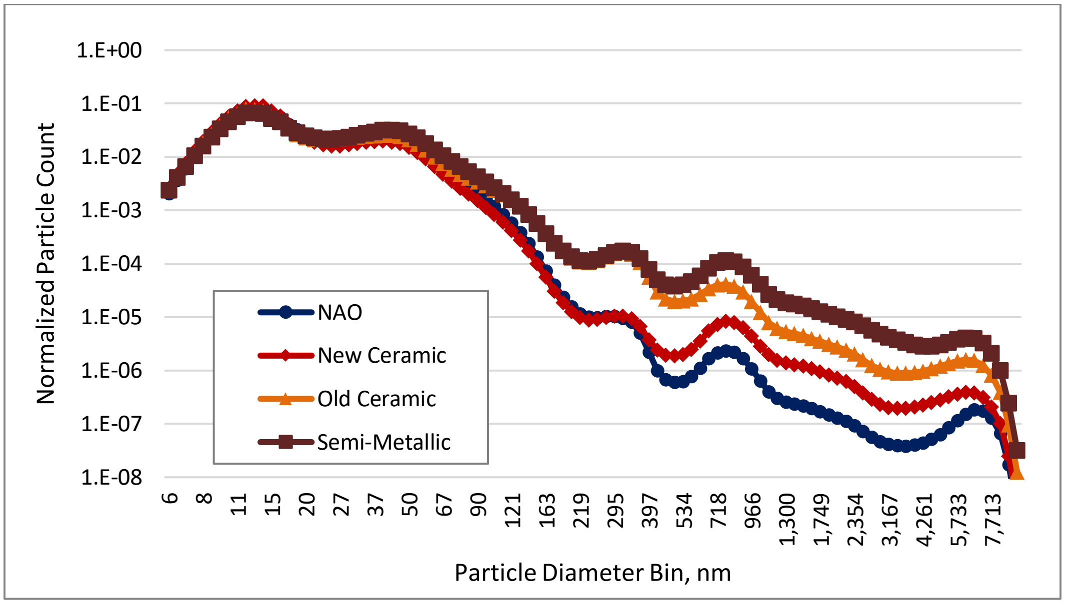

Figure 58. Corrected size distributions for brake tests over the Riverside Route, standard test weight.

Likewise, Figure 59 presents similar curves for the HLW tests over the Riverside route. In these tests, the higher fraction of larger particles for the semi-metallic pads and lower fraction for NAO pads is even more pronounced, though the location of observed peaks does not appear to be shifted.

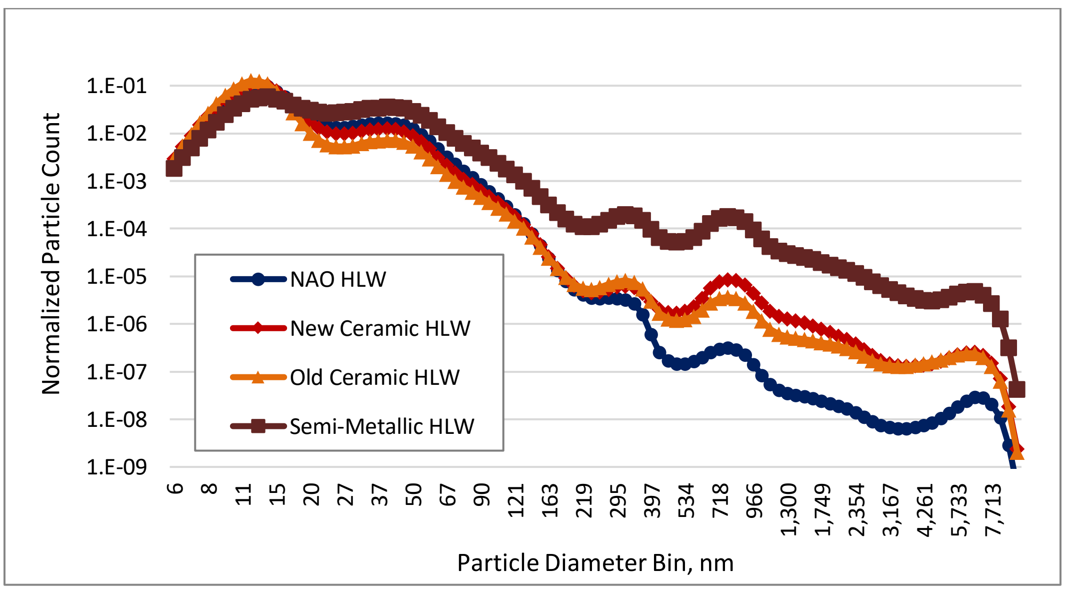

Figure 59. Corrected size distributions for brake tests over the Riverside Route, loaded test weight.

The size distributions for the CA-60 highway routes, both at standard weight and HLW, are presented in Figure 60 and Figure 61, respectively. The highway routes tend to have fewer large particles than the Riverside route tests, though the size range of the primary and secondary peaks appear within the same ELPI+ size bins.

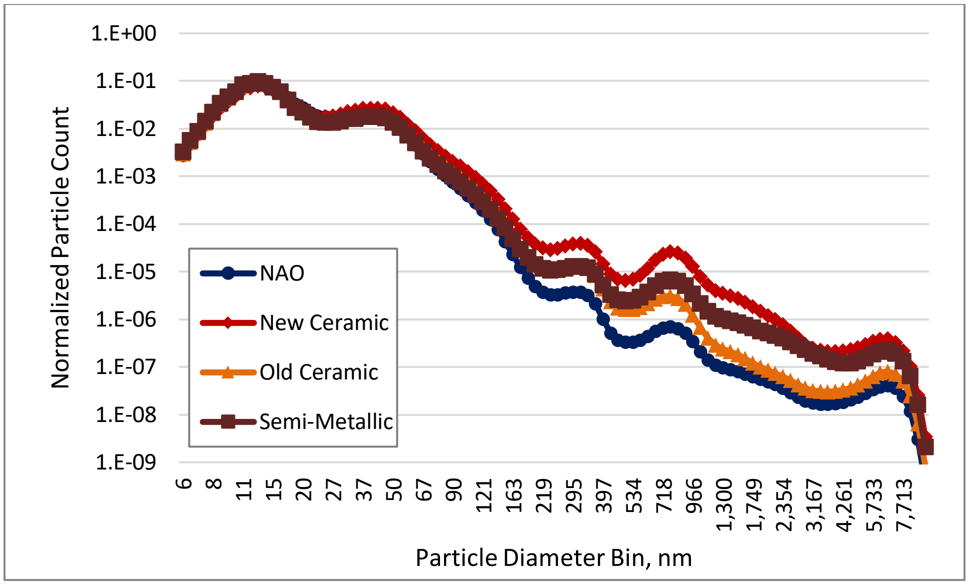

Figure 60. Corrected size distributions for brake tests over the Highway (CA-60) Route, standard test weight.

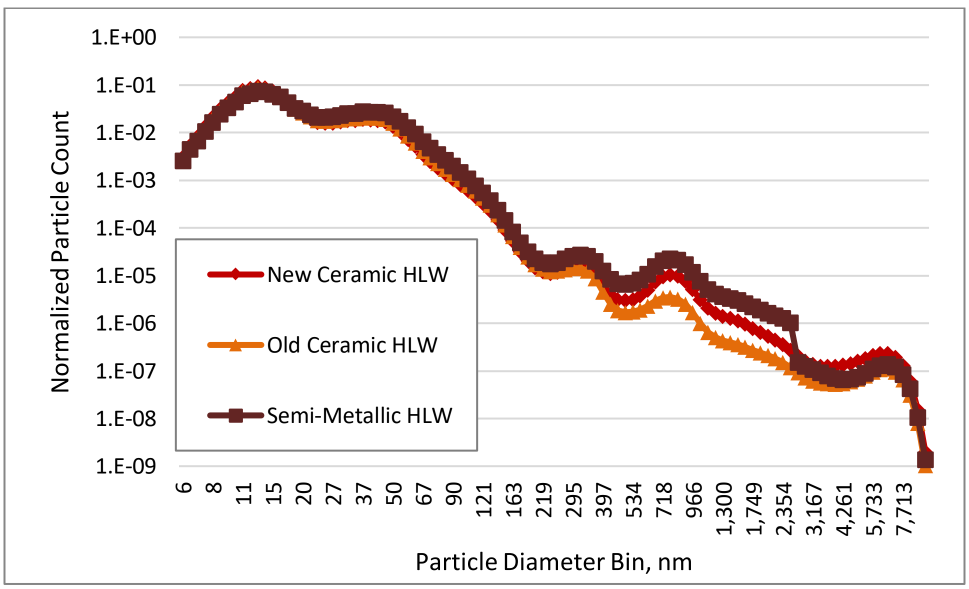

Figure 61. Corrected size distributions for the HLW brake tests over the Highway (CA-60) Route.

Corrected brake mass emission rates are presented in Section 5.4.1, as they represent the emission factors that are the purpose of Task 5c. The analyses in Task 5b are not applicable to the brake testing, however, as the brake measurement system was closed to outside contamination.

5.1.5 Processed Tire Emission Measurements

This section presents intermediate findings of PM sampling during tire tests, with a focus on PN and morphology. This section presents results of the tire tests, corrected only for sample and transport efficiency and not for collected tire fraction, which is described in later sections. The particle number and PSD are presented in this manner as they reflect the collected particle sample itself, irrespective of whether the collected sample contains bound roadway or road dust material. Only

PM mass from tire testing will be further corrected for those contaminants and so will be presented after those mass-based adjustments.

Figure 62 presents the total PN emission rates for the rear wheel of the test vehicle, corrected for collection and transport efficiency in the tire sampling system. Emissions are averaged within each group by tire, test route, and weight loading where applicable. Error bars represent the standard deviation in the results across tests. As described previously, counted particles cover an aerodynamic particle size range of approximately 6 nm to 10 µm. The average calculated emission rate in this size range is approximately 7.75 x 10^{11} particles per mile.

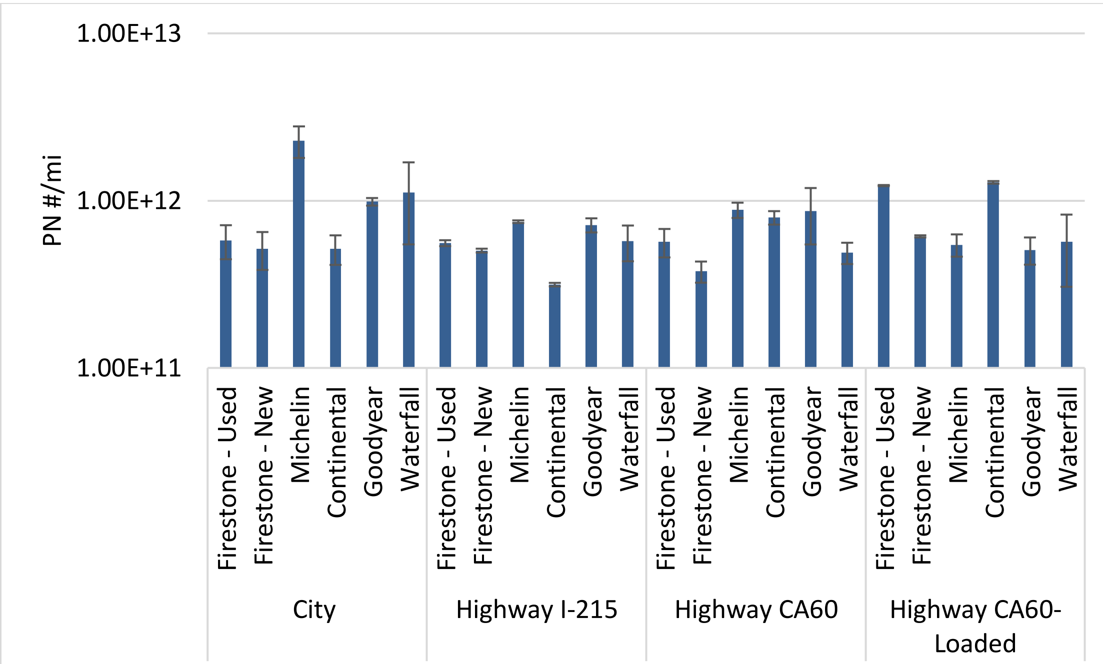

Figure 62. Total PN emission rates from tire tests, corrected for sample and transport efficiency and averaged by pad material and route

Measured particle size distributions, corrected for collection and transport efficiency, are presented by tire for each test route. Figure 63 presents the size distribution of collected sample over the Riverside Route tire tests of each tire, corrected for collection and transport efficiency. The distributions are normalized to sum to unity across the size range of the ELPI+. The tire PM measurements indicate a flatter size distribution than was observed for brakes. Most of the observable differences across tires occur in the size range from 200 nm to 1000 nm. Figure 64 presents a similar size distribution plot for the tire tests over the I-215 highway route.

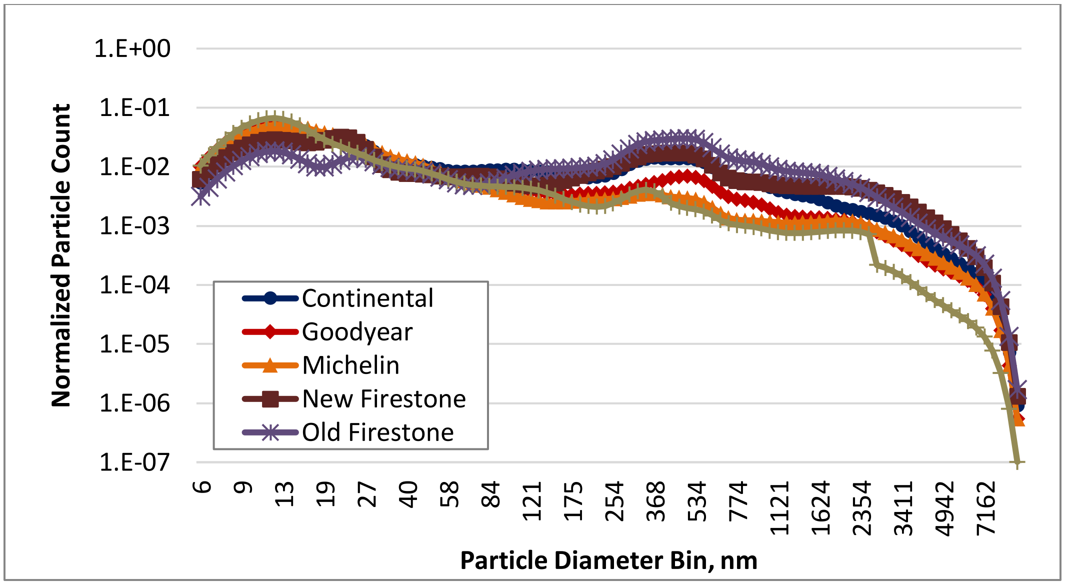

Figure 63. Sample-efficiency-corrected size distributions for tire tests over the Riverside Route at standard test weight

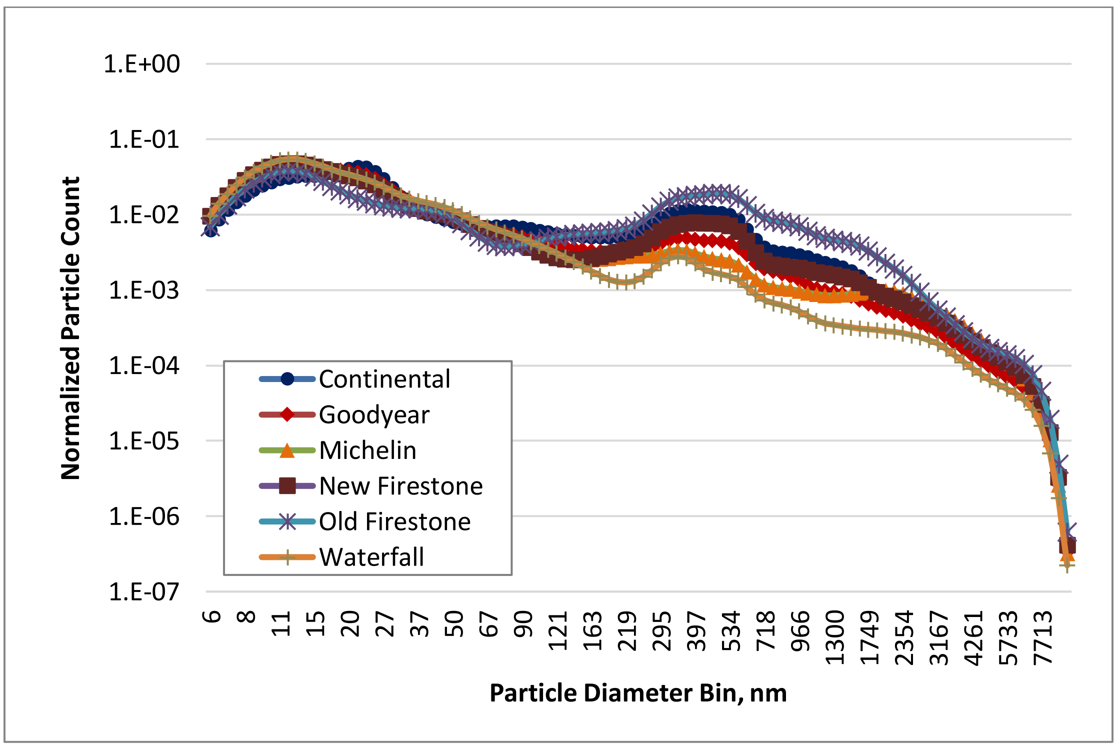

Figure 64. Sample-efficiency-corrected size distributions for tire tests over the I-215 route at standard test weight

Figure 65 presents the size distribution of tire tests over the CA-60 highway route at standard weight loading. The new and old Firestone tires tend to have more particles in the 200 to 1500 nm size range than the others.

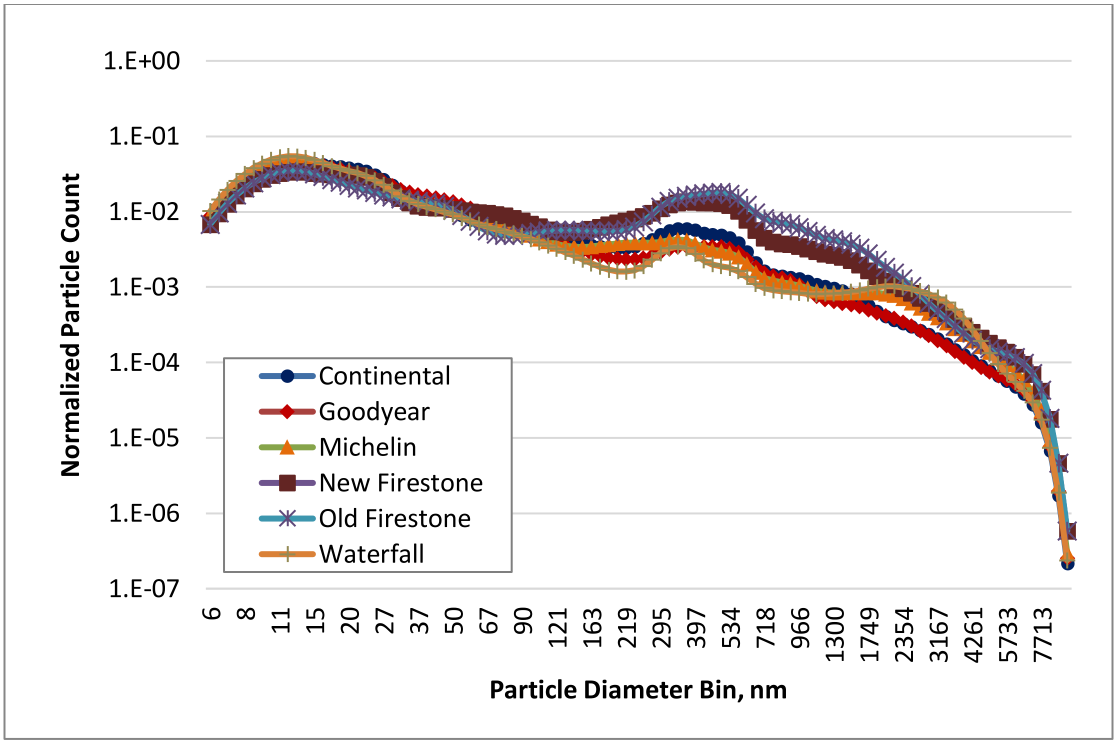

Figure 65. Sample-efficiency-corrected size distributions for tire tests over the CA-60 route at standard test weight

Figure 66 presents the size distribution data for the tire tests over the CA-60 route with the higher weight loading. In comparing the higher weight loading to the standard weight loading for this test route, the higher weight loading appears to elevate the relative concentration of particles at the smaller end of the range. However, it isn't clear whether this effect of weight is caused by increased tire wear or increased level of suspension of road dust or roadway wear.

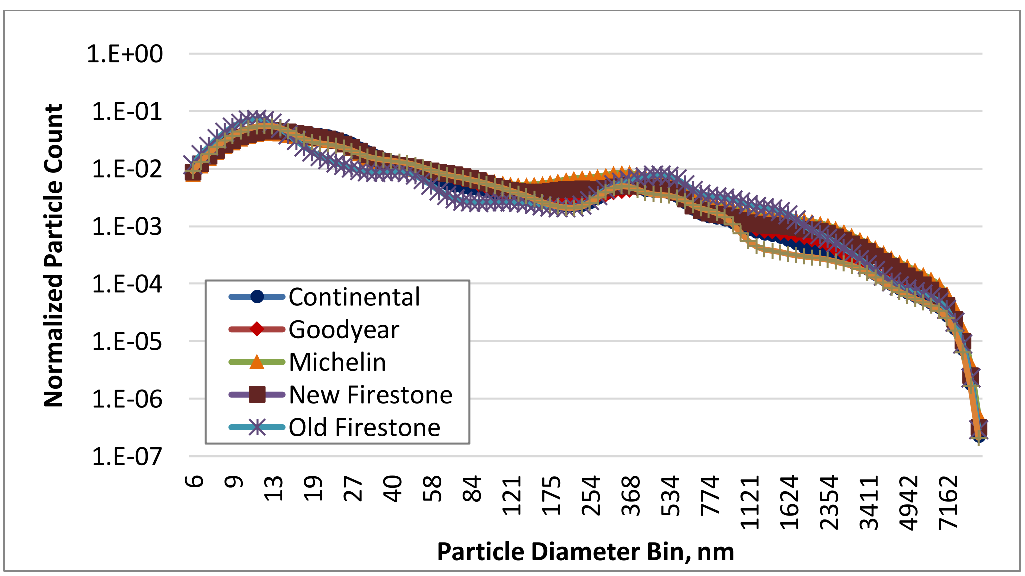

Figure 66. Sample-efficiency-corrected size distributions for tire tests over the CA-60 route, HLW

5.2 Task 5b: Chemical Analysis

A subset of PM2.5 and PM10 filters from both the brake and tire on-road testing were selected for X-ray fluorescence (XRF) analysis to determine the elemental composition of each sample. XRF was also performed on the on-road background samples and for dynamometer test with tire sampler for each tire over the US06 cycle to provide reference compositions for comparison to the on-road tests.

5.2.1 Brake Test Composition

Elemental mass emissions from XRF are shown in Figure 67 by friction material and route. Of note is the difference in composition between the New and Old Ceramic material, although this may be explained by difference in brand. All of the pads are dominated by Fe, though the Old Ceramic pad has significant amounts Ti and (on some cycles) Cu. The NAO and New Ceramic profiles are quite similar, while the SM pad is skewed further towards Fe and shows contribution of elements not found in the other material, notably Cr, while lacking elements common to the non-metallic pads (e.g., Na). Because the brake system is enclosed these XRF results present a more accurate picture of a "pure brake" elemental profile.

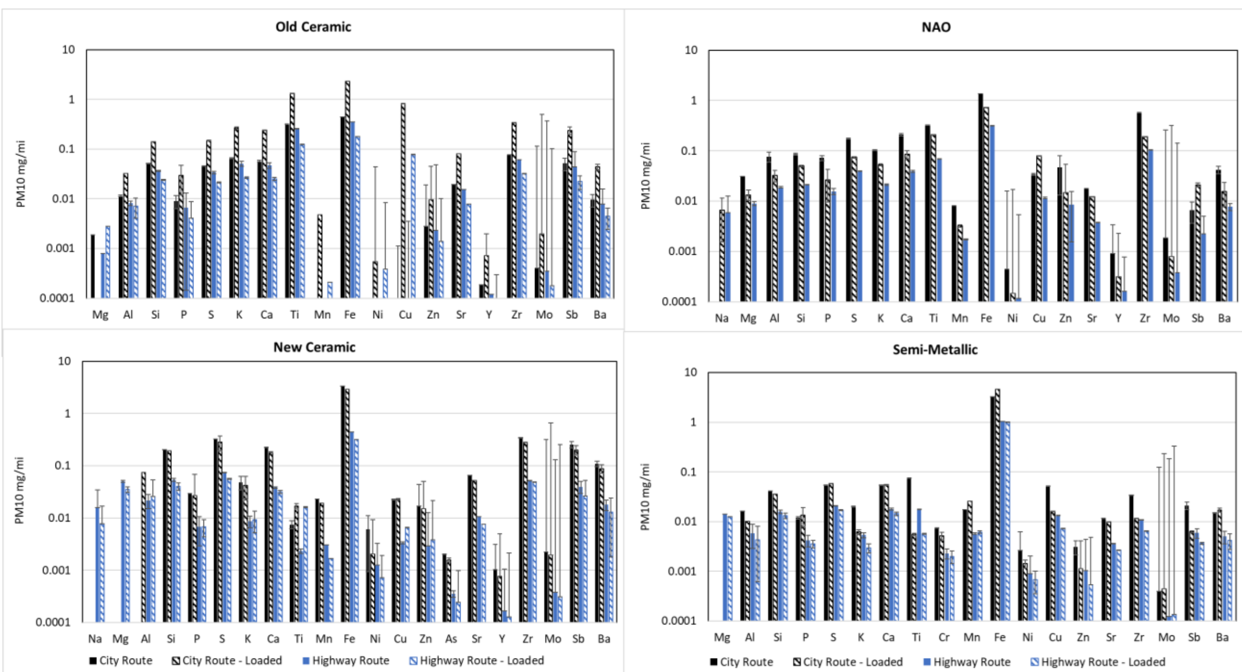

Figure 67. XRF Results from On-Road Brake Testing.

5.2.2 Tire Test Composition

Elemental mass emissions from XRF are shown in Figure 68 by tire and route. These profiles reflect all sources collected in the tire sampler from the road test (tire, brake, road dust, exhaust etc.) and hence are assumed to be road composite vs. pure tire. Of note in these samples is that Fe again dominates, an element common in many sources found in roadway environment (brake, tire, crustal material). Other crustal elements are prominent (Al, Mg, Si, Ca) as well as brake markers (Zr, Ba, Ti). Interestingly, Zn (a traditional tire marker) is not prominent in these samples. As discussed in Section 5.3.1, source apportionment analysis was conducted with these samples to estimate tire contribution.

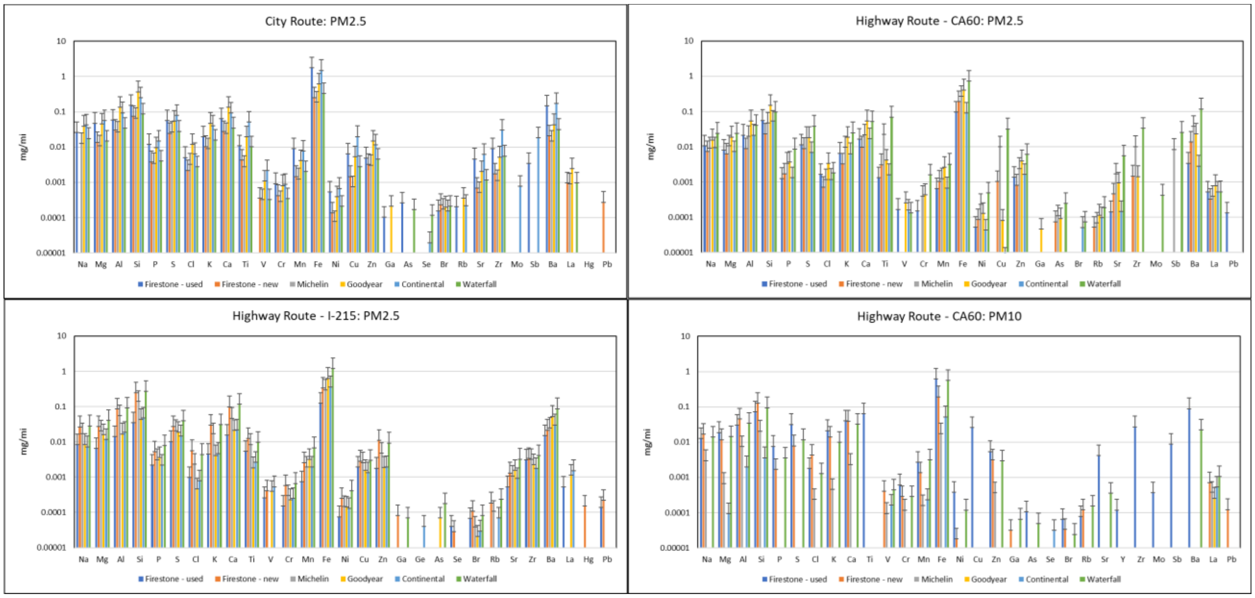

Figure 68. XRF Results from On-Road Tire Testing

Correlation analysis of the on-road tire testing shows high positive correlation between groups of elements shown in Table 12. The three groups align with signatures for brake, tire, crustal material and marine sources reported in a recent Caltrans study of ambient and road samples taken in the Riverside area indicating the presence of at least these four sources in the on-road tire testing samples.[57]

Table 12. Highly Correlated Elements in On-Road Tire Samples

Elements	Avg r	Min r	Indicative Source
Ba, Cu, Sb, Sr, Ti, Zr	0.88	0.71	Brake
Al, Ca, K, Si, Zn	0.81	0.70	Tire
Al, Ca, Mg, Si	0.90	0.86	Crustal Material
Br, Cl	0.52	0.52	Marine (Sea Salt)

5.3 Isolating Tire Emissions

The primary issue with interpreting emissions from the on-road tire testing is determine how much of the sample was generated from the specific test tire. This is an unprecedented analytical challenge since the testing was conducted in truly real-world conditions without any control of nearby traffic, amidst varying background emissions including particulate matter entrained in ambient air or on the road surface itself, which itself may contain tire particles from other vehicles.

Recognizing the tremendous uncertainty inherent in on-road testing, we present tire-specific emissions as a range of values derived from two independent methods of chemical source apportionment:

1. Analysis of the raw filter XRF results and total emissions using EPA's Positive Matrix Factorization model in conjunction with dynamometer and background data measured in this program.
2. Chemical Mass Balance using least squares regression of raw filter XRF results using tire chemical compositions from an independent study, published in EPA's SPECIATE database.

Methods 1 and 2 are detailed in the following sections.

5.3.1 Method 1: Positive Matrix Factorization

Positive Matrix Factorization (PMF) was used to conduct source apportionment on the XRF results from on-road tire testing. PMF is a multivariate receptor modeling technique used for source apportionment in air, water, soil, and other environmental monitoring applications. PMF is used to identify and quantify the sources contributing to measured environmental samples by decomposing complex datasets into a set of underlying factors. PMF incorporates measured sample values and corresponding uncertainties to estimate both the composition of each source and its relative contribution to individual samples. PMF identifies a pre-determined number of unique profiles from raw data; model users then assign profiles identified by PFM to specific sources based on similarities with independent source profiles and/or presence of specific markers.

The goal of PMF is to solve the chemical mass balance between measured species concentrations and source profiles (1-1):

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \qquad (1\text{-}1)$$

with number of factors *p*, the species profile *f* of each source, the amount of mass *g* contributed by each factor to each individual sample, and the residual for each sample/species *eij*. PMF derives a solution of factor profiles and contributions by minimizing the quality of fit Q defined below (1-2):

$$Q = \sum_{i=1}^{m}\sum_{j=1}^{n} \left(\frac{E_{i,j}}{\sigma_{i,j}}\right)^2 \qquad (1\text{-}2)$$

Once PMF determines a solution, bootstrapping is used to detect and estimate disproportionate effects of a small set of observations on the solution by randomly sampling blocks of observations from the original data set. Each bootstrap run produces its own set of contributions and factors, which are compared to the base run solution. Ideally each bootstrap factor maps one-to-one to the corresponding base run factor. Factor mapping over 80 percent indicates that the solution is stable and the chosen number of factors is appropriate.[58]

Tire Emissions PMF Analysis

In this analysis, EPA PMF version 5.0 (available free online) was used to resolve and quantify source profiles contributing to tire PM2.5 emissions. PM2.5 was used for the analysis because the majority of XRF results were from PM2.5 filters, providing a larger sample vs. PM10. It is important to note that the elements identified by XRF which are the basis of source apportionment are on average about 20 percent of overall filter mass in this sample; however, the PMF model does account for total filter mass in developing factor contributions. PMF uses conservation of mass to ensure that the XRF species in each factor times the factor contributions explain the mass of that species in each sample. The total filter PM2.5 mass adds an additional mass balance constraint to the solution to determine factor contributions on a mass basis. By telling the model that the total sample mass is greater than the sum of the XRF results, each factor is assigned a quantity of additional emissions. PMF adjusts the amount of additional emissions in each factor until it can replicate the sample masses. The resulting factor contributions are thus intended to apply to total filter PM2.5, with the caveat that the PMF model is working without specific knowledge of species beyond the XRF elements.

Multiple PMF runs were conducted with a different number of factors to determine the best solution. The best set of solution factors was determined by considering the trends in the value of Q, known characteristics of different emission sources, and bootstrapping runs.

Tire PM2.5 emissions samples measured using XRF and associated uncertainties were used as inputs for PMF. Given the sample measurements and uncertainties, EPA PMF calculates signal-to-noise ratio (S/N) which indicates whether the variability in the measurements is real or within the noise of the data. Considering the importance of marker species and S/N ratios, some species were excluded from the analysis while others were categorized as weak contributing variables. Co, Ge, Se, Y, Mo, Pd, Ag, Cd, In, Sn, and Hg were excluded, while Ga and Pb were treated as weak variables. All other species were categorized as strong contributing variables.

The 5-factor solution was chosen as the best solution for the tire PM2.5 runs. 50 base model runs were conducted, all of which reached convergence and produced stable Q values. Furthermore, bootstrapping was conducted on the base model solution, selected as the run with the lowest Q value, to assess the stability of the solution. 100 bootstrapping runs showed mapping of 89 percent or higher with the base model solution indicating that the factors are stable, well-resolved, and that the chosen number of factors is appropriate.

PMF Results

The 5-factor solution is shown in Figure 69, expressed as the contribution of each factor by element. To interpret and assign the factors determined in the PMF solution, PMF factor profiles were compared to independent source profiles, and factor contributions to elemental markers. The Total PM2.5 contribution on the far right provides an estimate of how much each factor contributes to total filter PM, including the non-XRF portion. As explained below, the five factors were identified as

- **Factor 1:** tire dynamometer (16 percent);
- **Factor 2:** marine (31 percent);
- **Factor 3:** crustal material (14 percent);

- **Factor 4:** measured background (23 percent);
- **Factor 5:** other (16 percent), possibly exhaust/industrial.

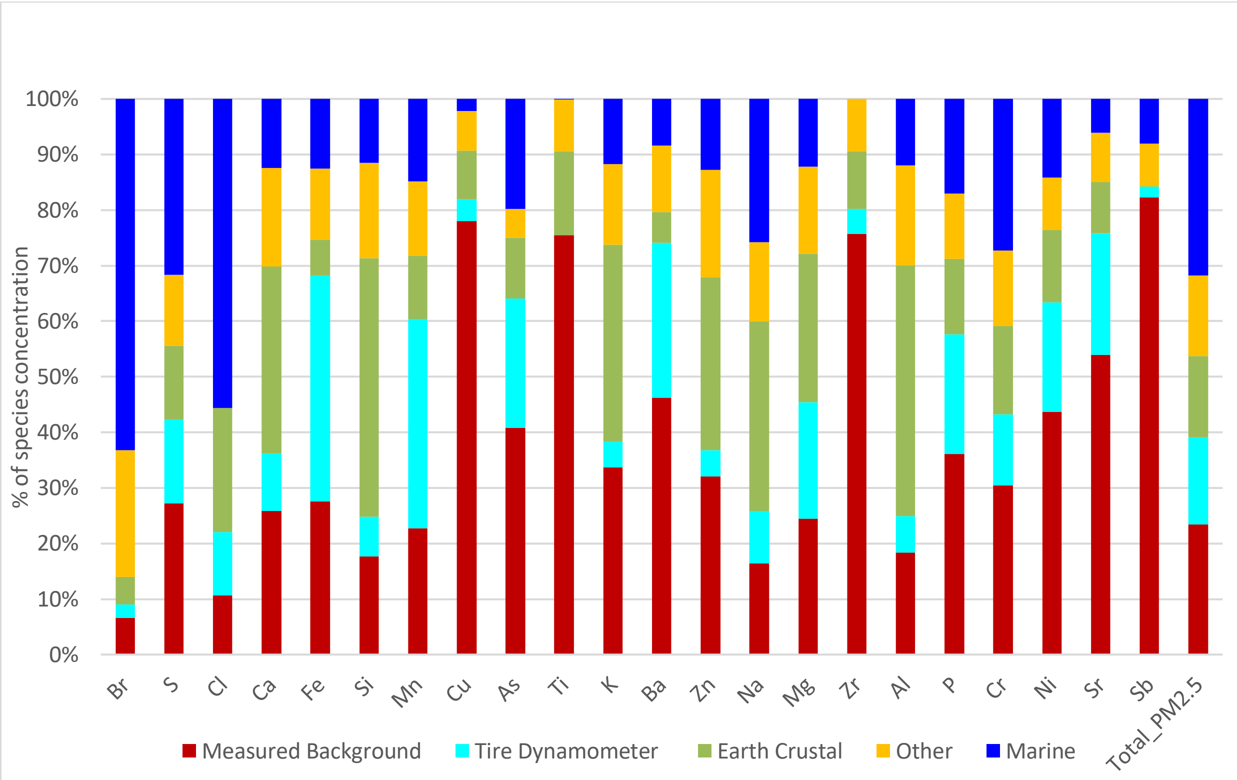

Figure 69. Factor contributions to individual species

The PMF-factor assignment for "measured background" was primarily based on the factor profile comparison to the measured XRF background sample profile (Figure 70). The large contribution of Zr indicates that brake wear is likely grouped with road dust in this factor. A Pearson correlation coefficient (r) of 0.96 confirms a satisfactory match.

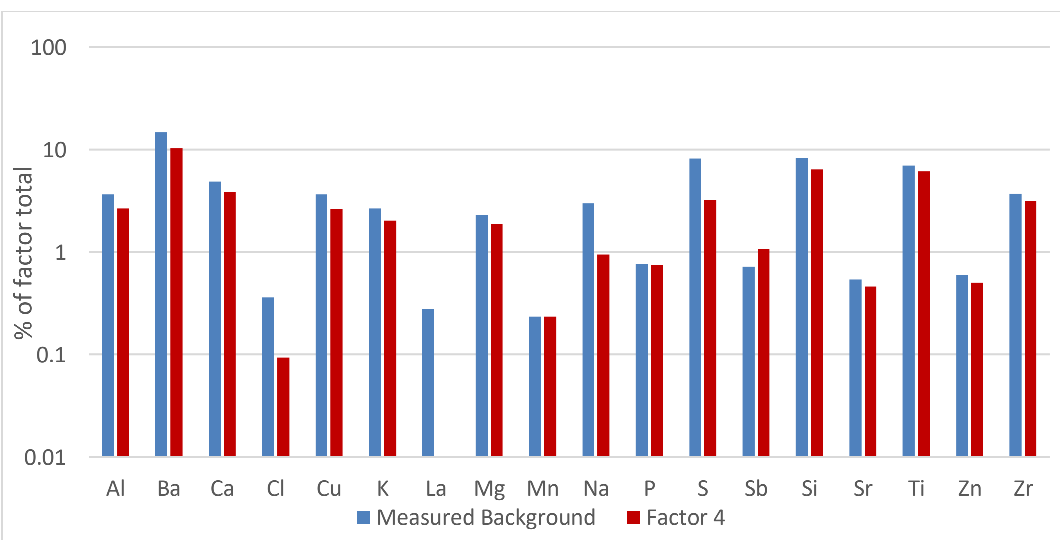

Figure 70. Comparison of PMF factor profile to XRF background sample profile

The “Tire Dynamometer” factor was assigned by comparing PMF-resolved factors to a tire wear source profile obtained from the mean of dynamometer tests conducted by UCR over the US06 cycle on each of the six test tires (Figure 71). A Pearson correlation coefficient (r) of 0.9996 confirms a near-perfect match.

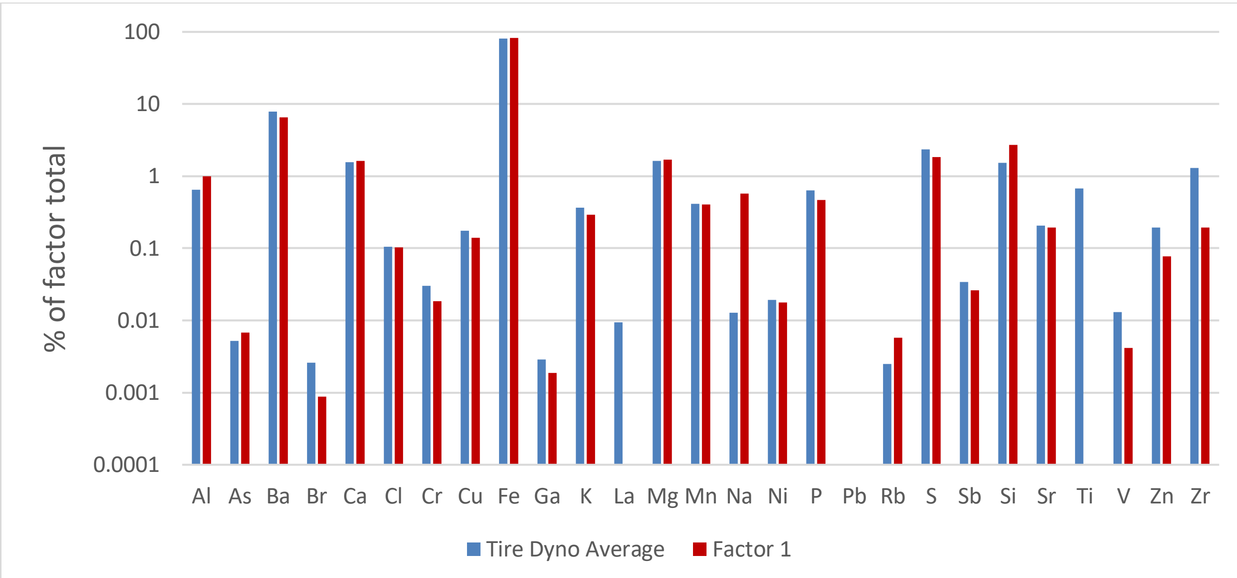

Figure 71. Comparison of PMF factor to Tire Dynamometer sample profile

The attribution of remaining factors was informed by prior ambient studies and source profiles in EPA’s SPECIATE database. “Marine” refers to sea salt aerosols (which can adhere to crustal material) and was assigned to the factor primarily due to its large contribution to Cl and Br. This source was also identified in Hopkins et al. (2025) and reflects the proximity of the test location to Salton Sea and Pacific Ocean. The remaining two factors showed similar contributions to several of the same species, making them more difficult to distinguish. However, the “Earth Crustal” factor was assigned based on its larger contributions to characteristic earth crustal marker species, including Al, Si, Ti, Ca, Mg, and K based on EPA’s SPECIATE database. The final factor is labeled “Other” but could be interpreted as a mixture of “Exhaust” and “Industrial” sources which are known contributors, where the larger contribution of Br suggests an influence from combustion-related industrial emissions.

Source apportionment results provide a means to estimate the contribution of the test tire to overall on-road sample for each test. The overall contribution of the factor identified as tire (Factor 1) across all tests is 15.7 percent. This may be an overestimate , however, since tire dynamometer data is atypical for tire speciation profiles in that Zn contribution is low. In addition, these samples have elevated levels of elements usually associated with brake and/or rotor material, such Ba, Fe, and Zr. This raises the concern that the tire dynamometer data identified as Factor 1 may include brake PM from the vehicle, in which case the entire Factor 1 contribution could not be attributed to tire only. For this reason, the research team pursued Method 2 as an alternative using more typical Zn-driven tire speciation profiles.

5.3.2 Method 2: Chemical Mass Balance with Independent Tire Profile

Many studies have employed Zn as a marker for tire-wear, including a) Hopkins et al. (2025), which assigned all observed Zn to tire wear; and b) a composite tire wear profile in the EPA SPECIATE database drawn from Lopez et al. (2023) from emissions collected on two tires (Figure 72).[59]

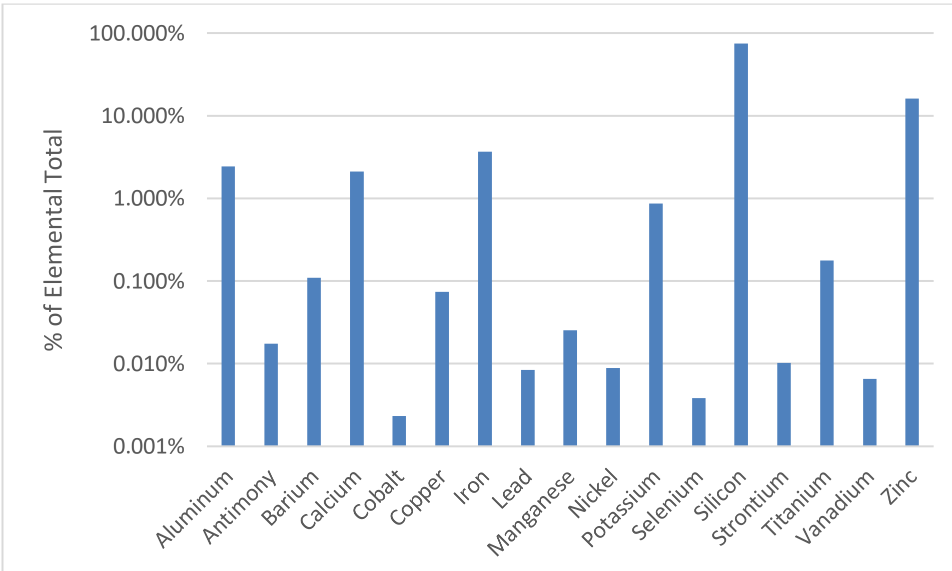

Figure 72. EPA SPECIATE Composite Tire Profile 95875 (Element Subset)

This profile can be compared to on-road test results to assess how much of the raw on-road samples are explained by an independent tire profile with higher Zn contribution. Following the standard method of Chemical Mass Balance (CMB), a least-squares regression was performed across each of the on-road tests using SPECIATE Profile 95875 in two ways:

- **Unconstrained**, allowing the model to find the best solution regardless of potential overprediction of Zn. This puts more weight on matching elements with larger contributions in both samples, mainly Si and Fe.

- **Zinc-constrained,** which constrains solutions to matching Zn levels in the on-road samples. This reduces the estimate of tire contribution, as it underestimate elements with larger contributions in the sample.

Unconstrained CMB with an independent tire profile from SPECIATE estimates a tire contribution of 18.1 percent, comparable to the 15.7 percent contribution from PMF using the dynamometer samples measured by UCR. However, the Zn-constrained CMB estimates a tire contribution of only 3.8 percent for PM2.5 and 4.8 percent for PM10 across all on-road tests (to put this in context, a recent on-road study using an Hg-doped tire estimated tire contribution between 1.9-7.5 percent).[60] This is considered a conservative lower-bound as it assumes the proportion of the elemental sample explained by tire applies to the entire filter mass, though major non-tire sources (brake, crustal material, sea salt) are predominantly elemental.

5.3.3 Tire Contribution Range

The independent estimates of tire contribution from Zinc-constrained CMB (3.8 percent) and PMF (15.7 percent) are used as lower and upper bound estimates in presenting corrected $PM_{2.5}$ emission factors in Section 5.4.

Because PM10 was collected on a smaller number of tests than PM2.5, independent PMF analysis was not conducted for PM10. The difference in elemental composition between PM10 and PM2.5 is shown in Figure 73, controlling for tire and route. PM_{10} is relatively enriched in crustal/road dust elements (Si, Al, Ca, K, Na, Zn) and relatively depleted in brake/metal-associated elements (Cu, Zr, Ba, Ti). That pattern is consistent with PM_{10} containing more coarse road dust and resuspended material, while $PM_{2.5}$ contains proportionally more fine metallic wear.

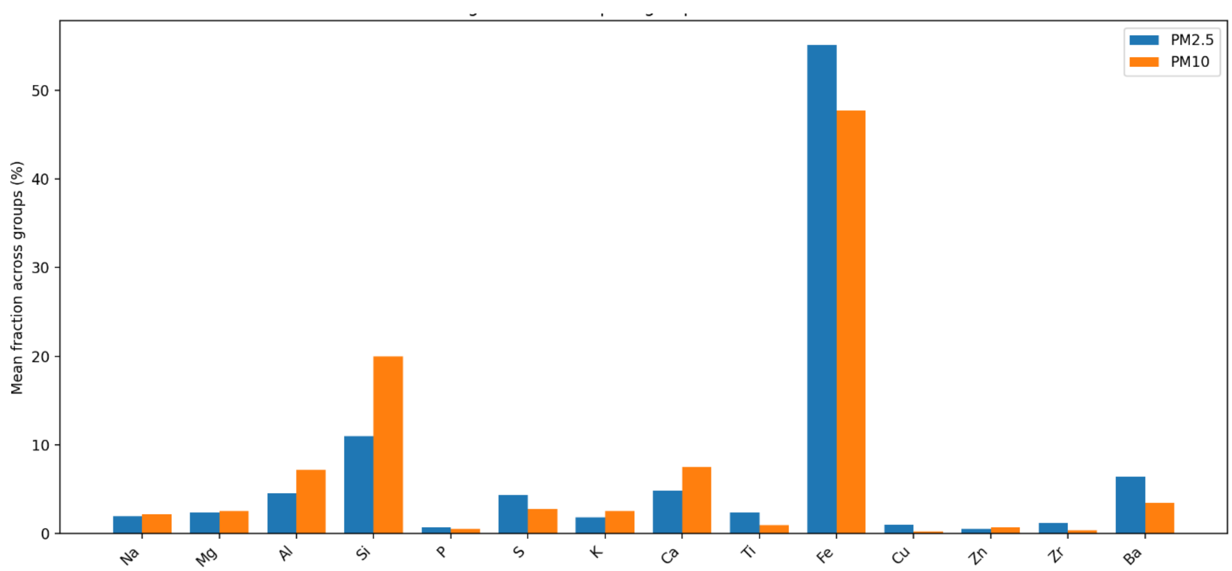

Figure 73. Comparison of PM2.5 vs. PM10 Elemental Composition from On-Road Tire Tests

Zinc-constrained CMB performed on PM10 found that the SPECIATE tire profile accounts for 4.8 percent of the PM10 sample, though the difference with the PM2.5 contribution (3.8 percent) is not statistically significant.

5.3.4 Statistical Analysis of On-Road Measurements

Statistical tests were run on the corrected on-road tests to determine what factors are significant in determining the variability across on-road samples, and to assess if there are statistically significant differences between factors built into the test matrix (e.g., city/highway, loaded/unloaded, asphalt/concrete for tires). These provide insight into important variables in determining emissions, and the level of disaggregation needed for emission factors for modeling.

Brake Measurements

Analysis of Variance (ANOVA) results for on-road brake emission measurements are shown in Table 13 and Table 14. Route (City vs. Highway) and Friction Material are significant factors. Paired t-test of New vs. Old Ceramic finds no significant difference for PM2.5 (p=0.166) and marginal significant difference for PM10 (p=.0516); average emissions for New are higher than Old as expected in most cases but not all, with City route PM2.5 emissions notably the same . Paired t-test of Loaded vs. Unloaded finds marginal significance for both PM2.5 (p=0.055) and PM10 (p=0.086), with Loaded emissions higher than Unloaded as expected. Marginal significance for these factors may be attributable to sample size.

Table 13. ANOVA Results for On-Road Brake PM2.5 Samples

Factor	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Route	1	66.12	66.12	10.80	0.0025
Friction Material	3	85.14	28.38	4.64	0.0086
Route: Material	3	7.90	2.63	0.43	0.7328
Residual	31	189.75	6.12		

Table 14. ANOVA Results for On-Road Brake PM10 Samples

Factor	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Route	1	177.5	177.5	12.2	0.0014
Friction Material	3	194.8	64.9	4.5	0.0100
Route: Material	3	44.5	14.8	1.0	0.3971
Residual	32	466.1	14.6		

Tire Measurements

Corrected $PM_{2.5}$ and PM_{10} from on-road tire sampling measurement formatted to use for the ANOVA tests is provided in the Appendix. There are four factors defined for analysis in this data set: Tire, Route Type (city/highway), Road Type (highway tests only, asphalt/concrete), and Load (for Highway CA-60 tests, unloaded/loaded). "Tire" refers to one of the six specific test tires, including Firestone New and Used; since age was only specified for Firestone and kept the Tire category values unique, there was no need to create an Age factor for this dataset.

Two-way ANOVA was conducted on the entire sample, separately for $PM_{2.5}$ and PM_{10}. As shown in Table 15 and Table 16, Tire and Route are both highly significant (p-value well below .05), as well as the Tire:Route Interaction.

Table 15, ANOVA Results for Corrected On-Road Tire PM2.5 Samples

Factor	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Tire	5	1141	228.1	6.406	0.000166

Factor	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Route	1	1674	1674.1	47.007	2.33E-8
Tire:Route	5	545	109.0	3.061	0.019140
Residuals	42	1496	35.6		

Table 16. ANOVA Results for Corrected On-Road Tire PM10 Samples

Factor	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Tire	5	3970	794	2.480	0.04727
Road Type	1	4626	4626	14.450	0.00047
Tire:Road Type	5	4408	882	2.754	0.03103
Residuals	41	13127	320		

Post -hoc analysis using Tukey HSD (log scale) reveals that the significance of Tire as a factor is driving by one pairwise comparison: only Firestone New vs Goodyear is significant (p-adj = 0.0015), with Goodyear and 15 percent of Firestone New's mean. No other tire pairs cross the Tukey threshold, including Firestone New and Used. For PM10 there were no significant tire pairs using the Tukey test.

Paired t-test were performed to check for significant differences between paired factors for load (loaded vs. unloaded), road material (asphalt vs. concrete), and tire age (based on Firestone New vs. Old), as shown in Table 17.

Table 17. Paired t-test Results for Load, Road Material, Tire Age

Paired test	Subset / pairing	Metric	n (pairs)	Ratio†	95 percent CI (ratio)	p (log)	Conclusion
Loaded vs Unloaded	Highway – CA60, paired by **Tire**	PM2.5	6	0.94	[0.31, 2.86]	0.887	Not significant
		PM10	6	0.91	[0.64, 1.29]	0.512	Not significant
Asphalt vs Concrete	Highway only, paired by **Tire**	PM2.5	6	0.65	[0.33, 1.27]	0.158	Not significant
		PM10	6	0.61	[0.35, 1.07]	0.071	Marginally significant

Paired test	Subset / pairing	Metric	n (pairs)	Ratio†	95 percent CI (ratio)	p (log)	Conclusion
Firestone New vs Firestone Used	Matched **conditions** (same Route Type, Route, Material, Loaded)	PM2.5	4	2.03	[0.61, 6.71]	0.156	Not significant
		PM10	4	1.93	[0.93, 4.01]	0.0637	Marginally significant

As shown, none of the paired factors show significance for $PM_{2.5}$ or PM_{10}, although roadway material and tire age are marginally significant for PM_{10}. The import of this result for tire age (also reinforced by Tukey test which did not identify Firestone New vs. Old as having significant differences) is that tire emission factors from this study do not support an age or odometer effect.

5.4 Task 5c: Corrected Emission Factors

Results from Task 5a and 5b yield brake and tire emissions factors which are the basis of emissions model and inventory development. Individual brake emission factors are presented in 5.4.1, and individual tire emissions in 5.4.2. Individual brake and tire emissions are scaled to whole-vehicle emissions in 5.4.3 for comparison to current EMFAC emission rates, and as the basis for emissions and inventory modeling discussed in 5.5.

5.4.1 Individual Brake Emission Factors

Table 18 presents the calculated single-wheel emission factors for the rear brakes of the test vehicle. Emissions are presented for the Riverside Route (i.e. City) and the CA-60 Highway route. On average, the PM2.5 fraction of PM10 is approximately 40 percent.

Table 18. Individual Brake Emission Factors

Friction Material	$PM_{2.5}$ mg/mi		PM_{10} mg/mi	
	City	Highway	City	Highway
Old Ceramic	3.68	0.52	5.20	2.15
New Ceramic	3.68	1.10	10.41	2.73
NAO	2.71	0.89	5.91	3.46
Semi-Metallic	2.66	2.07	8.79	2.97

5.4.2 Individual Tire Emission Factors

Tire emission factors (EFs) are estimated from the raw results presented in Section 5.1 by first adjusting raw results for dilution and collection efficiency factor discussed previously, which increased raw results for $PM_{2.5}$ by a factor of 2.8 and PM_{10} by a factor of 2.2. The tire-only EFs were then estimated using lower- and upper- bound estimates of tire contribution of 3.5 – 15.7 percent (labeled "Zn CMB" and "PMF"). The lower bound range was applied to corrected emissions after subtracting measured background emissions of 1.81 mg/mi $PM_{2.5}$ (4.50 mg/mi PM_{10}) for city routes, and 0.65 mg/mi $PM_{2.5}$ (1.0 mg/mi PM_{10}) for highway routes, to account for background tire particles. The upper bound estimate was applied without this adjustment, because background tire particles are already accounted for in PMF analysis. The resulting average individual tire EFs are presented in Table 19. Results for each test are provided in the Appendix.

Table 19. Individual Tire Emission Factors

Tire	$PM_{2.5}$ mg/mi				PM_{10} mg/mi			
	City		Highway		City		Highway	
	Zn CMB	PMF	Zn CMB	PMF	Zn CMB	PMF*	Zn CMB	PMF*
Continental	0.4	2.0	0.1	0.4	1.7	6.3	0.4	1.6
Firestone New	0.7	3.2	0.2	0.9	3.3	11.6	0.5	1.8
Firestone Used	0.2	1.1	0.1	0.4	1.1	4.2	0.2	1.0
Goodyear	0.02	0.3	0.01	0.1	0.2	1.3	0.1	0.3
Michelin	0.4	1.8	0.1	0.4	0.5	2.1	0.6	2.1
Waterfall	0.3	1.4	0.04	0.3	0.5	2.4	0.2	0.9

* PM2.5 PMF solution applied to PM10 also

5.4.3 Aggregate Whole-Vehicle Emission Factors

EMFAC uses whole-vehicle emission factors as the basis for emission inventory calculation. For brakes, whole-vehicle emissions are estimated by scaling up the individual rear brake to front and rear axle using a 65/35 weighing to account for vehicle weight distribution. Whole-vehicle emission rate for tires is simply 4x the individual tire, as information on weight impact across axles is insufficient. Whole-vehicle emissions by brake material, and for tires overall, are shown in Table 20. These emission factors apply to the Chevrolet Silverado 2500 test vehicle (EMFAC LHD1 class) specifically, but are the starting point for further emissions modeling in Task 5d (Section 5.5).

Table 20. Aggregate Whole-Vehicle Emission Rates

Equipment	$PM_{2.5}$ mg/mi		PM_{10} mg/mi	
	City	Highway	City	Highway
Old Ceramic	13.6	1.9	19.2	8.0
New Ceramic	13.6	4.1	38.5	10.1
NAO	10.0	3.3	21.9	12.8
Semi-Metallic	9.8	7.7	32.5	11.0
Tire	1.4-6.6	0.3-1.6	5.2-19.6	1.3-4.9

5.5 Task 5d: Brake and Tire Modeling

The objective of this task is to develop a model to estimate representative brake and tire emission factors (EF) based on emissions test results from this program in conjunction with market and activity data presented in prior sections. For brake emissions, the EF generated from this study are compared to EMFAC emission factors based on 17RD006 to gauge the magnitude of potential differences resulting for on-road results (further comparison between on-road brake emissions and 17RD006 is provided in Section 6.0). Comparison to EMFAC EFs is the natural stopping point for brake emissions, as the on-road results can't credibly be extended across the vehicle fleet as readily as tires. For Tire EFs, an emission factor model was developed which transforms the corrected emission results for the Silverado presented in the prior section to representative emission factors for each EMFAC class. These emission factors were then applied to EMFAC activity to estimate state-wide emissions inventory.

5.5.1 Brake Emission Modeling

A composite brake emission factor can be estimated using the market shares for different brake materials provided by MECA (Table 21). Whole-vehicle emission rates for individual friction materials shown in Table 22 are weighted using the market shares for Light Vehicles and HD Light Trucks, which vary significantly from one another. The test vehicle falls in the category MECA refers to as HD Light Truck, but Light Vehicle results are shown as well to demonstrate the sensitivity overall brake emissions to friction material market share. The EMFAC LDT rates account for speed correction using average speed from this study's City (25 mph) and Highway (47 mph) routes. Deterioration is accounted for by defining the aftermarket (AM) value as a 22 percent increase from original equipment (OE), reflecting the EMFAC deterioration rate over 100K miles. Resulting EFs are 4-5 times higher than the EMFAC rates for PM2.5, and 2-3 times higher for PM10. The reasons for this are detailed in the comparison of on-road results to the 17RD006 dynamometer results in Section 6.0, but are generally attributable to a) more brake intensity on the City route than in the dynamometer test cycle; b) a heavier vehicle than those used to generate the EMFAC LD and LHD brake emission rates; and c) testing of new brakes out of the box, without burnishing procedure used in 17RD006.

Table 21. Brake Market Share for LD and LHD Vehicles

Vehicle Class	Original Equipment (OE) Mix	Aftermarket (AM) Mix
Light Vehicle (1500 and below)	95 percent NAO, 5 percent LS	75 percent Ceramic, 25
HD Light Truck (2500-4500)	10 percent NAO, 90 percent SM	95 percent SM, 5 percent NAO

Table 22. Composite Brake Emission Factors

	$PM_{2.5}$ mg/mi				PM_{10} mg/mi			
	City		Highway		City		Highway	
Brake Mix	OE	AM	OE	AM	OE	AM	OE	AM
Light Vehicle	10.0	12.7	3.5	4.2	22.4	29.8	12.7	9.5
HD Light Truck	9.8	9.8	7.3	7.5	31.4	32.0	11.2	11.1

Brake Mix	$PM_{2.5}$ mg/mi				PM_{10} mg/mi			
	City		Highway		City		Highway	
	OE	AM	OE	AM	OE	AM	OE	AM
EMFAC LDT	2.2	2.6	1.1	1.3	11.7	14.3	4.2	5.1

5.5.2 Tire Emission Modeling

Based on statistical analysis presented in Section 5.3.4, tire emission factors were developed aggregated to route (city and highway) only. Though Tire is also a significant factor in the overall ANOVA, post-hoc analysis reveals this isn't broadly supported with comparison of individual tire pairs. Tests across different loads, road materials, and tires were pooled to generate the Tire EFs shown in Table 23 for the Silverado, classified as a Light Heavy-Duty 1 (LHD1) vehicle in EMFAC. City and highway emissions are kept separate to account for the impact of average speed on emissions as modeled in EMFAC. As shown, the range of EFs for the City route estimated from this study cover the EMFAC LHD1 EFs (which don't vary by speed), but are lower than EMFAC for the Highway route.

Table 23. LHD1 Whole-Vehicle Tire Emission Factors

Equipment	$PM_{2.5}$ mg/mi		PM_{10} mg/mi	
	City	Highway	City	Highway
This Study	1.4-6.6	0.3-1.6	5.2-19.6	1.3-4.9
EMFAC LHD1	3.4	3.4	7.8	7.8

Tire Emission Inventory Calculation

A state-wide emissions inventory for tire emissions is estimated based on results of this study. Tire EFs from the test vehicle were applied across all EMFAC vehicle classes accounting for tire size and number of tires per vehicle.

Tire Size

Differences in tire size between vehicle class is represented by the Tire Wear Index (TWI) described in Section 2.2.3. TWI is a proxy for overall tire wear rate calculated as the total wearable mass (accounting for tire width, tread depth, void volume, aspect ratio, and tire diameter) dividing by the tire mileage rating. TWI was calculated for the test tires and for each EMFAC vehicle class, with emissions assumed to scale linearly with TWI. The first part of the analysis was to calculate the wearable mass of the tires for each light duty vehicle and commercial truck provided by UC Riverside. Wearable mass (g/km) is calculated using the nominal road area, tread depth, tire rating milage, and void area. Nominal road area, which is the surface area of the tire that touches the road, is derived from tire width (mm), aspect ratio, and tire diameter (in), which were all provided in the dataset developed by LINK based on high-sales vehicles and tire sizes. Tread depth (mm) values for each tire were sourced from online sources, like discounttire.com, and were converted from inches to mm. Tire rating (mi) values were also sourced online, but only for the tires with the highest count for each vehicle. A python script developed by LINK analyzed pixel imaging to estimate the void area percentage for each tire tested. With all these values, wearable mass was calculated for each tire-vehicle combination; the weighted average of the wearable mass for each tire was calculated using the individually calculated wearable mass and vehicle count to represent an accurate picture of the current fleet's tire emissions. The resulting TWI for the six test tires is shown in Table 24; the average TWI across the test tires is 0.21.

Table 24. Tire Wire Index for Six Test Tires

Test Tire	Tread Depth (mm)	Void Percent	Mileage Rating (mi)	TWI (g/km)
Firestone Transforce HT	11	34.4	65,000	0.20
Firestone Transforce HT	11	34.4	65,000	0.20
Michelin LTX M/S2	10	30.1	70,000	0.17
Goodyear Wrangler Territory HT	9.5	26.7	60,000	0.20
Continental Terrain Contact HT	11	29.2	70,000	0.20
Waterfall Terra X H/T	11	39.6	45,000	0.27

TWI was then estimate for all EMFAC classes to account for differences in wearable mass for different vehicle sizes based on corresponding tire sizes, as a method for scaling emission factors based on emissions from a single tire size. This was estimate for LDV and LDT based on examples of top-selling tire sizes for each class sourced from the USTMA Factbook.[61] The tire specs for were gathered from online sources and averaged, and then, using the same method as above, wearable mass was calculated. Then, for each EMFAC Class, the weighted average of wearable mass was computed, and then scaled to the reference tire by taking the ratio. Resulting TWI by EMFAC class along with data sources are shown in Table 1Table 25. The "per-tire emissions scaling factor" is calculated as TWI for a given vehicle class divided 0.21, i.e. average TWI for the Silverado test tires.

Table 25. Tire Emission Scaling to EMFAC Vehicle Classes

EMFAC Class	TWI Source	Wearable Mass (TWI)	Per-Tire Emissions Scaling Factor
Motorcycle	USTMA LDV	0.12	0.58
LDV	USTMA LDV	0.12	0.58
LDT1	USTMA LDT	0.21	1.00
LDT2	USTMA LDT	0.21	1.00
MDV	USTMA LDT	0.21	1.00
LHD1	Silverado Test Tires	0.21	1.00
LHD2	Class 3	0.24	1.16
MH	Class 3	0.24	1.16
T6	Class 4-7	0.23	1.11

EMFAC Class	TWI Source	Wearable Mass (TWI)	Per-Tire Emissions Scaling Factor
T7	Class 8	0.22	1.07

Tires per Vehicle

The next step in the analysis was to get the average number of tires for each EMFAC vehicle class, including trailers. The data used to get these numbers is from the California Vehicle Inventory and Use Survey (CA-VIUS).[62] The number of tires on a truck (including double wheeled-axles, aka "duallies") was derived from C-VIUS fields reporting (for each truck class) the number of axles on a truck, number of wheels per rear axle, trailer useage, and number of wheels per trailer. Some assumptions were made: for Class 8 vehicles, "5p" values for REARAXLETIRES have 8 tires on trailers, "0" values for REARAXLETIRES have 2 tires on rear axle, and there are 2 brakes per axle. Three values were wanted from this data set: total tires, vehicle tires, and trailer tires. From CA VIUS data, PAXLECONFIG, REARAXLESTIRES, and TCONFIG. PAXLECONFIG is the total number of axles on the vehicle, including axles on most common trailer configuration. REARAXLETIRES is number of pairs of tires on rear axle, either 0, 1, or 2, meaning 0, 2, or 4 tires respectively. TCONFIG is the trailer configuration, which is Y if yes, N if no, Z and X if not provided or applicable. The total number of tires was calculated using PAXLECONFIG and REARAXLETIRES. The number of axles from PAXLECONFIG is multiplied by 2 if REARAXLETIRES is 0; if REARAXLETIRES is not 0, then PAXLECONFIG is subtracted by 1 multiplied by 2, the REARAXLETIRES value is multiplied by 2, and the results are summed. If PAXLECONFIG is "5p", 10+ tires were assumed. Next, the vehicle tires were calculated, which are the tires on the vehicle, not including tires on the trailer. If TCONFIG was N, then vehicle tires equaled total tires; if REARAXLETIRES was 0, 4 tires were assumed to be on the vehicle; otherwise, the vehicle tires value was 2 plus 2 times the REARAXLETIRES value. Trailer tires were calculated by subtracting vehicle tires from total tires. For tests that resulted in non-integer numbers (i.e. "10+") assumptions were made. For Class 8 vehicles, the assumption is as mentioned above. For REARAXLETIRES that had value of 1 and Y for TCONFIG, 4 tires on the trailer were assumed, and 6 was assumed otherwise. Results by truck class categories in CA-VIUS were aggregated to align with EMFAC truck categories (Table 26).

Statewide Inventory

A statewide tire emissions inventory is calculated as the product of Tire EFs and statewide VMT by EMFAC vehicle class, using 2026 VMT projections (Table 26 and Table 27). Emissions and VMT are disaggregated by city and highway. Total $PM_{2.5}$ emissions are estimate to be between 322 – 1,606 tons per year, and Total PM_{10} emissions are estimated to be between 1,277 – 4,802 tons per year. By comparison, EMFAC2025 projects 814 tons of tire $PM_{2.5}$ and 3,250 tons of tire PM_{10} statewide, well within the ranges generated from this study. Although EMFAC-based totals compare well with study results overall, this study suggests a need to revisit speed corrections and EF differences between vehicle classes in EMFAC.

Table 26. Statewide Tire Emissions $PM_{2.5}$ Inventory (2026)

EMFAC Classes	Scaled Per-Tire EF (mg/mi)		Tires per Vehicle	Annual Statewide VMT (Billion Miles)		Annual $PM_{2.5}$ Emissions (Tons)
	City	**Highway**		**City**	**Highway**	
MCY	0.20–0.96	0.04–0.23	2.0	1.2	0.8	1–3
LDA	0.20–0.96	0.04–0.23	4.0	117	63	113–561
LDT1	0.34–1.66	0.07–0.39	4.3	10	6	18–90
LDT2	0.34–1.66	0.07–0.39	4.3	57	38	105–520
MDV	0.34–1.66	0.07–0.39	4.5	6	6	12–61
LHD1	0.34–1.66	0.07–0.39	5.7	3	3	8–39
LHD2	0.39–1.93	0.08–0.46	5.7	2	3	7–33
MH	0.39–1.93	0.08–0.46	5.0	1.2	1.8	3–17
T6	0.38–1.84	0.08–0.44	6.2	5.5	5.5	17–86
T7	0.36–1.78	0.08–0.42	14.3	3	17	38–197
Total						**322–1,606**

Table 27. Statewide Tire Emissions PM_{10} Inventory (2026)

EMFAC Classes	Scaled Per-Tire EF (mg/mi)		Tires per Vehicle	Annual Statewide VMT (Billion Miles)		Annual PM_{10} Emissions (Tons)
	City	**Highway**		**City**	**Highway**	
MCY	0.8–2.9	0.2–0.7	2.0	1.2	0.8	2–9
LDA	0.8–2.9	0.2–0.7	4.0	117	63	443–1,668
LDT1	1.3–4.9	0.3–1.2	4.3	10	6	71–268
LDT2	1.3–4.9	0.3–1.2	4.3	57	38	412–1,549
MDV	1.3–4.9	0.3–1.2	4.5	6	6	49–183
LHD1	1.3–4.9	0.3–1.2	5.7	3	3	31–116
LHD2	1.5–5.7	0.4–1.4	5.7	2	3	26–99
MH	1.5–5.7	0.4–1.4	5.0	1.2	1.8	14–52
T6	1.5–5.5	0.4–1.4	6.2	5.5	5.5	68–256
T7	1.4–5.3	0.4–1.3	14.3	3	17	160–602
Total						**1,277–4,802**

5.6 Task 5e: Remaining Questions

22RD002 project undertook many "firsts" with respect to on-road measurement of brake and tire wear. The following research questions are designed to address uncertainties identified during the development of the sampling system, on-road testing, and interpretation of results in CARB Project 22RD002.

1. How can the brake enclosure design be optimized to maintain representative brake temperatures without compromising collection efficiency?
2. What methods can be employed to minimize particle losses within complex geometries of the brake enclosure?
3. How can tire sampling systems achieve higher collection efficiency given the open nature of the tire-road interface?
4. What design modifications or flow control strategies can reduce impaction losses at the tire sampling inlet?
5. How does variability in vehicle speed, payload, and driving cycles influence PM and PN emissions for both brakes and tires?
6. What is the effect of pavement type and condition on tire PM emissions under real-world conditions?
7. How can background PM and resuspended road dust be accurately quantified and subtracted during on-road tests?
8. What repeatability metrics are needed to establish confidence in on-road measurements given traffic and environmental variability?
9. What advanced chemical source apportionment techniques can reliably separate tire wear particles from road dust and brake emissions?
10. How can elemental markers (e.g., Zn for tires, Ba for brakes) be standardized for consistent interpretation across studies?
11. What is the best method for characterizing the chemical composition of tires to reflect on-road operation while minimizing contamination from other sources, for use in source apportionment studies?
12. What is the uncertainty range in estimating tire contribution to total PM using PMF and CMB models, and how can it be reduced?
13. How do particle size distributions differ between brake and tire sources, and what implications does this have for health risk assessment?
14. What assumptions in scaling emission factors to statewide inventories introduce the greatest uncertainty, and how can these be validated?
15. How can wear indices (BWI and TWI) be refined to better represent variability in real-world conditions? How well do these metrics track variations in per-mile emissions?
16. What additional data are needed to model emissions from electric vehicles and regenerative braking systems accurately?

6.0 Task 6: Comparison of on-road brake to Dynamometer

In this task, ERG analyzed the on-road brake PM measurements to compare them with the measurements and results from Project 17RD016. In 17RD016, LINK collected and measured brake emissions from actual light duty vehicle brake assemblies operating over a prescribed test cycle on a brake dynamometer. Particle measurements included PM mass, measured continuously and gravimetrically, particle number, and particle size distributions. The goal of comparison with 17RD016 is to determine similarities and differences between on-road in-use brake-wear PM measurement and laboratory measurement.

6.1 Project 17RD016 Review

Project 17RD016 involved the development of a novel brake dynamometer test cycle, testing of the front and rear brake assemblies of six light duty vehicles, and measurement of PM and PN. During the project ERG developed the California Brake Dynamometer Cycle (CBDC), and testing was conducted at Link's Dearborn, MI automotive test laboratory.

6.1.1 Test Vehicles

Six vehicles were selected for testing, representing high-sales volume vehicles across a range of LDV types. Front and rear brake assemblies from the following vehicles were tested on the brake dynamometer:

- 2011 Toyota Camry LE
- 2013 Honda Civic LX
- 2013 Toyota Sienna LE
- 2015 Ford F-150 Supercrew
- 2016 Toyota Prius Two Eco
- 2016 Nissan Rogue S

All test vehicles were equipped with front and rear disc brakes except the Civic, which was equipped with front discs and rear drum brakes. For comparison with the Silverado 2500 test vehicle from 22RD002, which had a test weight of 6,360 lbs, the two closest vehicles in test weight are the F-150 at 5,640 lbs, and the Sienna at 4,750 lbs. The analyses in this section will compare with only these two most relevant vehicles. Also, because only the rear brake of the Silverado was measured during 22RD002, only the rear brake findings for the F-150 and Sienna will be used for comparison.

6.1.2 Test Cycle

One of the early tasks of 17RD016 was to determine if an existing chassis dynamometer test cycle would allow for brake testing that would be representative of real-world braking operation or if a new test cycle would be needed. ERG used the 2010-2012 Caltrans Household Travel Survey data as the source of typical California driving. This data included onboard diagnostic (OBD) speed trace data from thousands of vehicles operating across the state. Using this data, ERG determined that a novel test cycle could better represent the braking of actual in-use vehicles. ERG used the OBD data to develop the CBDC, a representative braking test cycle that was created to best match the braking of the in-use vehicles on the basis of brake event duration, average speed during braking, average deceleration rate during braking, and average modeled brake temperature during braking. The final test cycle was just over four hours in duration and represented a distance of 131 km. It should be noted that, to minimize unnecessary representative steady-state cruising, the CBDC represents a driving distance that is greater than would be calculated from the total revolutions of the dynamometer. The represented distance is larger than the dynamometer revolutions in part because the distance traveled between braking events is much longer than the distance traveled during braking events but, in a brake cycle, only the braking (and brake cooling between events) needs to be simulated. The test cycle is purely a dynamometer test cycle; it is not intended to be able to be driven on a vehicle operating on a test track.

One limitation of the mechanical function of the brake dynamometer used in Project 17RD016 was that it was unable to accurately simulate braking events with a duration of less than three seconds. So, the test cycle did not include any brake events of one or two seconds but was over-weighted with events of three second duration to partially mitigate this.

6.1.3 Test Articles

Multiple brake pad materials were selected for the front and rear assemblies of all test vehicles. For the case of the F-150, the rear pad materials were:

- Original Equipment Service (OES), which was a non-asbestos organic (NAO)
- A selected aftermarket NAO
- A selected aftermarket low metallic (LM)

For the case of the Sienna, only two pad types were tested:

- OES, which was NAO
- A selected aftermarket NAO

During 17RD016, no brake pads that were specifically marketed or labeled as ceramic were tested.

6.1.4 Test Lab Setup

The LINK test laboratory that was used in 17RD016 was built around a constant volume (i.e. air velocity) sampling system that operates in a closed-airflow circuit. The airflow through the test enclosure provided the sampling medium for emitted PM as well as the cooling flow for the brake assembly. The cooling and airflow rates were held constant during the test and were set for each brake assembly to result in representative operating temperatures. A schematic of the LINK laboratory layout is presented in Figure 74.

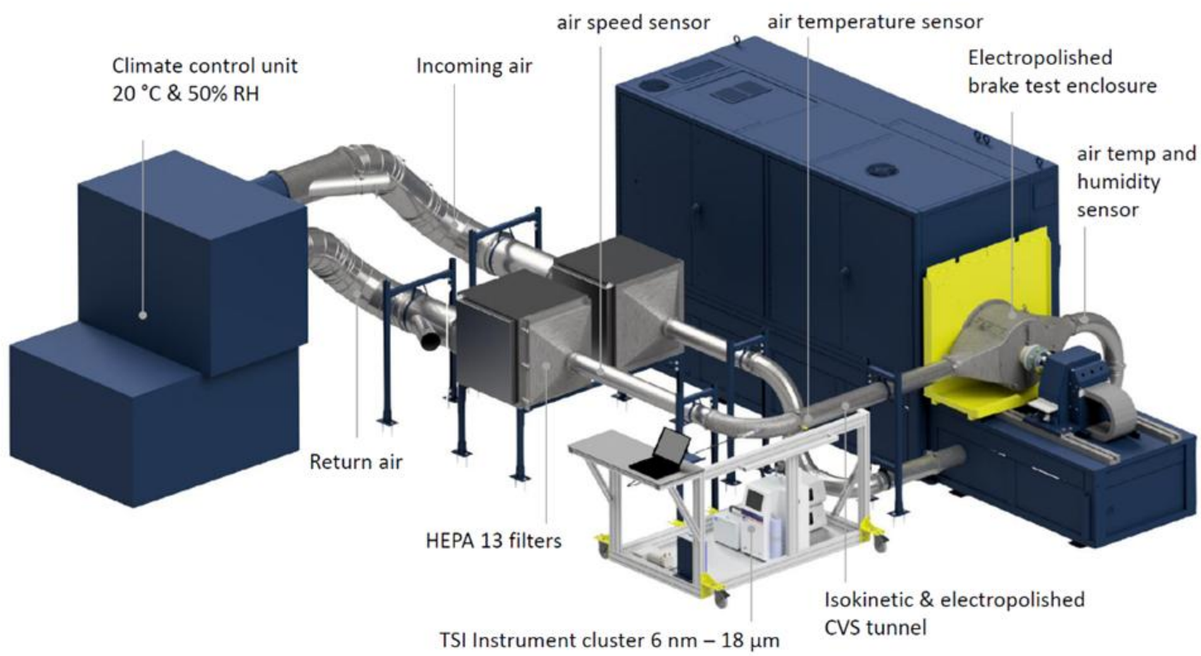

Figure 74. Schematic of LINK Laboratory Setup

The airflow circulating layout used round ducting in stainless steel with internal electropolished finish and eight diameters without disturbances between the brake assembly enclosure and the point of sampling. The sample duct was oriented horizontally, and samples were taken at the point of entry of flow into the 90° elbow downstream of the brake enclosure. Sampling took place using four separate sampling lines, each originating from an isokinetic sample nozzle arranged in parallel at the upstream end of the sampling elbow. From the brake assembly enclosure to the sampling instrumentation, the layout was designed to minimize aerodynamic losses with minimal bends and constrictions. Sampling was performed isokinetically (0.95 to 1.15 isokinetic according to ISO 9096) to avoid skewing the particle size distribution data. A transport time of less than five seconds from brake assembly to instrument was specified, with a target transport time of two seconds.

The LINK brake dynamometer simulated the rotation and braking functions for a single brake assembly. The system used both an electric servo motor and the line pressure of the hydraulic brakes to follow a set speed trace over time. The dynamometer controller balanced the braking and motor torques based on the programmed vehicle road load and inertia. The inertia is the simulated wheel load at the tested brake corner, and the road load describes the force curve representing the drag on the vehicle across a range of speeds when traveling along a level road. One significant difference in the operation of the brake dynamometer and a chassis dynamometer is the need to split the braking force between the front and rear brakes. Because vehicle weight is transferred forward during braking, the front brakes are designed to absorb and convert a larger amount of energy than rear brakes. To estimate this, LINK used the Society of Automotive Engineers (SAE) standard J2789, Inertia Calculation for Single-Ended Inertia-Dynamometer Testing, which specifies how this energy split can be simulated. For the F-150, the front inertia was set at 161 kg·m^2 and the rear was set at 58.6 kg·m^2. The Sienna front inertia was 98 kg·m^2, and the rear was 47.5 kg·m^2.

6.1.5 Measurement Instruments

Table 28 presents the instrument and/or techniques used during 17RD016 and the respective measurement capability of each. The instruments allowed for both batch and real-time measurement of PM mass, and also included particle counts and particle size distribution.

Table 28. Project 17RD016 Measurement devices and their respective measurement capabilities

Measurement device	Measurement Capability
47mm filter holder	Batch gravimetric measurement of PM10
TSI 100S4	Batch PM mass with various size cutpoints
TSI Quartz Crystal Microbalance (QCM) MOUDI	Real-time PM2.5 mass concentration
TSI Condensation Particle Counter (CPC)	Real-time particle counts
TSI Aerodynamic Particle Sizer (APS)	Real-time particle size distribution between 0.5-20 µm.
TSI Engine Exhaust Particle Sizer (EEPS)	Real-time particle size distribution from 5.6 – 560nm

6.2 Comparison of Test Cycles

The on-road test routes followed in this work were not intended to match the CBDC on any specific basis. So, to compare the emission rates measured over these routes as compared to the CBDC, it is necessary to consider the characteristics of each so that measurements can be compared on an appropriate basis.

In Project 17RD016, the brake dynamometer continuously measured brake torque while controlling the brake hydraulic pressure and axle speed to follow the test cycle. However, during the on-road testing in this project, the driver followed only the route while logging vehicle speed; no specific control or measurement of braking torque or hydraulic pressure was included. So, for the on-road testing, the assignment of brake events and their relative intensity must be assigned in the post-processing of the logged data. The project team used the GPS log from each test to assign braking events and calculate braking parameters based on an energy balance calculated by the vehicle's speed and elevation.

The following equation describes the overall energy balance of the vehicle with respect to the braking system. It describes the sum of the energy sources and sinks during braking.

$$P_b = -aVM - P_{ro} - P_l - P_{st} - P_{fric}$$

Where:

Pb - Braking Power

a – Vehicle acceleration (negative during deceleration)

V – Vehicle velocity

M – vehicle mass

P_{ro} – The power dissipated by the vehicle's rolling resistance

P_l – The power dissipated by the vehicle's aerodynamics

P_{st} – The rate of change in potential energy associated with change in elevation

P_{fric} – The power dissipated by the engine during deceleration (i.e. engine braking and engine friction)

EPA publishes road load information for all vehicles sold in the United States as a part of publishing new vehicle chassis-dyno exhaust emissions test results.[63] The road load data is generated from performing a coast-down of each vehicle with the transmission in neutral. The project team used the published road load coefficients for the test vehicle to help inform the estimates of Pro and Pl, but the published data does not include any information that can inform Pfric during deceleration and braking because the coastdowns are performed in neutral. The project team assumed that, because the test vehicle has a diesel engine, that engine braking would be minimal and that the engine friction would be the dominant aspect of the Pfric term. The project team used the Willans-line friction correlation estimate to assume that the engine friction would be 1.9kW during deceleration.

The Pst term can become dominant in the calculation of brake power with even moderate changes in vehicle elevation. Because GPS data is less accurate in vertical measurement than in horizontal measurement, the elevation signal tends to have more noise than the speed signal. To mitigate large effects on the power calculation due to noise in elevation, the GPS elevation signal was smoothed using Savitzy Golay smoothing of order two and a frame length of 21 seconds (i.e. ten seconds forward and ten seconds backward).

In the braking analysis, the braking power was calculated on a second by second basis. Any second of data in which Pb was calculated to be greater than zero was considered to be braking. If Pb was negative, braking energy was set to zero for that second of data and it was flagged as not braking. Using this method, the project team could calculate the number of braking events, the total duration of braking, the total braking energy of a given test. Likewise, for comparison with the CBDC, the same calculations were used to estimate the braking energy statistics for the same test vehicle if it were operated over the CBDC (i.e. the same road loads and vehicle mass assumptions were used).

Table 29 presents various braking statistics for the Riverside route, the CA-60 highway route, and the CBDC. For the two on-road test routes, the table presents the averages calculated over all valid tests. The distance and cycle duration are averages of all respective tests; however, braking and energy calculations are presented only for the base test weight, not the heavily loaded weight. Likewise, CBDC values are estimated for the Silverado at the vehicle level (i.e. operating at test weight, not isolated only to a single wheel). Note that, for the CBDC results, factors that include or are calculated from the cycle distance use the cycle's represented distance as the basis.

Table 29. Various Braking Statistics for the On-Road Test Routes and the CBDC (calculated for Silverado test vehicle)

Route	Distance (km)	Duration (s)	Average speed (m/s)	Braking Time (s)	Braking Energy (kJ)	Avg Spd During Braking (m/s)
Riverside Local	41.3	4,147	10.1	851	20,993	11.3
CA - 60 Highway	88.1	4,514	19.9	589	14,629	13.8
CBDC	131	14,933	8.8	1,282	24,253	10.3

To facilitate comparison of results across cycles, it is necessary to normalize measurements against an appropriate basis. The following series of graphs presents the cycle statistics for the Silverado operating at test weight, normalized in different ways. Figure 75 presents the total braking time on a distance basis. The Riverside route has more braking time per unit distance; the CA-60 highway has the least. Of the two cycles used in this work, the CBDC is more directly comparable with the CA-60 highway route on the basis braking time per distance traveled.

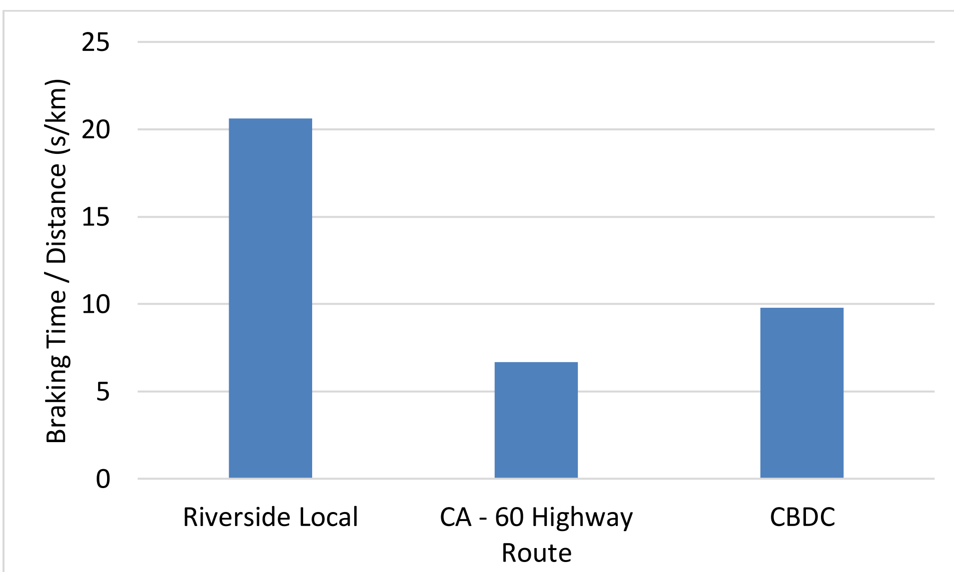

Figure 75. The total braking time per unit distance for the two on-road cycles and the CBDC.

Figure 76 presents the total vehicle-level braking energy for the Silverado, calculated on a distance basis. The Riverside route has the highest braking energy. Of the two on-road routes used in this work, the CBDC is more comparable to the CA-60 Highway route on the basis of brake energy per distance traveled.

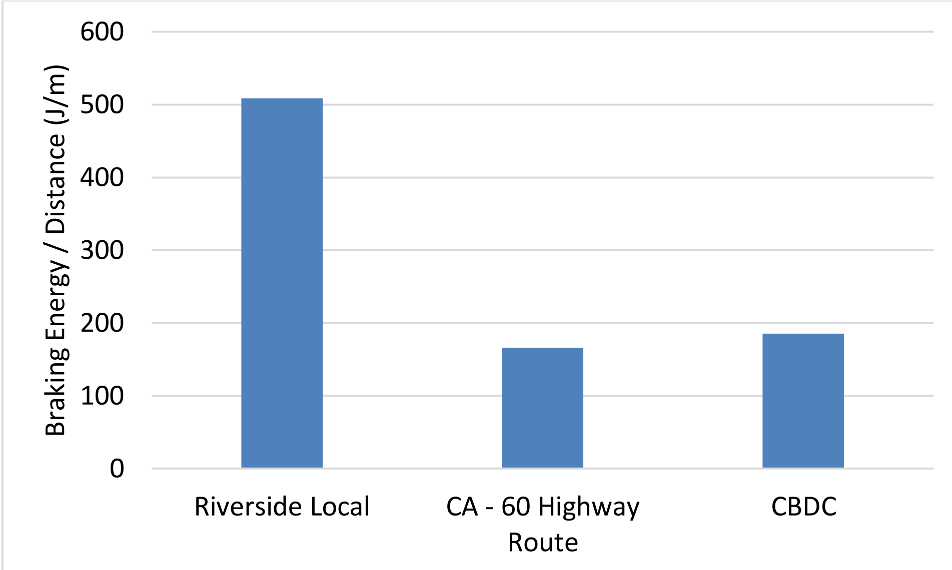

Figure 76. The total braking energy per unit distance for the two on-road cycles and the CBDC

Figure 77 presents the total braking energy on the basis of total braking time. This is a measure of the relative braking intensity during the braking events themselves (irrespective of the frequency of braking). The three cycles are more similar when normalized in this manner; but the CBDC has lower braking intensity than the on-road cycles.

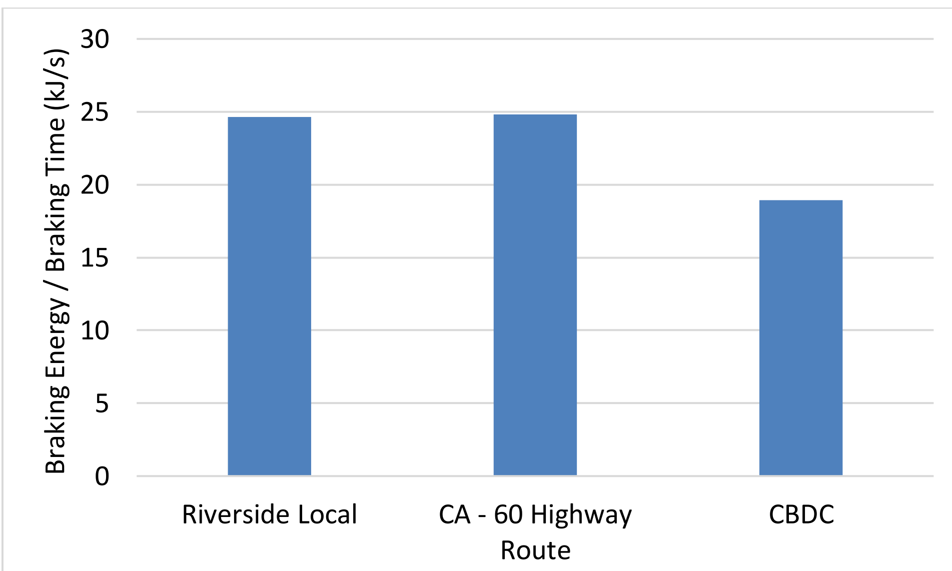

Figure 77. The total braking energy per divided by total braking time for the two on-road cycles and the CBDC

6.3 Emission Measurements

The first comparison of the measured emission rates of the on-road tests in this project with the brake dynamometer tests in 17RD016 is brake PM emission mass as calculated with gravimetric filter measurements of PM2.5 and PM10. Emission rates presented in this section will be on the basis of emissions for a single wheel; either the single wheel mounted to the brake dynamometer, or the single wheel instrumented for brake measurement in this study.

Figure 78 presents the overall mass emissions per mile, averaged by vehicle, test cycle, and pad material for the two projects. Emission rates are classified by PM2.5 and PM10 and error bars represent the standard deviation across tests (missing error bars indicate only a single test was performed for the combination). The graph shows a general trend of increasing emission rates with increasing vehicle weight. Also, the emissions of the Silverado on the Riverside route are notably higher than the emissions on the Highway route due to the greater levels of braking in that cycle.

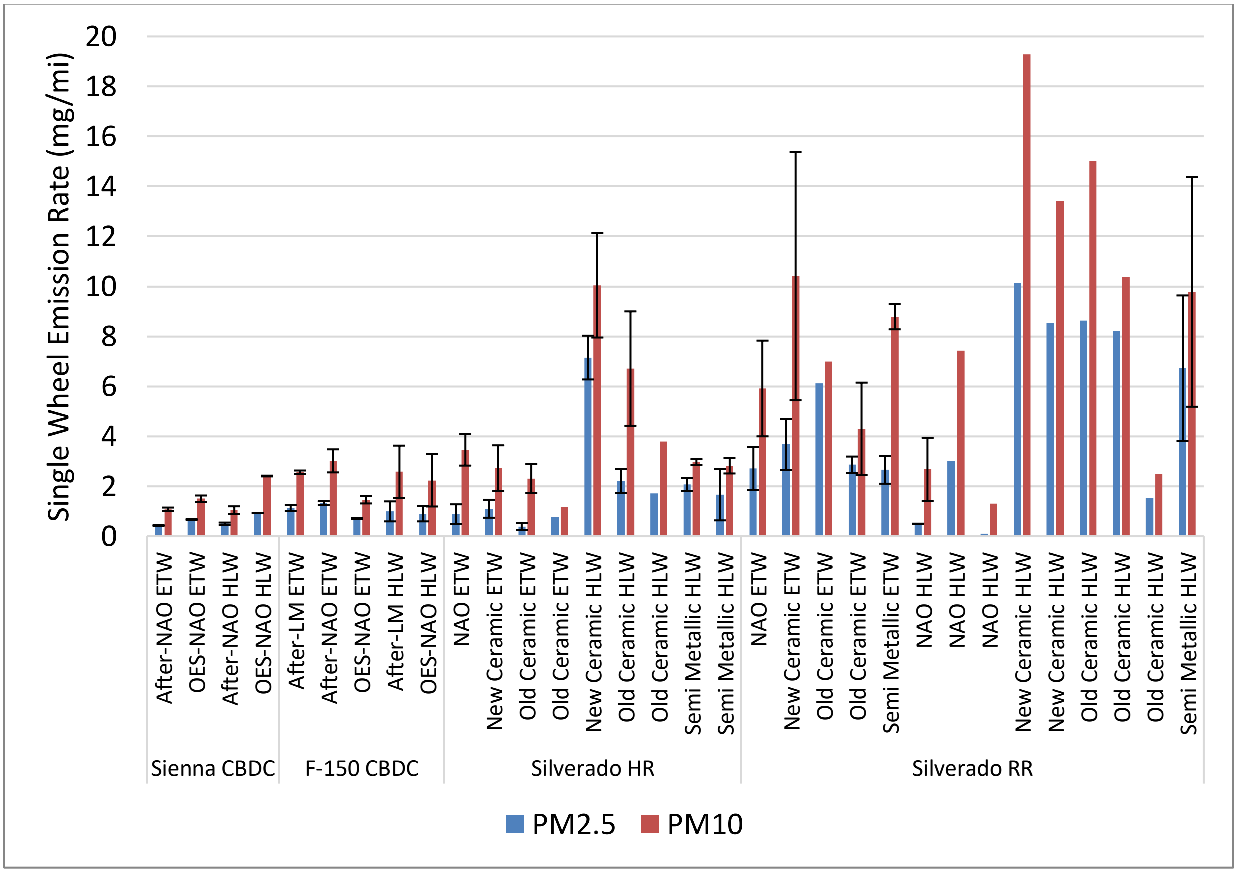

Figure 78. Rear wheel per-distance emission rates of the 17RD016 vehicles compared to the measurements in this work

The two key confounding factors in comparing the emission rates observed across projects are the different vehicle weights and the different intensity of braking over the three test cycles. To further analyze the differences in observed measurements, Figure 79 presents the average PM2.5 emission rates on the basis of vehicle weight, showing the trend of increasing emissions with increasing vehicle weight. Likewise, Figure 80 presents a comparable plot for PM10. Note that the figures present the Sienna and F-150 results over the CBDC, and the Silverado results over the CA-60 Highway route as that was the most comparable in terms of the relevant cycle statistics. Presented values represent the average emission rates of a given model, loading, and pad type, and dashed lines show linear fits for each pad material type. Both figures are labeled with the vehicle model and payload corresponding to the respective test weight along the x-axis. Note that the OES-NAO pad was only tested for the 17RD016 vehicles; likewise, the ceramic pad was only tested on the Silverado. “After-“ indicates aftermarket pads; all 22RD002 pads were aftermarket pads. In the plot, low metallic and semi metallic pads are grouped under LM. Due to the elevated noise in the measurement of the new ceramic pad and inability to directly compare it to 17RD016 tests, the new ceramic pad results are excluded from the graphs.

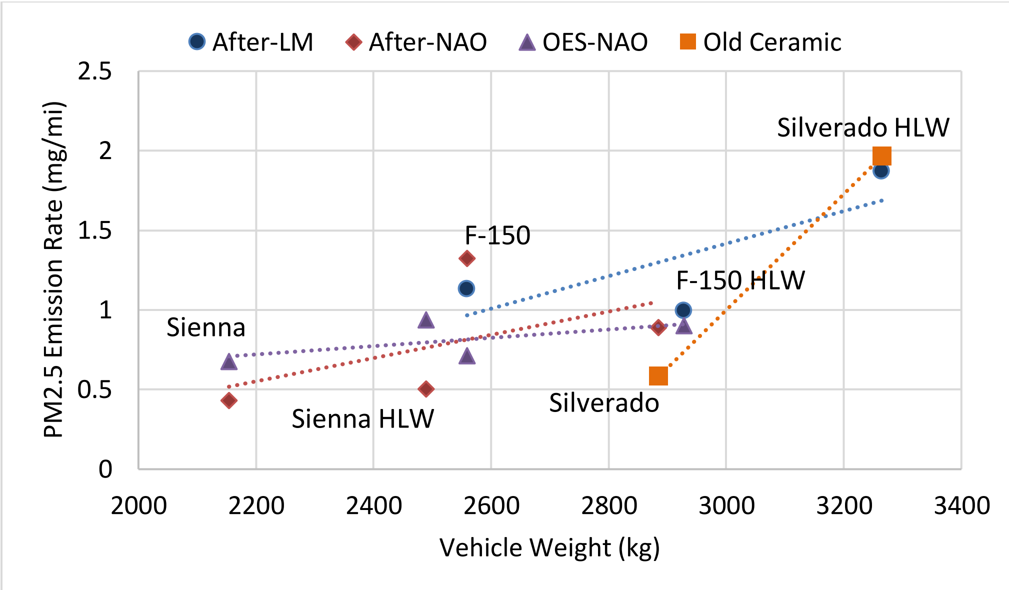

Figure 79. Individual wheel (rear) PM2.5 emission rates presented on the basis of vehicle test weight.

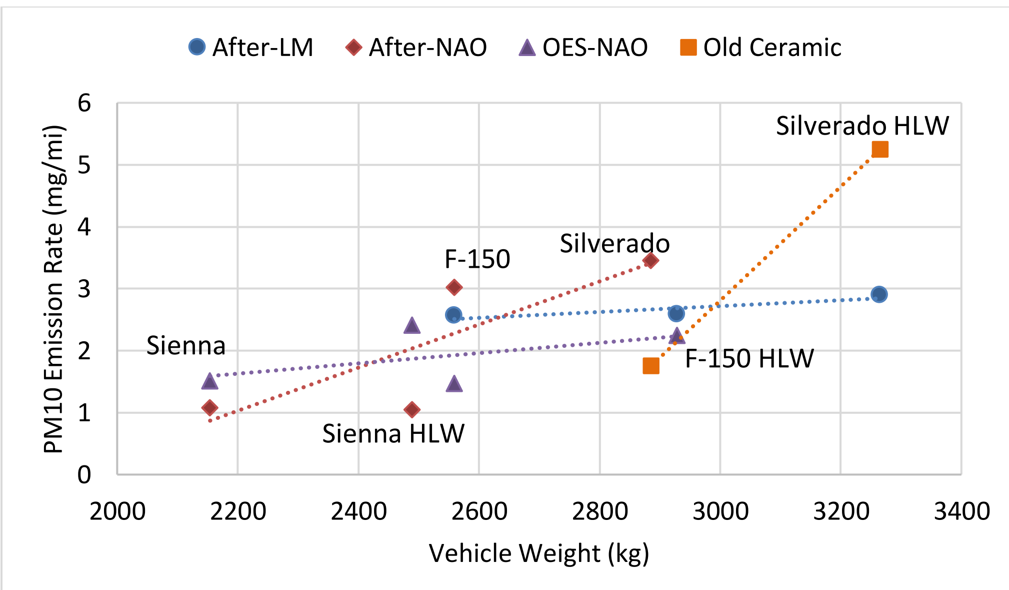

Figure 80. Individual wheel (rear) PM10 emission rates presented on the basis of vehicle test weight.

The effects of different vehicle weights and braking characteristics of the test cycles can be further accounted for by presenting the emission rates on the basis of emission mass divided by total braking energy, which will normalize for both the vehicle weight and cycle braking intensity. Figure 81 displays the emission rates averaged for each combination of vehicle, route, test weight, and brake pad type, presented on the basis of total single-wheel emission mass divided by total vehicle-level braking energy over the cycle. Error bars present the standard deviation across tests. It can be seen that the emission rates show much greater levels of agreement across projects, test vehicles, and routes when presented on this basis. Note that vehicle-level braking energy levels are calculated specifically with the mass and road load of each respective test vehicle. It can be seen that the on-road tests have greater variability in results. It is likely that the on-road measurement system has more noise than the laboratory setup, but some of the increased variability is due to the variability in the driving route such that caused by traffic and stoplights, etc., whereas the CBDC was conducted in the same manner by the laboratory dyno controller in every test.

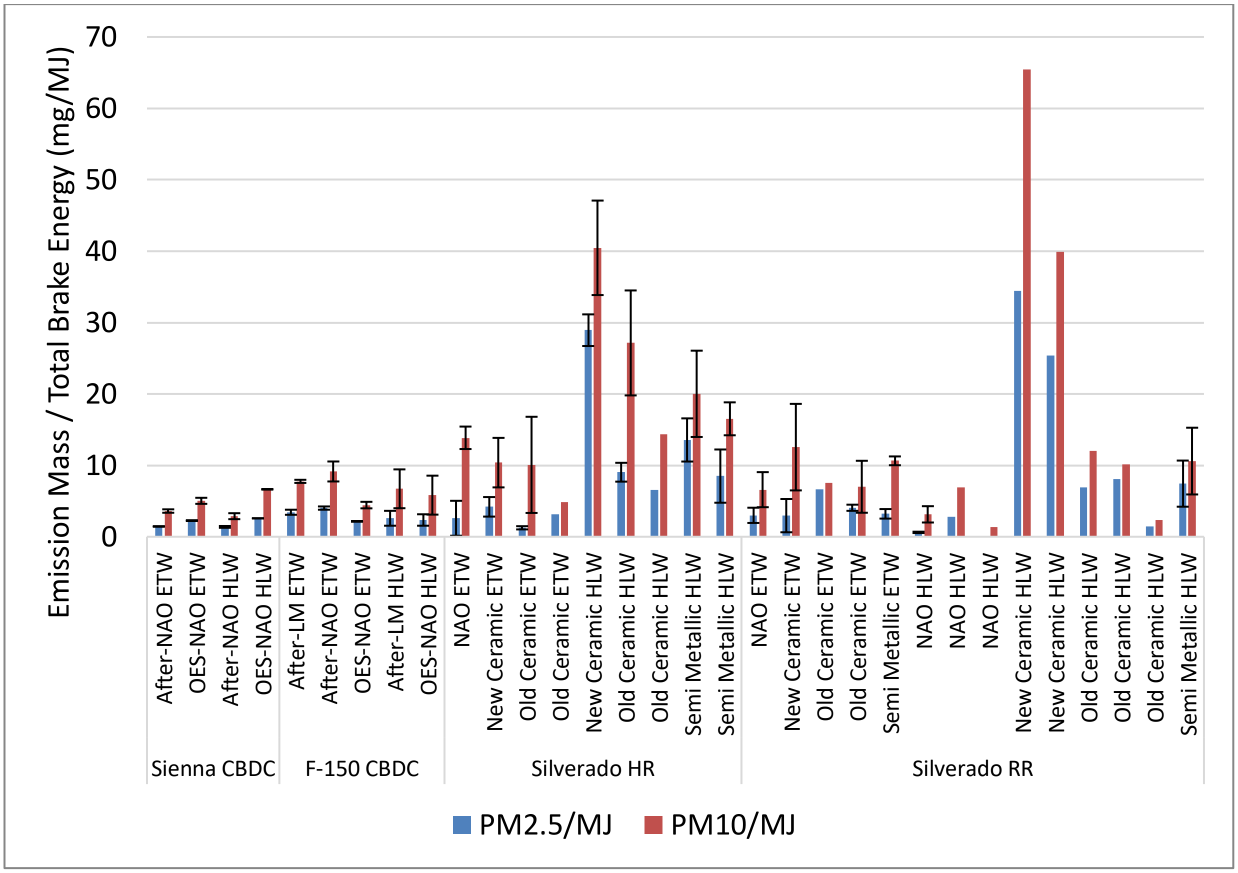

Figure 81. Rear-wheel braking emission rates divided by braking energy for the 17RD016 and 22RD002 test vehicles

Both projects included measurement of PN. In 17RD016, PN was measured by a TSI CPC, which measures total particle number concentrations by growing particles above activation size through vapor condensation and is largely insensitive to particle composition or electrical charge. The ELPI+ used in this project sizes and counts particles based on electrical charging and subsequent current measurements across impactor stages. Table 30 presents statistics on the measured brake PN emission rates for a single rear wheel at the test level across both projects. The measured brake PN emission rates differed by multiple orders of magnitude across the two projects, and it is likely that the different measurement instruments are a main cause of the large observed differences. The ELPI+ used in this work has a nominal particle size range of 6nm - 10µm. The TSI 3790A CPC used in 17RD016 has a nominal particle size range of 23nm – 3µm.

Table 30. Statistics of the observes PN measurements across tests in 17RD016 vs. this work, in particle counts per mile.

#/mi	17RD016, All Sienna and F-150 Tests	22RD002, All Silverado Tests
Average	1.22E+09	3.12E+14
Median	1.18E+09	3.66E+13
Maximum	2.58E+09	5.40E+15
Minimum	4.82E+08	4.29E+12

Both projects also included measurements of particle size distributions. As with the particle counts, the different instruments had different nominal size distributions of measurement. The ELPI+ size distribution is the same as it is for particle counts, 6nm - 10μm. Project 17RD016 included measurement with a TSI EEPS, size range 5.6 to 560 nm, as well as a TSI APS, size range 0.5 to 20μm. So, the range of the ELPI+ is covered by both projects, though the APS and EEPS use different measurement techniques so they do not measure equivalently across the entire range of both instruments. For comparison, size distributions for the ELPI+ are separately normalized (i.e. particle counts sum to 1) in the range from 5.6 to 560 nm for comparison with the APS, and again from 0.5 to 10 μm for comparison with the EEPS.

Figure 82 presents the normalized size distributions for the rear brake assemblies of the test vehicles from 17RD016 and the Silverado tests over the Riverside and Highway Routes, grouped by brake material and weight loading. All four sets of tests indicate a clear dominant peak in the range of 10-15 nm, and a secondary minor peak across a larger range from 35-60 nm. Note that the x-axis is scaled according to the outputs of the two measurement devices; the smaller size bins are spaced more widely, and the larger size bins are spaced more closely to better depict resolution at the smaller end. The overall trends in particle size distributions in this size range show good agreement between vehicles across the two projects. The prominent peak around 10-15 nm may, in part, be the cause of the large differences in particle number described previously as that peak is below the measurement range of the TSI CPC used for PN measurement in Project 17RD016.

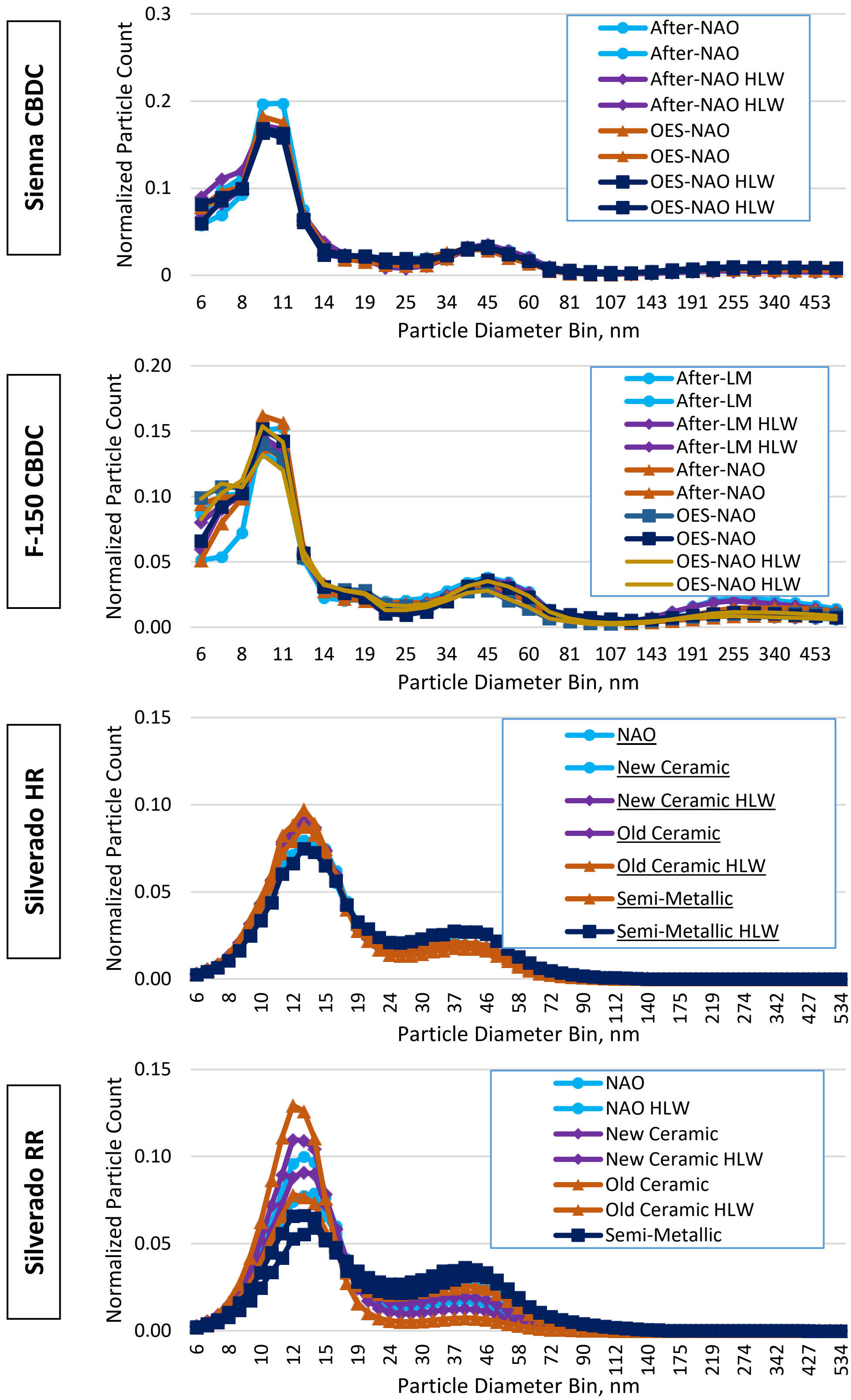

Figure 82. Normalized size distributions in the range of 6 – 560 nm

Figure 83 presents similar size distribution graphs, normalized for the size ranges from 0.5 to 10 µm. The APS measurements in 17RD016 show a single or double peak in the range from 1-3 µm.

However, the ELPI+ measurements in this project show a single peak at 0.7 to 0.9 μm. It is possible that the size differences of these peaks are due to differences in the ELPI+ and APS measurement types. The APS measures on an aerodynamic diameter equivalent, which may bias the measured size distribution of dense and irregularly shaped brake particles upward. Conversely, the ELPI+ determines particle size from stage-specific aerodynamic cutoffs combined with electrical detection, for which brake particle bounce and particle charging can shift the measured size distribution downward slightly in apparent diameter.

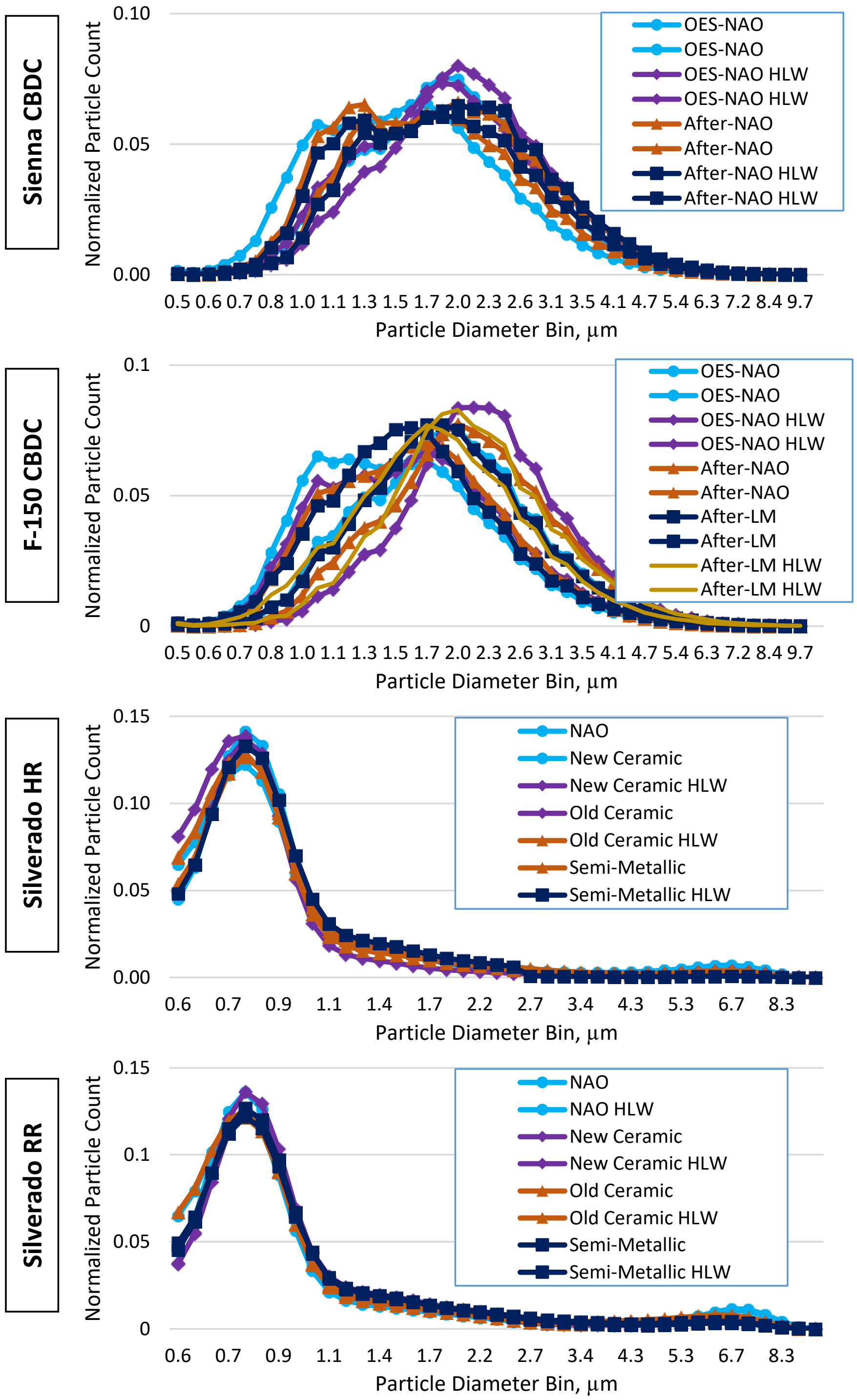

Figure 83. Normalized size distributions in the range of 0.5 – 10 μm.

7.0 SUMMARY OF FINDINGS

The ambitious scope of CARB Project 22RD002 has yielded several new findings which can inform researchers and policy makers on the challenges and opportunities of real-world measurement of brake and tire emissions. Foremost, the work of the research team confirms that on-board measurement of brake and tire emissions in real-world conditions is feasible, and can provide valuable insights difficult to ascertain in controlled environments. However, the results also confirm significant uncertainty in isolating tire emissions from on-road testing. The following are highlights of important findings from this work, which provide a strong foundation for ongoing assessment of on-board measurement pros and cons:

On-road brake and tire sampling is feasible: The project successfully designed and fabricated two innovative on-vehicle PM sampling systems—a fully enclosed brake system and a semi-closed tire system—adapted for real-world operation on a Chevrolet Silverado 2500. These systems integrated gravimetric filters and real-time instruments (ELPI+, APS, DustTrak) to measure PM2.5, PM10, and particle number under actual driving conditions.

Accurate quantification of collection efficiency is paramount: The collection efficiency analysis showed that the brake sampling system, being fully enclosed, achieved very high recovery rates, with transport efficiency exceeding 90 percent for particles smaller than 4 µm and remaining above 70 percent for particles up to 10 µm. In contrast, the tire sampling system, which is open to ambient air, exhibited lower overall efficiency across most size ranges despite design improvements such as added side panels and increased flow rates. Efficiency tests using particle generators confirmed that tire sampling efficiency is inherently more challenging to quantify, and even with enhancements, it remains significantly lower than for brakes due to the complex airflow and open geometry at the tire-road interface.

On-vehicle sampling allows testing under realistic conditions: On-road testing was conducted over city and highway routes (CA-60 concrete, I-215 asphalt) with varied payloads and traffic conditions, capturing representative braking intensities and tire-road interactions. This approach provided emissions data that reflect real-world variability, unlike controlled laboratory or dynamometer studies.

Brake emissions vary meaningfully by friction material: Brake PM emissions were highest on the city route and lowest on highways, correlating with braking intensity. Ceramic pads produced the highest PM emissions, while NAO pads emitted the least; PN emissions were dominated by ultrafine particles (10–15 nm), highlighting the importance of material choice and driving conditions.

Brake emissions on real-world city driving are higher than previous dynamometer studies: On-road brake mass emissions and size distribution compare well with dynamometer results for similar braking intensities after accounting for differences in vehicle weight; particle number did not, likely due to instrumentation differences although further investigation is required to confirm. However, on-road brake emission factors for city driving were 4–5 times higher than EMFAC estimates derived from the CARB 17RD006 program for PM2.5 and 2–3 times higher for PM10, due largely to higher braking intensity than the CDBC cycle, though differences in brake burnish may contribute as well. This underscores the need to update brake emissions inventories to account for real-world driving, and re-assess the representativeness of dynamometer cycles for brake emissions.

On-road tire sampling produced measurable results, but also confirms multiple sources in the sample : Tire PM emissions varied by route type and tire brand. City routes generated higher PM mass than highways, likely due to more frequent friction events (acceleration, deceleration, cornering). However, analysis of elemental profiles derived from XRF suggests the presence of brake, crustal material, and marine (sea salt) sources in the samples, confounding results.

Source apportionment shows promise for isolating tire emissions from on-road sample: The project applied chemical analysis and EPA PMF modeling to identify sources that matched well with independent source profiles, including tire testing on a dynamometer, estimating ~16 percent of the on-road sample is attributable to tire. An independent tire source profile was also applied to XRF results, and when conservatively using Zinc as a constraining marker element estimates ~ 4-5 percent tire contribution. This demonstrates that source apportionment is useful for isolating tire emissions from an on-road sample, but is subject to uncertainty depending on the quality of source profile inputs.

Tire Wear Index (TWI) provides a means for scaling emissions across tire size: A Tire Wear Index was developed to scale measured emissions to California's fleet based on tire size, tread depth, void percent and mileage rating. This metric provides a means to scale test results across a broad range of vehicles, but merits validation with emissions across different tire sizes.

Tire emission insights from this study can serve to improve EMFAC: Although EMFAC-based statewide tire PM estimates fall within the range derived from on-road estimates, test results from this study suggests a need to revisit speed corrections and EF differences between vehicle classes in EMFAC.

Overall, this study brings to light both the promise and challenge of on-road measurement of tire and brake emissions. Several important questions have emerged in considering how to improve on-board measurement for application in regulatory context. These include how to improve tire collection efficiency, how to refine the characterization of chemical markers for tire PM, and applicability of this method to a broad range of vehicles from passenger cars to Class 8 trucks. This first-of-its-kind study has produced both meaningful results and valuable lessons learned for the continued development of realistic characterization of non-tailpipe emissions.

APPENDIX

On-Road Brake Test Log

Date	Time	Cycle	Friction Material
2025/03/25	06:30	City Route	Original Ceramic
2025/03/25	14:00 ---- 15:30	City Route	Original Ceramic
2025/03/26	03:30 ---- 04:31	Highway -CA60 Route	Original Ceramic
2025/03/27	3:30---4:57	City Route	Original Ceramic
2025/03/27	5:40---7:12	Highway -CA60 Route Loaded	Original Ceramic
2025/03/27	7:45---8:55	Highway -CA60 Route Loaded	Original Ceramic
2025/03/27	16:13---17:22	City Route Loaded	Original Ceramic
2025/04/01	06:45	City Route	Nao
2025/04/01	08:05	City Route	Nao
2025/04/03	06:15—07:36	Highway -CA60 Route	Nao
2025/04/03	08:00—9:15	Highway -CA60 Route	Nao
2025/04/03	11:35—12:45	City Route	Nao
2025/04/03	14:20—15:40	City Route Loaded	Nao
2025/04/04	10:29 ----11:38	City Route Loaded	Nao
2025/04/07	12:18----13:34	Highway -CA60 Route Loaded	New Ceramic
2025/04/08	7:45—9:05	City Route Loaded	New Ceramic
2025/04/08	9:30—10:23	City Route Loaded	New Ceramic
2025/04/08	11:30----12:36	Highway -CA60 Route Loaded	New Ceramic
2025/04/08	13:30----14:35	City Route	New Ceramic
2025/04/09	11:37----12:43	City Route	New Ceramic
2025/04/09	13:38----14:46	City Route	New Ceramic
2025/04/10	07:30	City Route Loaded	Original Ceramic
2025/04/10	09:00	City Route Loaded	Original Ceramic
2025/04/10	10:40	Highway -CA60 Route Loaded	Original Ceramic
2025/04/10	12:25	Highway -CA60 Route	Original Ceramic
2025/04/10	14:20	City Route	Original Ceramic
2025/04/21	10:12----11:22	City Route	Semi-Metallic
2025/04/21	11:44----12:58	City Route	Semi-Metallic
2025/04/22	08:09----09:13	Highway -CA60 Route	Semi-Metallic
2025/04/22	10:37----11:37	Highway -CA60 Route	Semi-Metallic
2025/04/24	07:45----08:54	Highway -CA60 Route Loaded	Semi-Metallic
2025/04/24	09:31----10:29	Highway -CA60 Route Loaded	Semi-Metallic
2025/04/28	10:24----11:37	City Route Loaded	Semi-Metallic
2025/04/29	08:06----09:21	City Route Loaded	Semi-Metallic
2025/04/29	10:10----11:07	City Route	Semi-Metallic

On-Road Tire Test Log

Date	Time	Route	Tire
06/27/2025	12:00	City Route	Original Firestone
07/01/2025	09:40	City Route	Original Firestone
07/10/2025	8:50	Highway Route -I215	Original Firestone
07/10/2025	11:15	Highway Route -I215	Original Firestone
07/10/2025	13:45	City Route	Original Firestone
07/11/25	08:50	Highway Route -CA60	Original Firestone
7/14/25	11:15	Highway Route -I215	Original Firestone
07/14/25	13:45	Highway Route -CA60	Original Firestone
7/15/25	06:30	Highway Route -CA60 Loaded	Original Firestone
7/15/25	08:15	Highway Route -CA60 Loaded	Original Firestone
8/7/25	8:00	City Route	New Firestone
8/7/25	10:00	City Route	New Firestone
8/7/25	11:45	Highway Route -I215	New Firestone
8/7/25	13:45	Highway Route -CA60	New Firestone
8/11/25	10:40	Highway Route -I215	New Firestone
8/11/25	12:35	City Route	New Firestone
8/12/25	8:10	Highway Route -CA60 Loaded	New Firestone
8/12/25	9:50	Highway Route -CA60 Loaded	New Firestone
8/12/25	11:35	Highway Route -CA60	New Firestone
8/14/25	07:15	City Route	New Firestone
8/19/25	08:25	Highway Route -I215	Michelin
6/27/2025	12:00	City Route	Michelin
8/19/25	10:10	Highway Route -CA60	Michelin
8/20/25	08:25	Highway Route -CA60	Michelin
8/20/25	10:30	Highway Route -I215	Michelin
8/20/25	13:00	City Route	Michelin
8/21/25	07:10	City Route	Michelin
8/21/25	10:30	Highway Route -CA60 Loaded	Michelin
8/21/25	13:10	Highway Route -CA60 Loaded	Michelin
8/22/25	6:30	City Route	Michelin
8/26/25	6:15	City Route	Goodyear
8/26/25	7:50	City Route	Goodyear
8/26/25	10:35	Highway Route -I215	Goodyear
8/26/25	12:05	Highway Route -CA60	Goodyear

Date	Time	Route	Tire
8/26/25	13:30	Highway Route -I215	Goodyear
8/27/25	6:25	Highway Route -CA60	Goodyear
8/27/25	8:15	Highway Route -CA60 Loaded	Goodyear
8/27/25	10:05	Highway Route -CA60 Loaded	Goodyear
9/2/25	6:10	Highway Route -I215	Goodyear
9/2/25	11:00	Highway Route -CA60	Goodyear
9/3/25	7:05	Highway Route -CA60	Continental
9/3/25	9:15	Highway Route -I215	Continental
9/3/25	11:35	Highway Route -CA60	Continental
9/3/25	13:00	Highway Route -I215	Continental
9/4/25	6:25	City Route	Continental
9/4/25	8:20	Highway Route -CA60 Loaded	Continental
9/4/25	11:15	Highway Route -CA60 Loaded	Continental
9/4/25	13:40	City Route	Continental
9/8/25	10:15	Highway Route -CA60	Waterfall
9/8/25	11:35	Highway Route -CA60	Waterfall
9/8/25	13:15	Highway Route -I215	Waterfall
9/9/25	06:50	City Route	Waterfall
9/9/25	08:40	City Route	Waterfall
9/9/25	10:20	Highway Route -I215	Waterfall
9/15/25	6:35	Highway Route -CA60 Loaded	Waterfall
9/15/25	11:15	Highway Route -CA60 Loaded	Waterfall

Corrected Tire Emission Results

Tire	Route	Material	Loaded	Total PM2.5 (mg/mi)	Total PM10 (mg/mi)	Tire-Only PM2.5 (High)	Tire-Only PM2.5 (Low)
Firestone Used	City			7.77		1.22	0.21
Firestone Used	City			17.35	40.23	2.72	0.55
Firestone Used	City			8.16	16.37	1.28	0.22
Firestone Used	Highway - I215	asphalt	no	6.37	4.56	1.00	0.20
Firestone Used	City			9.43	19.04	1.48	0.27
Firestone Used	Highway - CA60	concrete	no	2.85	5.52	0.45	0.08
Firestone Used	Highway - I215	asphalt	no	2.65	6.78	0.42	0.07
Firestone Used	Highway - CA60	concrete	no	4.90	6.81	0.77	0.15
Firestone Used	Highway - CA60	concrete	yes	1.25	4.35	0.20	0.02
Firestone Used	Highway - CA60	concrete	yes	5.48	6.60	0.86	0.17
Firestone New	City			38.86	156.75	6.10	1.30
Firestone New	City			40.03	34.90	6.28	1.34
Firestone New	Highway - I215	asphalt	no	5.83	7.56	0.92	0.18
Firestone New	Highway - CA60	concrete	no	24.03	21.34	3.77	0.82
Firestone New	Highway - I215	asphalt	no	0.88	3.61	0.14	0.01
Firestone New	City			19.12	16.74	3.00	0.61
Firestone New	Highway - CA60	concrete	yes	5.05	12.98	0.79	0.15
Firestone New	Highway - CA60	concrete	yes	7.58	12.09	1.19	0.24
Firestone New	Highway - CA60	concrete	no	9.91	6.77	1.56	0.32
Michelin	Highway - I215	asphalt	no	7.55	18.19	1.19	0.24
Michelin	Highway - CA60	concrete	no	3.10	19.63	0.49	0.09
Michelin	Highway - CA60	concrete	no	1.43	12.55	0.22	0.03
Michelin	Highway - I215	asphalt	no	1.26	9.01	0.20	0.02
Michelin	City			13.90	17.05	2.18	0.43
Michelin	City			2.26	21.58	0.35	0.02
Michelin	Highway - CA60	concrete	yes	4.13	6.26	0.65	0.12
Michelin	Highway - CA60	concrete	yes	4.67	9.39	0.73	0.14
Michelin	City			37.27	-1.33	5.85	1.24
Goodyear	City			1.85	9.70	0.29	0.00
Goodyear	City			4.90	6.01	0.77	0.11
Goodyear	Highway - I215	asphalt	no	0.78	1.45	0.12	0.01
Goodyear	Highway - CA60	concrete	no	2.85	2.96	0.45	0.08
Goodyear	Highway - I215	asphalt	no	0.94	1.78	0.15	0.01
Goodyear	Highway - CA60	concrete	no	1.43	1.37	0.22	0.03
Goodyear	Highway - CA60	concrete	yes	1.42	3.08	0.22	0.03

Tire	Route	Material	Loaded	Total PM2.5 (mg/mi)	Total PM10 (mg/mi)	Tire-Only PM2.5 (High)	Tire-Only PM2.5 (Low)
Goodyear	Highway - CA60	concrete	yes	0.67	1.62	0.11	0.00
Goodyear	Highway - I215	asphalt	no	1.36	2.27	0.21	0.03
Goodyear	Highway - CA60	concrete	no	2.48	1.77	0.39	0.06
Continental	Highway - CA60	concrete	no	10.18	17.43	1.60	0.33
Continental	Highway - I215	asphalt	no	1.87	3.54	0.29	0.04
Continental	Highway - CA60	concrete	no	3.84	7.26	0.60	0.11
Continental	Highway - I215	asphalt	no	1.57	5.02	0.25	0.03
Continental	City			18.22	50.53	2.86	0.58
Continental	Highway - CA60	concrete	yes	2.54	12.01	0.40	0.07
Continental	Highway - CA60	concrete	yes	3.37	12.04	0.53	0.10
Continental	City			22.14	25.22	3.48	0.71
Waterfall	Highway - CA60	concrete	no	1.04	7.47	0.16	0.01
Waterfall	Highway - CA60	concrete	no	0.83	4.70	0.13	0.01
Waterfall	Highway - I215	asphalt	no	2.19	2.40	0.34	0.05
Waterfall	City			7.73	9.42	1.21	0.21
Waterfall	City			19.56	19.46	3.07	0.62
Waterfall	Highway - I215	asphalt	no	2.59	2.71	0.41	0.07
Waterfall	Highway - CA60	concrete	yes	5.32	7.24	0.84	0.16
Waterfall	Highway - CA60	concrete	yes	5.04	8.39	0.79	0.15

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