Characterizing Brake PM Emissions for Passenger Cars and Trucks Using a Novel Brake-Dynamometer Testing Method

Final Presentation

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CARB-Sponsored Research Project 17RD016

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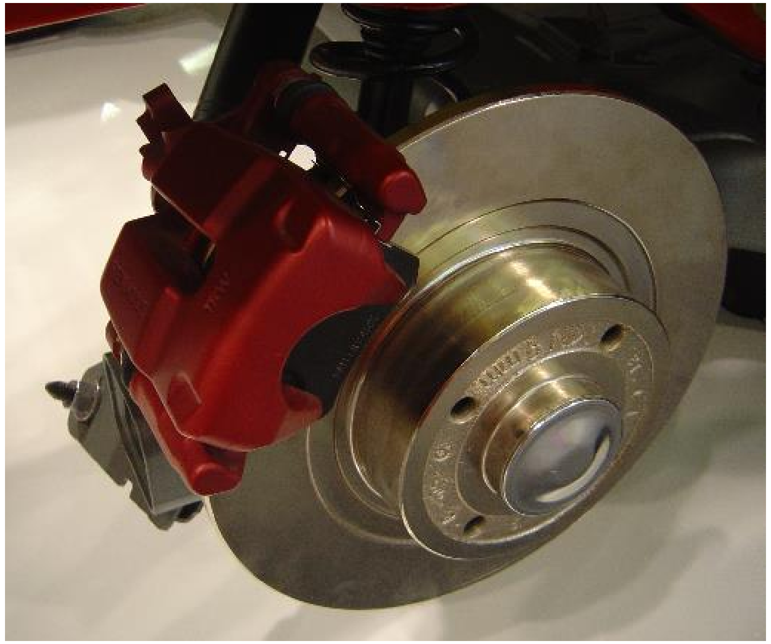
In cooperation with

Outline

- Project motivation/introduction
- Test vehicle/component selection
- Test cycle development
- Dynamometer lab setup
- Emissions testing
- Results
- Implications



Brake emissions

- Sliding wear at friction couple
- Emitted into the air or settle on body, wheels, chassis, or roadway

Project Motivation

- Increasing non-exhaust share of total light-duty PM emissions
- CARB ready to update braking-related emissions factors in their EMFAC inventory model due to potential effects of changes in:
  - Fleet makeup including new technologies such a regenerative braking
  - Driving habits
  - Brake assembly geometry and materials (notably metal content)
- Shift from brake-event-matrix style studies to full driving cycle simulation with by-distance outputs

Project Overview

- Project Goals
  - Improve Emission Factors Related to Light Duty Braking in EMFAC
  - Better understand brake PM Emissions and refine brake testing procedures
- Develop a Brake Dynamometer Test Cycle
  - Use existing on-road data as a basis for representativeness
  - Compare with existing cycles for representativeness, use most representative
    - EMFAC Unified Cycle (UC) and Speed Correction Cycles (SCC) and WLTP-Brake
- Identify Candidate Test Vehicles and Conduct Temperature Measurements on a Test Track
- Conduct Brake Dynamometer Testing
  - Develop Test Matrix of up to 90 tests
  - Conduct dynamometer testing and perform continuous and/or batch measurements of:
    - Particle mass (via multiple methods; EPA participation)
    - Particle number
    - Particle size distribution

Test Vehicle Selection and Market Share Analysis (1/3)

- Goals for Test Vehicle Selection
  - Representativeness of common vehicles in California
  - Cover a wide range of LD vehicle types
  - Include a vehicle with regenerative braking

- Started with a Scrubbed Query of the 2017 CA Vehicle registration
  - Provided to ERG by ARB
  - Contained counts of all vehicle makes, models, Trimlines, and Model Years
  - No further editing was required

- Then began narrowing down to the top 25 most common vehicle models (making sure all vehicle types of interest were included)
  - Sedan, Compact, Pickup, Minivan, SUV, Hybrid

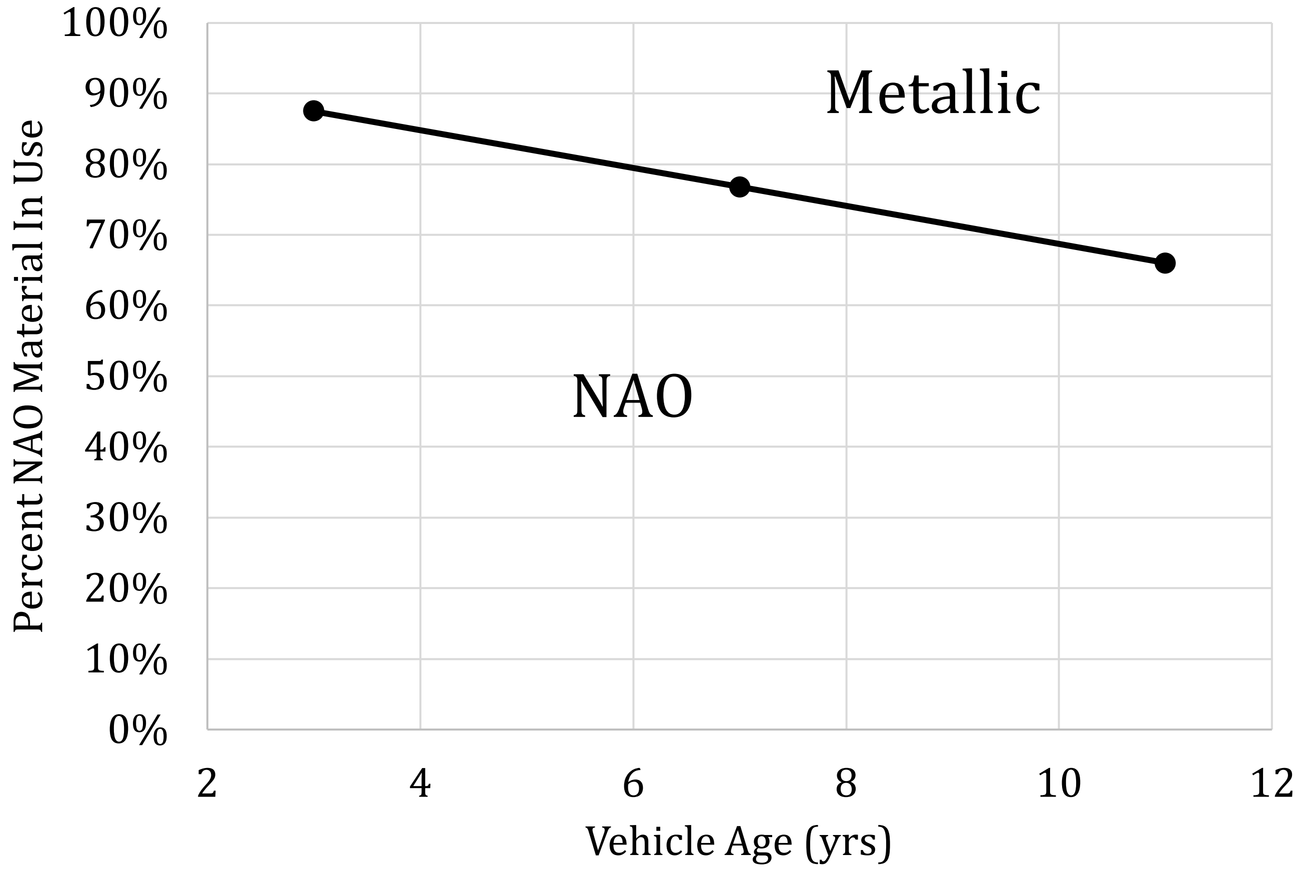
Test Vehicle Selection and Market Share Analysis (2/3)

- Group each by brake FMSI (Friction Materials Standards Institute) codes
  - model years and trimlines of a given model were grouped as one if they had the same FMSI codes and the new, combined model was recounted
- Brake wear index (BWI) was created to prioritize vehicles that are typical in terms of wearable mass (BWI1) and replacement rate (BWI2)

Selected Test Vehicle	Registration RANK	BWI_1 RANK	BWI_2 RANK	COMMENTS
2011 Toyota Camry LE	1	1	1	Top rank by all three metrics
2013 Honda Civic LX	5	4	3	Rear drum brakes
2013 Toyota Sienna LE	8	8	6	Top in the list of class 'D' VIOs, Minivan
2015 Ford F-150 Supercrew	17	11	10	Top in the list of class 'E' VIOs, Large Pickup, Very common vehicle for friction material formulation evaluations
2016 Toyota Prius Two Eco	2	3	15	Regenerative braking
2016 Nissan Rogue S	10	14	16	Top in the list of non-luxury SUVs Medium level ranking based on BWI_1 and BWI_2

Test Vehicle Selection and Market Share Analysis (3/3)

- General Brake Pad Formulation Trend vs Vehicle Age



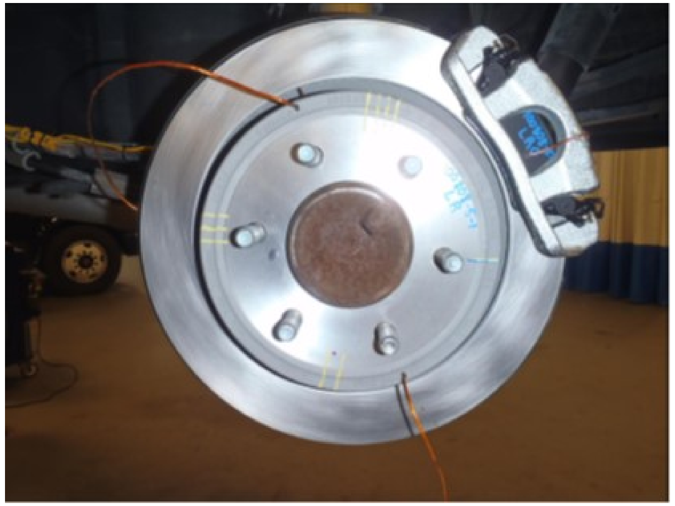
NAO – Non-asbestos Organic

Proving Ground Testing at LINK

- Instrumentation
  - Vehicles were logged for:
    - Inner and outer pad temperature
    - Inner and outer rotor temperature
    - Vehicle speed
    - Prius was also instrumented for brake pressure
- Test Cycles
  - Vehicles were tested over two test cycles
    - Heating and Cooling Matrix: A specific series of discrete braking events and cruises
      - Braking events at specified starting and ending speeds and deceleration rates
      - Cruises at specified steady state speeds
    - WLTP-Brake cycle, converted for driving on a track
  - LINK also performed coastdowns to measure road load

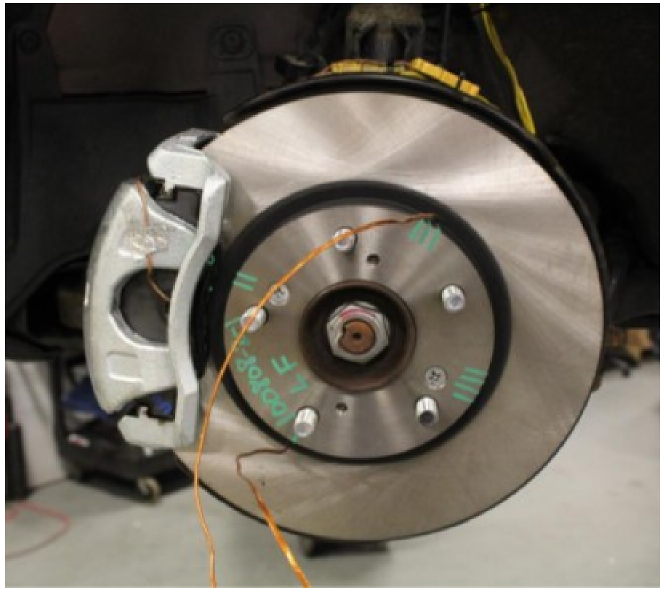
Proving Ground Testing at LINK


Front

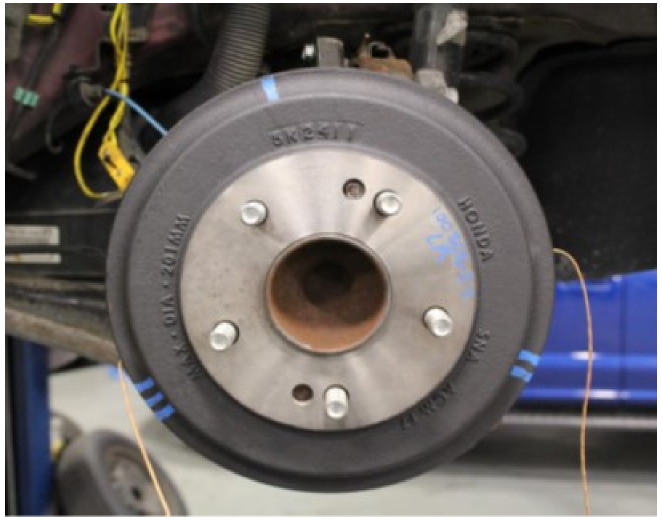

Rear

Proving Ground Testing at LINK

Honda Civic



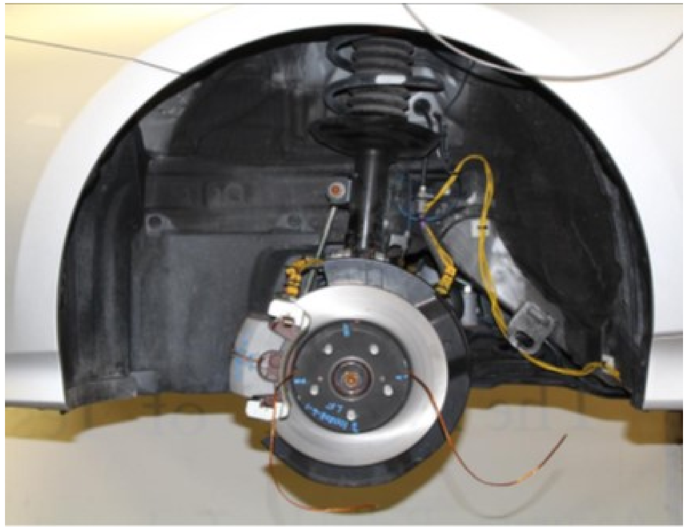
Front



Rear

Proving Ground Testing at LINK

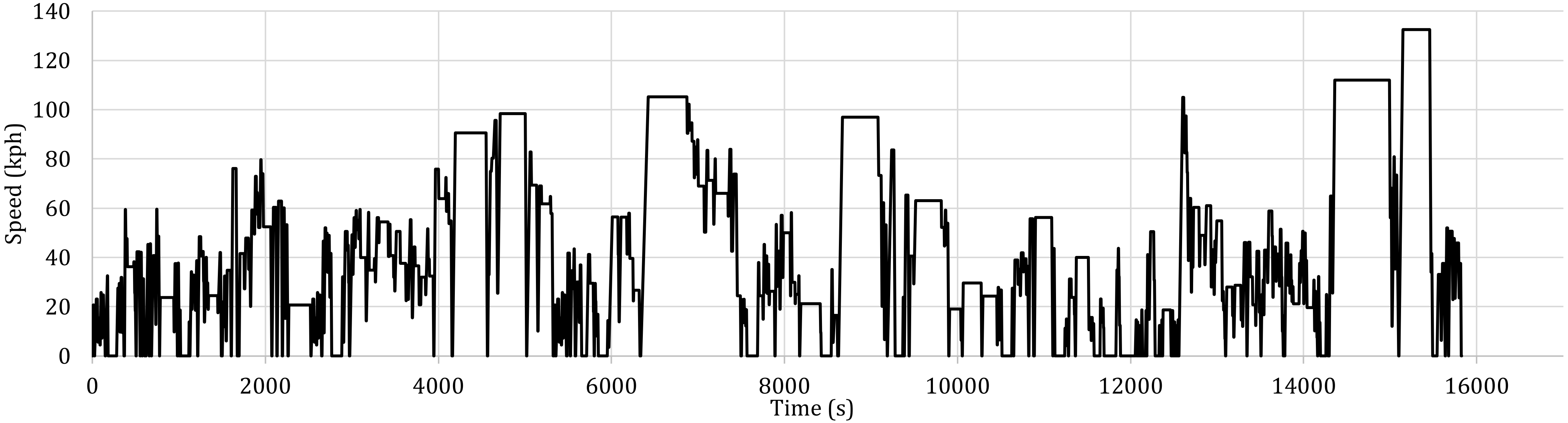
Toyota Prius


Front,
Wheel Off

Front,
Wheel On

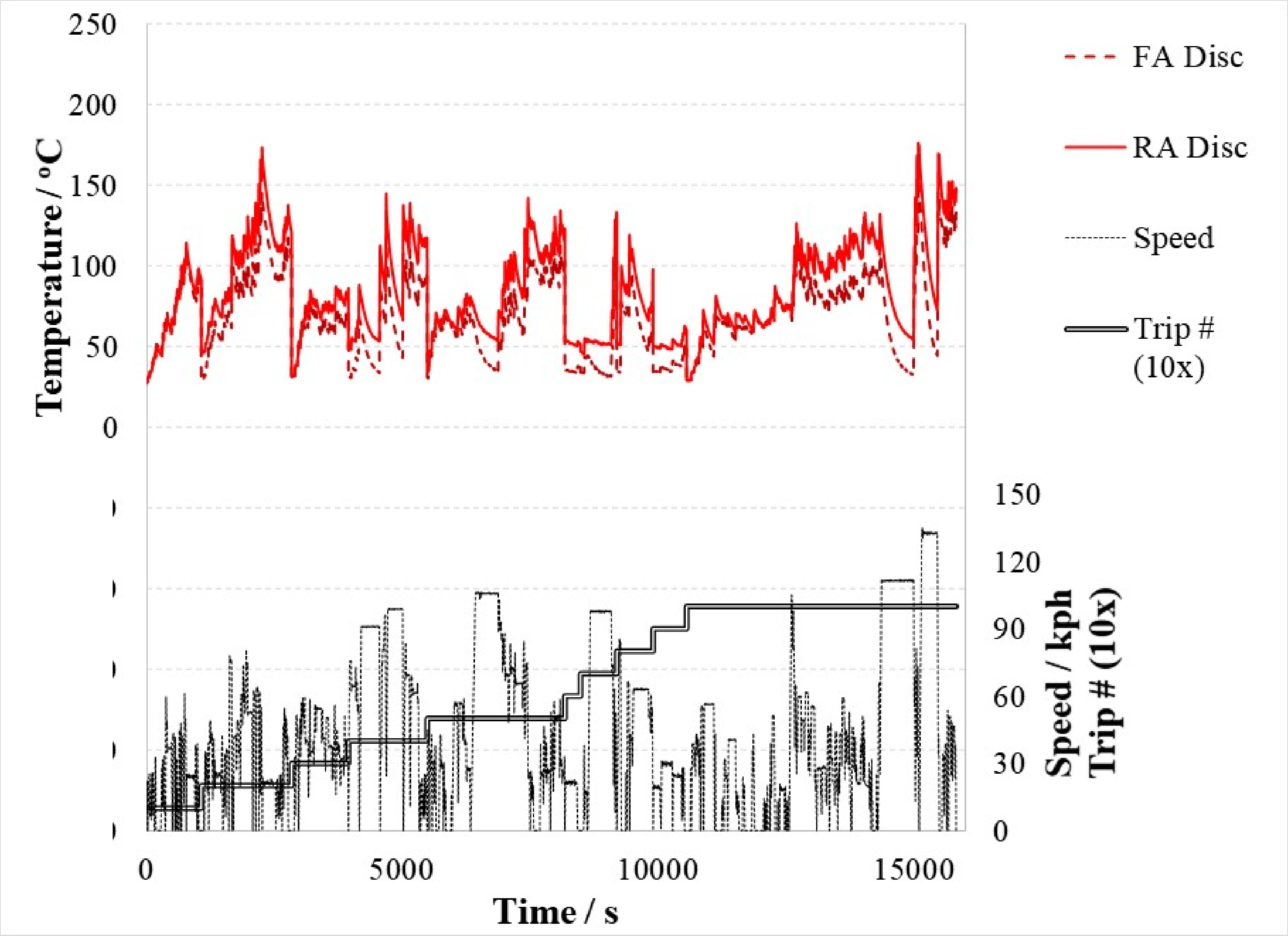
WLTP brake dynamometer cycle

- 300 brake events
- Divided into 10 trips
- 6 hour duration (including soaks)
- Decels starting from 40-130 kph (25-80 mph)
- Moderate braking at unchanging deceleration rates

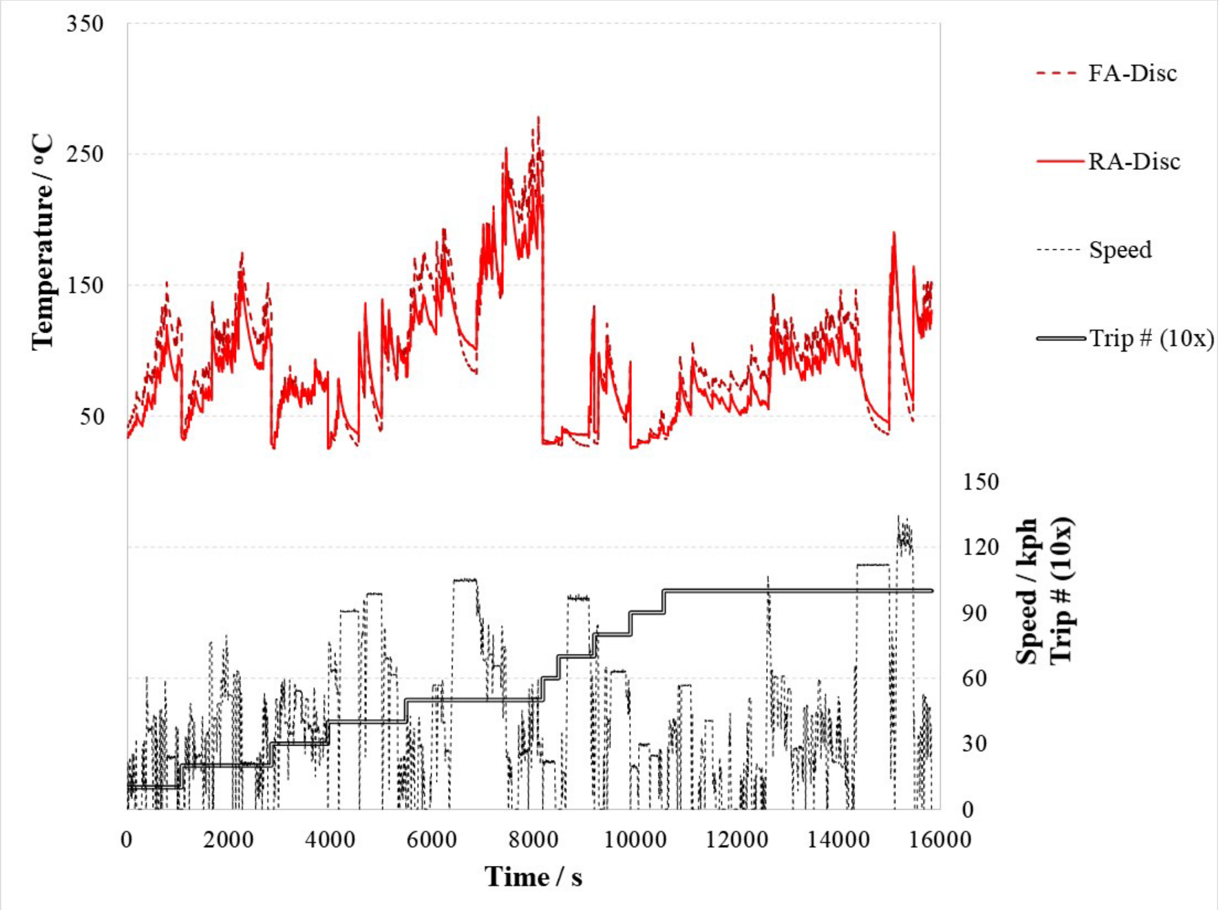


Proving Ground Testing – Temperature Results

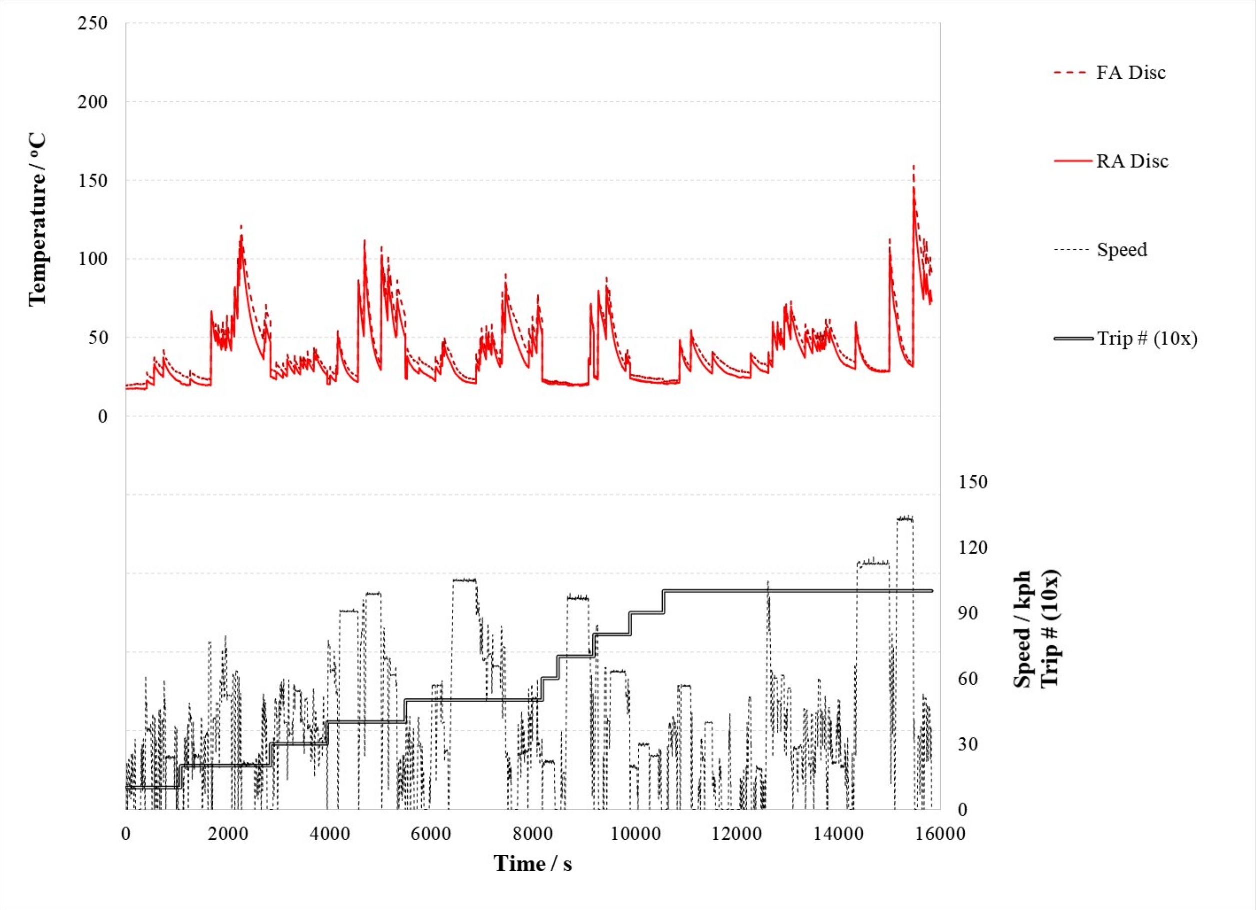
Camry Sedan



Proving Ground Testing – Temperature Results



Sienna
Minivan



Prius
Hybrid

Representing On-Road California Driving

- Goal is to use a driving cycle representative of real on-road driving on the basis of:
  - Speed
  - Deceleration Rate
  - Brake Event Durations
  - Brake Temperature
- Use the continuously logged OBD data from the 2010-2012 Caltrans Household Travel Survey to represent typical on-road driving

	OBD Files	OBD+GPS Files	GPS Files
Number of Vehicles	2130	365	677
Hours of Data	14001	1819	3162
Time gaps of 2s in data	1.6%	0.1%	0.1%
Time gaps in data 3-10s	0%	0.6%	0.6%

- QA Process
  - Vehicles with large number of speed discontinuities were dropped
  - Application of general coastdown curve to determine braking
  - OBD speed digitization – smoothed using moving regression

Temperature Modeling of On-Road Data

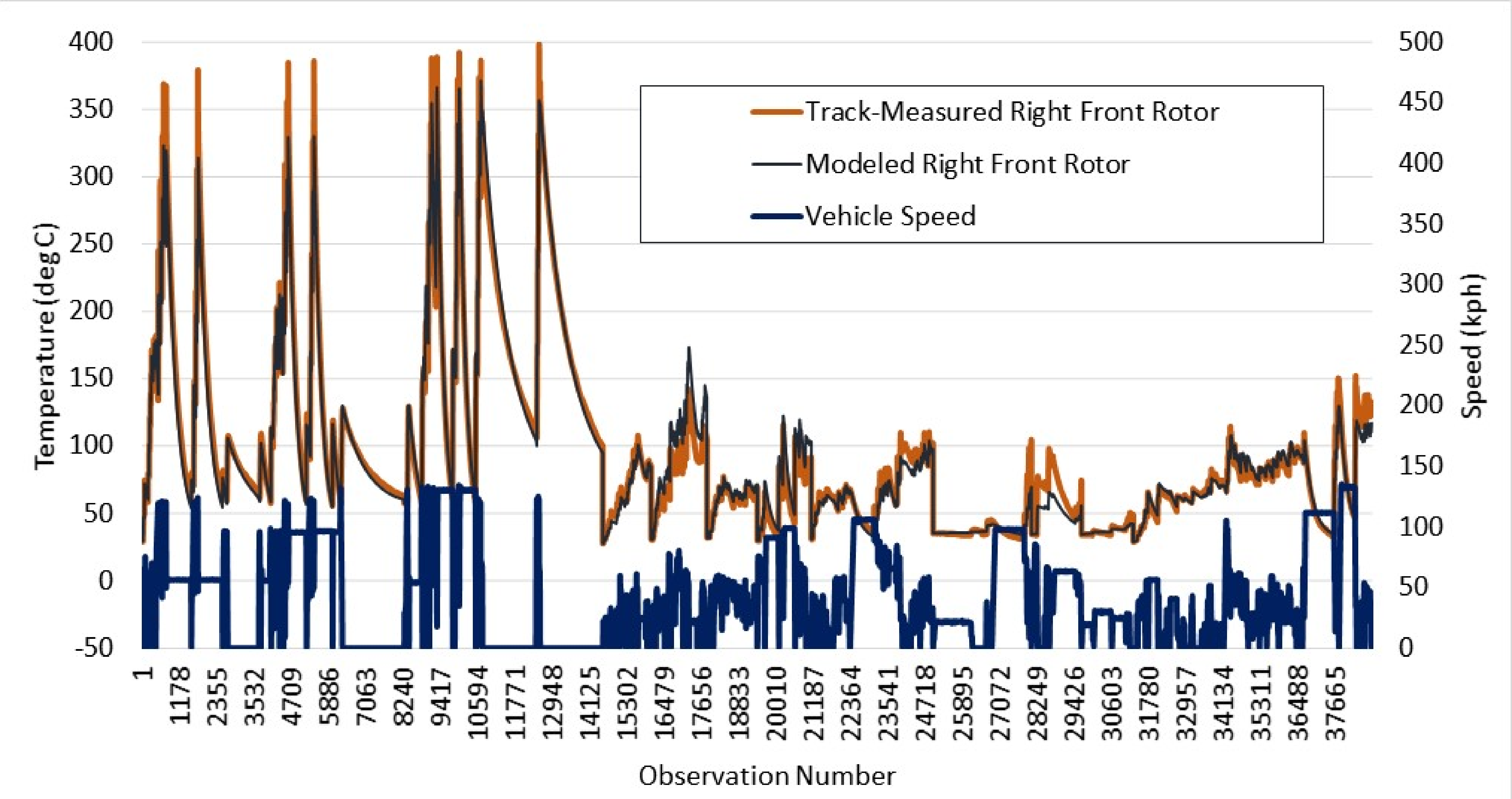
- Use proving ground logged temperature data to develop a model of brake heating and cooling during operation
  - Model depends on coast down data, speed, deceleration rates
- Then apply model to all Caltrans data to estimate temperature during operation
- The temperature model has heating and cooling terms
  - Cooling term is always in effect from one observation to the next
  - Heating term is only active during braking (ie vehicle deceleration exceeds coastdown deceleration)

$$\Delta T = \underbrace{(A + B \cdot V_0 + C \cdot V_0^2) \cdot (T_0 - T_{amb}) \cdot \Delta time}_{\text{COOLING}} + \underbrace{D \cdot (v_0^2 - v_1^2) \cdot \Delta time}_{\text{HEATING}}$$

Temperature Modeling

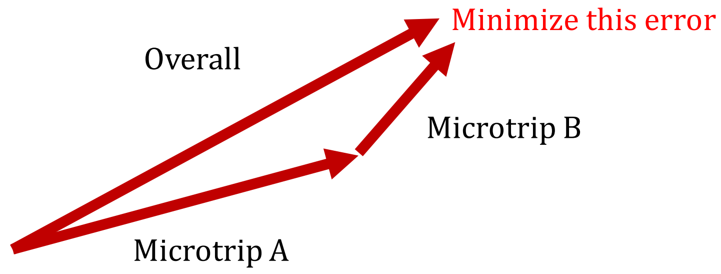
HEATING/COOLING MATRIX

WLTP



Cycle Building/WLTP Representativeness

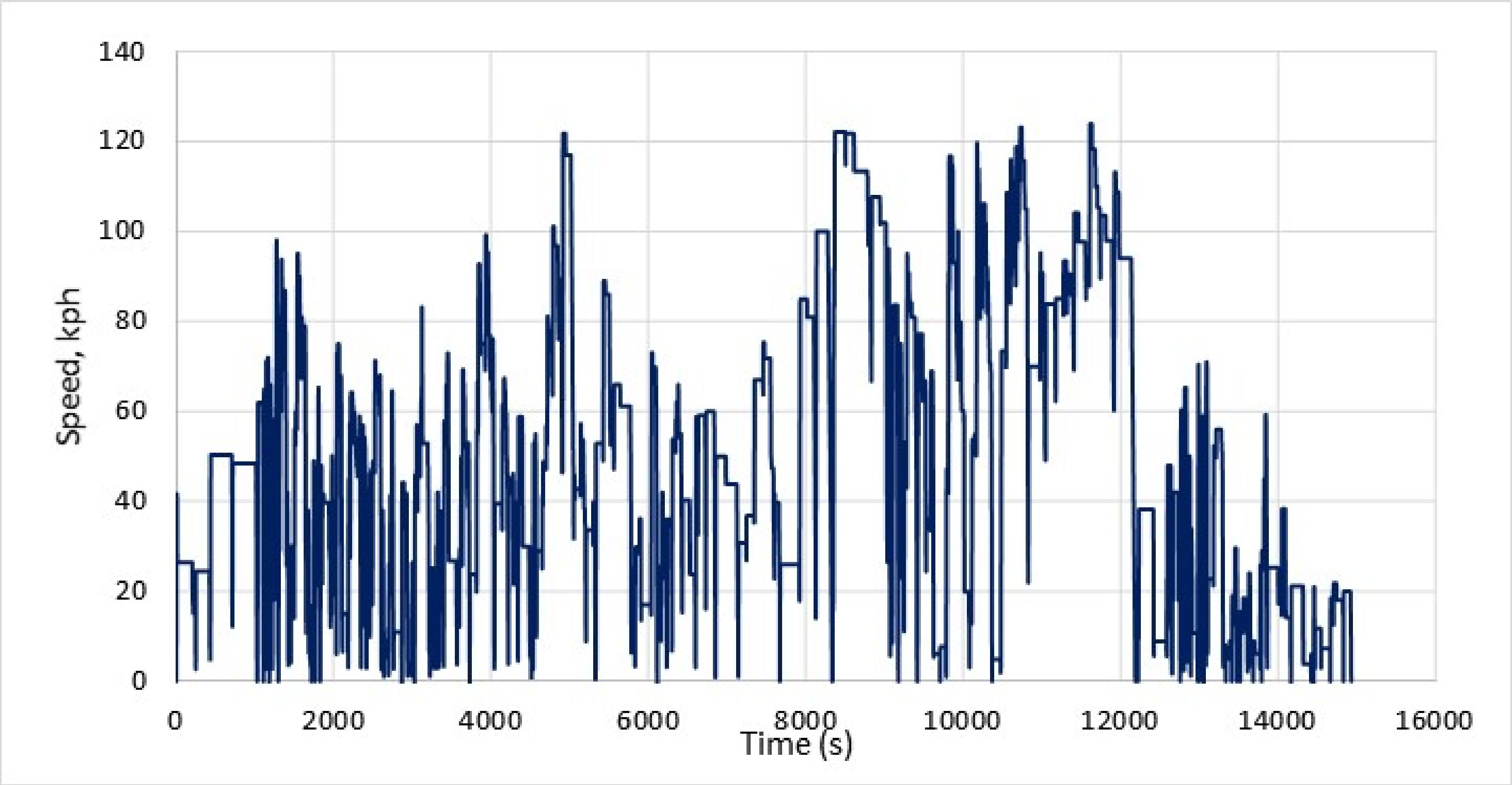
- ERG will use vector co-linearity method for cycle building
  - This method has been used for past projects including EPA nonroad cycle building and TxDOT fuel evaluation
  - Method involves describing a cycle in terms of a vector using dimensions representing the distributions of key attributes of the time series
    - Speed
    - Acceleration
    - Temperature
    - Braking Event Duration



  - Test cycles are based on concatenating microtrips (consisting of single contiguous braking events)
    - Each successive individual microtrip is selected based on making the overall vector of the created cycle as parallel as possible with the vector describing the entire dataset
  - End result is a cycle that has distributions of the above that best match overall Caltrans data (including temperatures modeled at each second)

California Brake Dynamometer Cycle (CBDC)

Consider deceleration rates, event durations, brake temperatures, and speeds



~4.1 hr duration
347 braking events

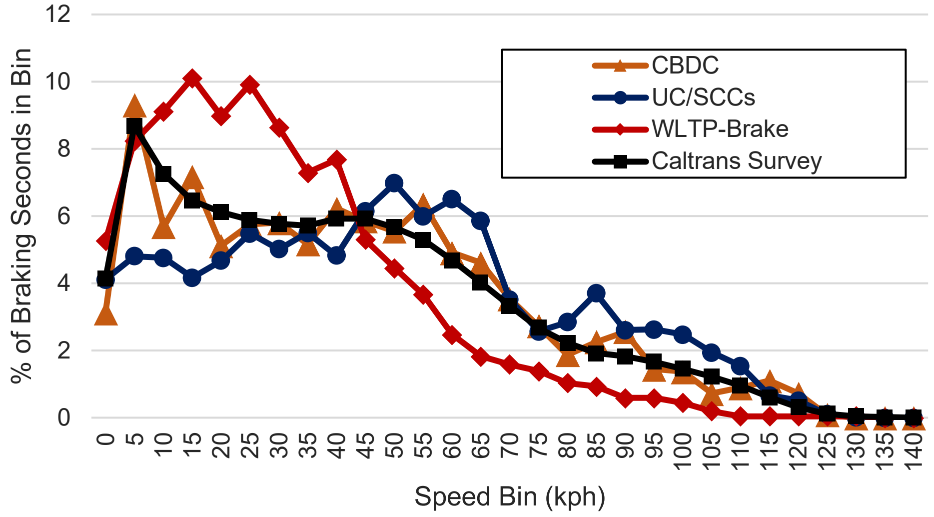
Represents 131 km (81.55 mi) of driving

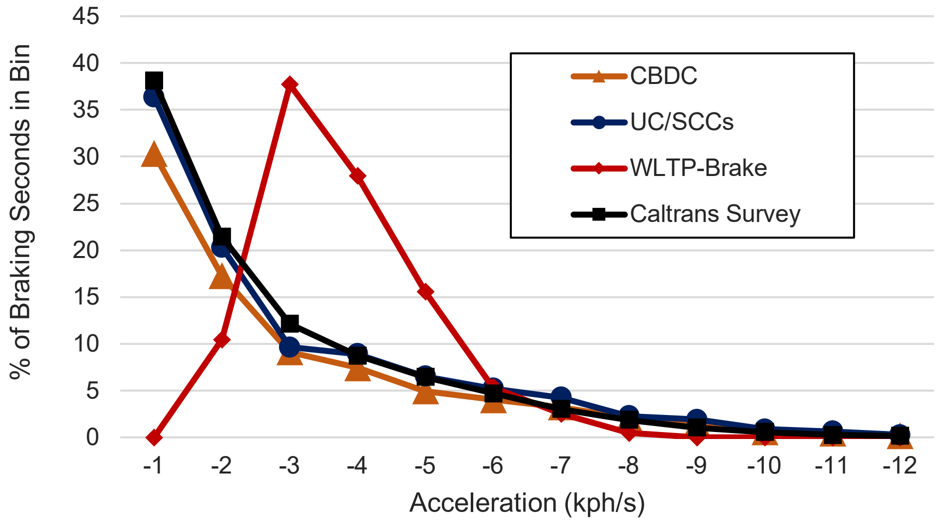
Can be subdivided into 3 cycles representing medium, high, and low trip average speeds

California Brake Dynamometer Cycle (CBDC)

Consider deceleration rates, event durations, brake temperatures, and speeds

Caltrans Survey = 2010/12 Household Travel Survey Data
CBDC = California Brake Dynamometer Cycle
UC/SCCs = EMFAC Unified Cycle and Speed Correction Cycles
WLTP = Worldwide Harmonized Light-Vehicle Test Procedure





Development of a Brake Burnish Cycle

- Brakes must be burnished prior to testing
  - Pad and rotor to be bedded in together at the friction surface
  - Increases repeatability of testing
  - Test results are more representative of long-term emission rates
- Goal is to use high energy, short duration cycle
- ERG developed an ~11.5 hr burnish cycle
  - Selected a high energy subset segment of the CBDC
  - Repeated segment until reaching the equivalent braking energy of 5 WLTP-Brake
  - Appended our low average speed segment as cool down/final stabilization
- One project goal was to evaluate this cycle as acceptable for burnishing
  - Repetitive nature of cycle helps determine when steady-state emissions are reached

CVS-Based Measurement of Brake PM

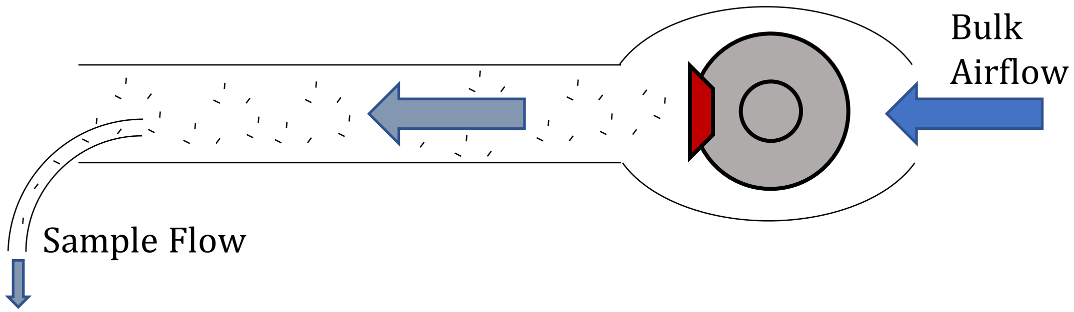
Brake dynamometer

- Electric motor spins a single brake rotor or drum (and inertia-simulating weight)
- Brakes are operated hydraulically
- Brake mounted in a duct enclosure
- Constant-speed airflow provides
    - Cooling for brake assembly
    - Medium to transfer particles to sample

The test basis

- Past studies have been event-based
    - Matrix of standard brake events
    - Interpret for representativeness
- This study involved a representative vehicle speed trace w/ results on per-mile basis
- Developed an 85-test matrix varying assemblies, friction materials (NAO, LM), vehicle weight loading

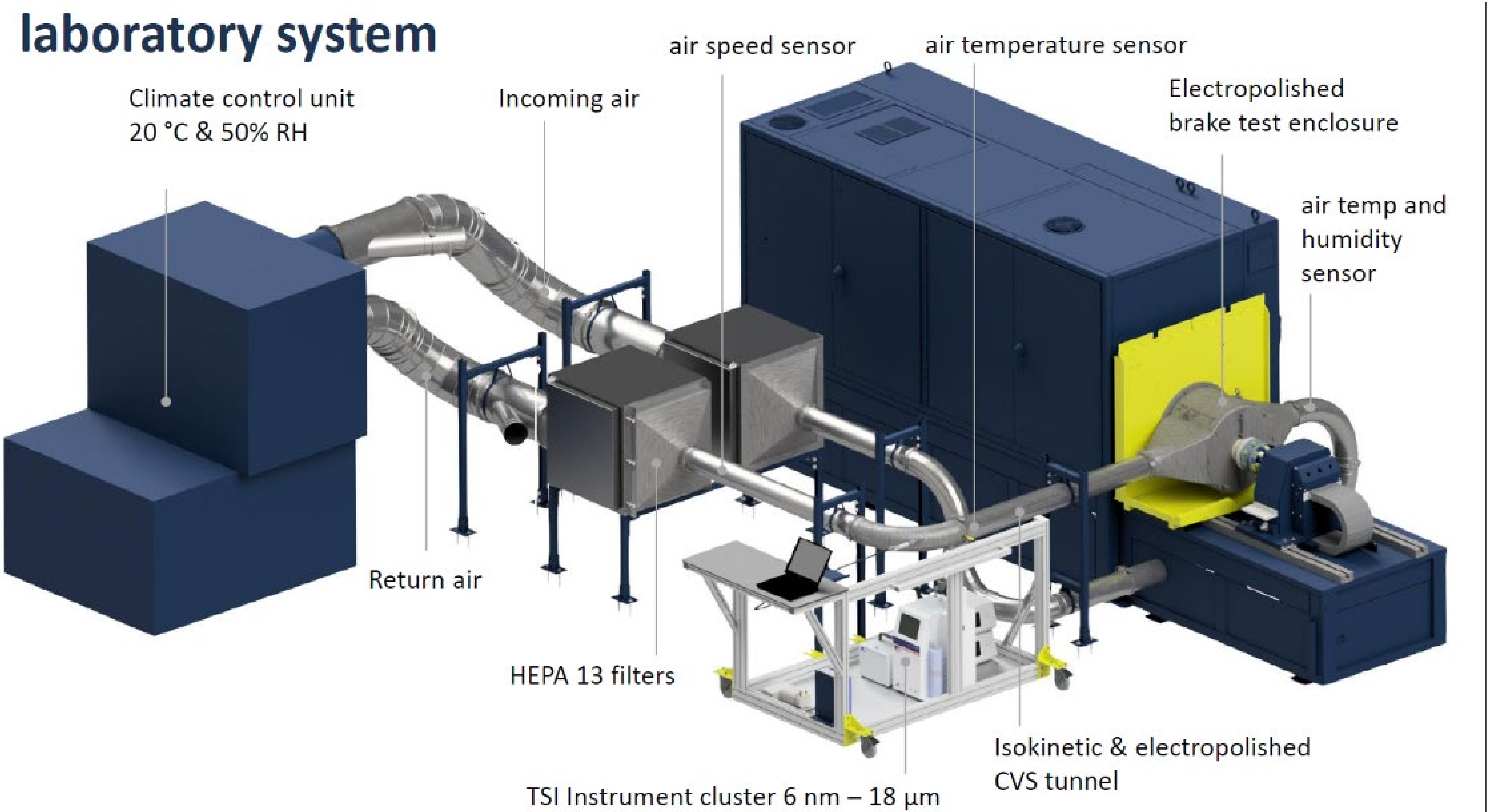
Constant Volume Sampling (CVS)



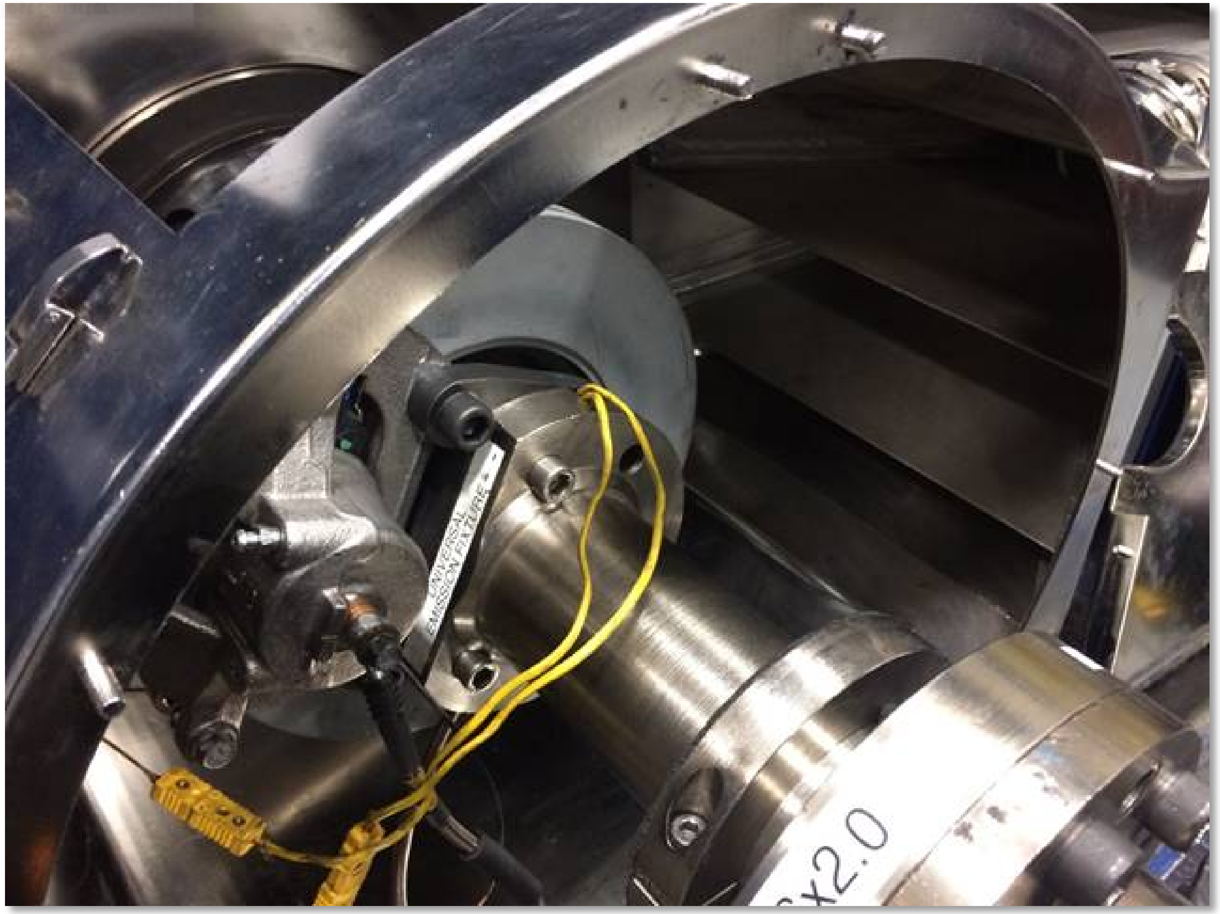
Point of sampling – flow to various instruments

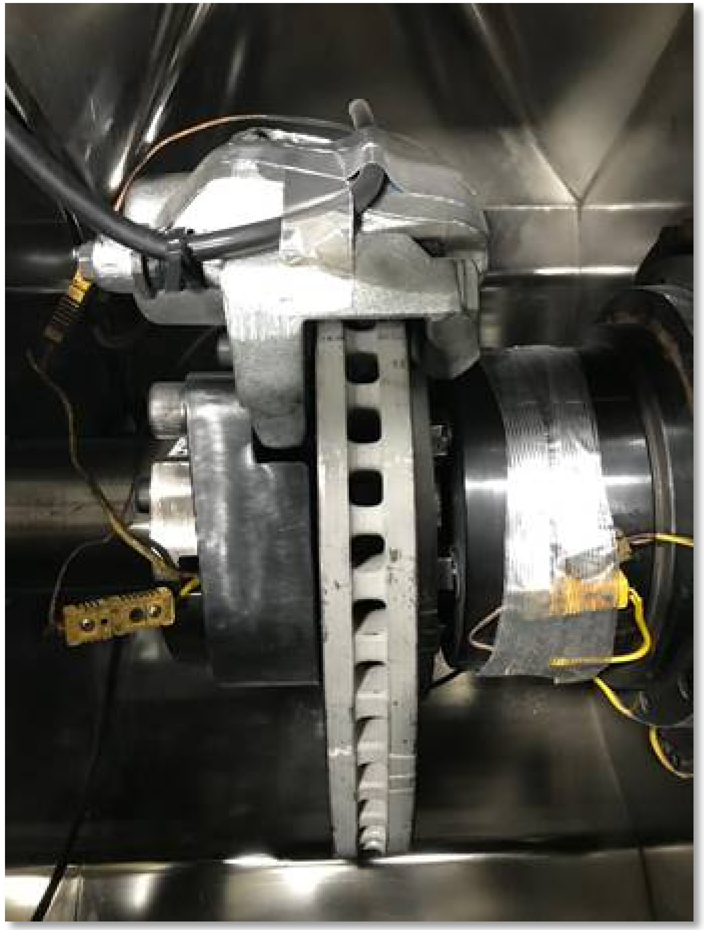
- Batch measurement (collect on filters and measure mass)
- Continuous measurement (mass, particle size and count)

Test Laboratory Setup

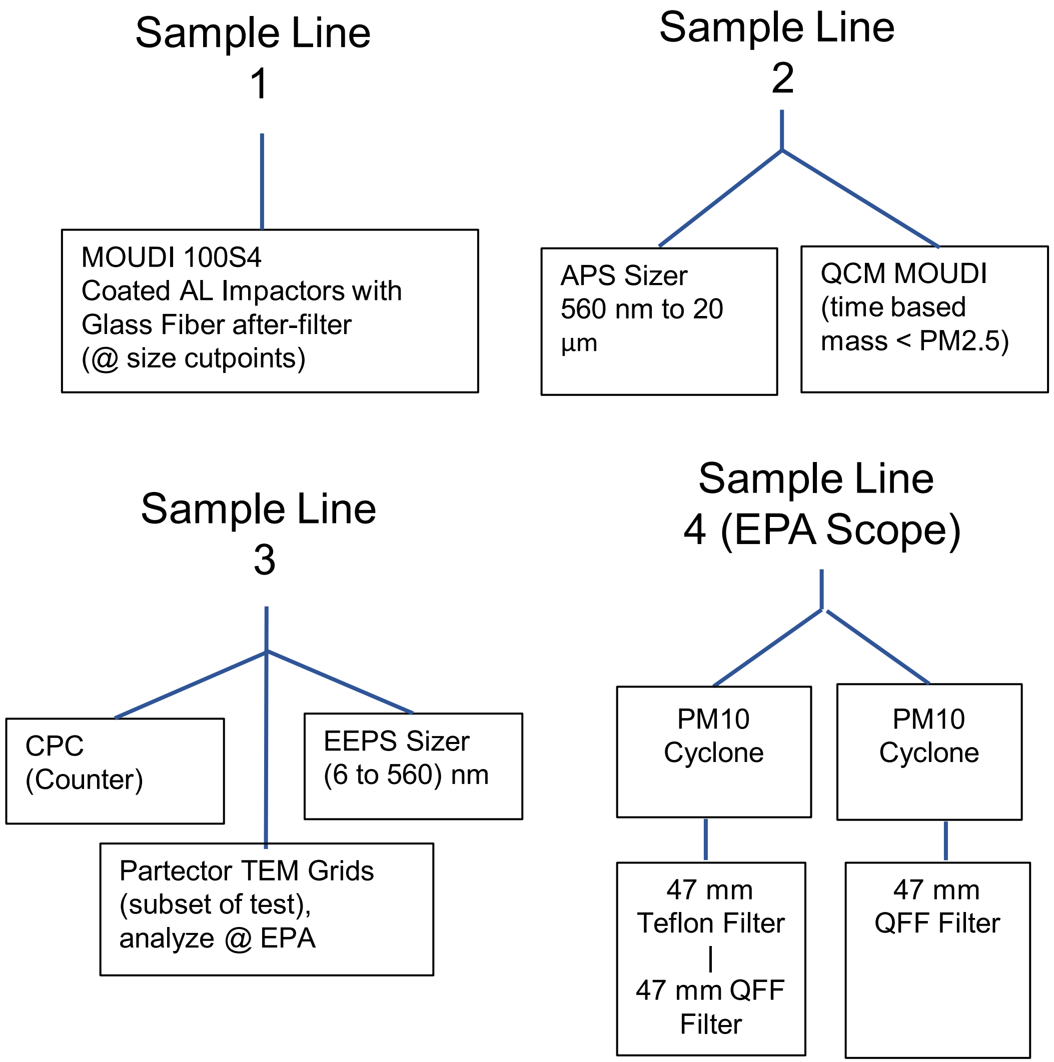


Brake Dynamometer and CVS





Test Laboratory Setup - Instrumentation



Filter Material	**Analysis Options**
Teflon	• Gravimetric Mass (@LINK, EPA, ARB) • XRF elemental (@ ARB)
Quartz Fiber (QFF) – Following Teflon	• Volatile Organics that pass through Teflon (artifact collection) (@EPA)
Quartz Fiber (QFF) – Lone	• Particle Phase Organic Molecular Weight Distribution (which can inform further test types) (perform on initial filters only?) (@EPA) • EC/OC
Coated AL Impactor (100S4)	• Gravimetric (@LINK)
Glass Fiber (100S4)	• Gravimetric Mass (@ LINK)

Test Matrix Summary

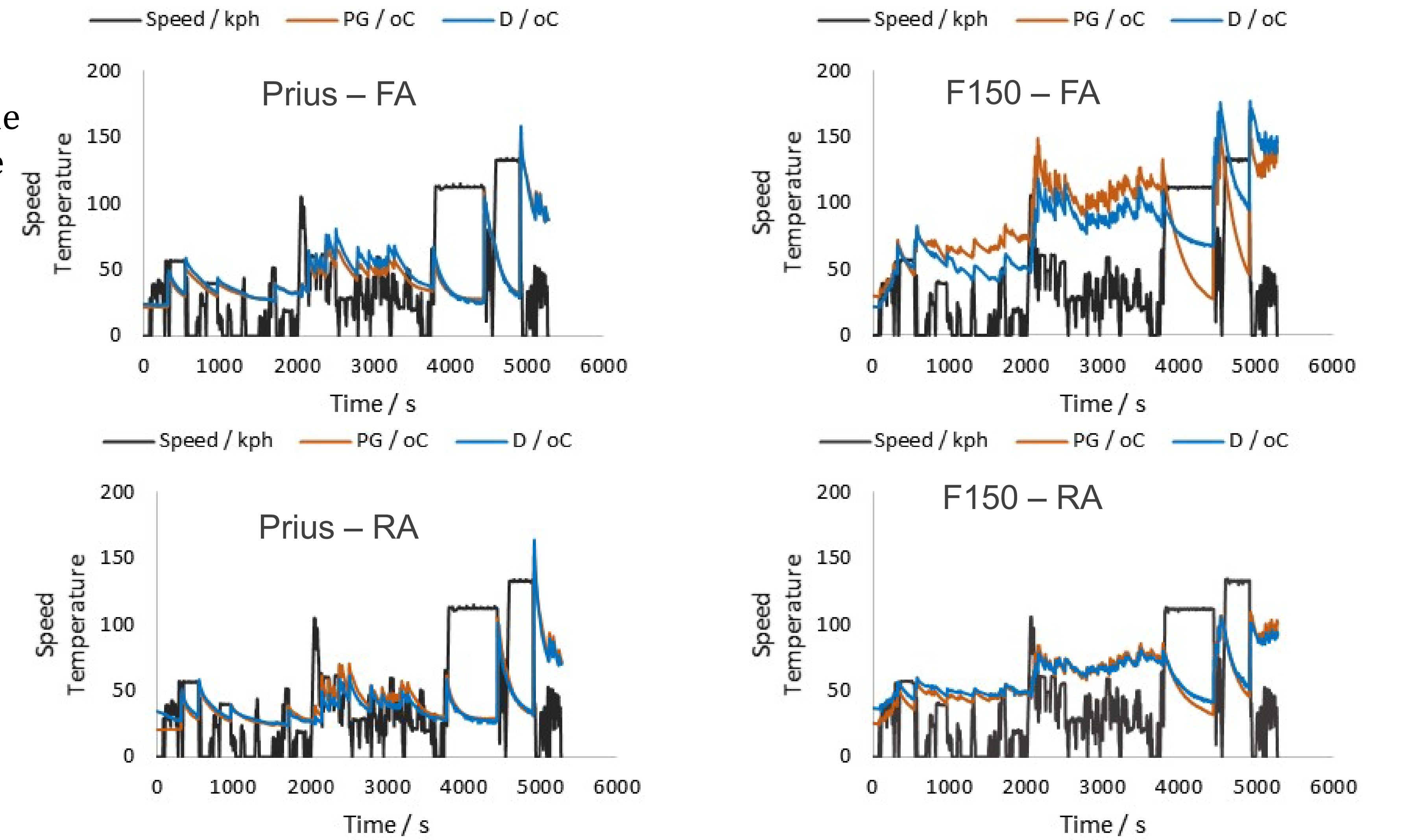
Number of Test Subjects within each Parameter for each Vehicle						
Test Vehicle	**Front/ Rear**	**Pad Material**	**Wheel Loading**	**# Replicates**	**Reference Repeats**	**# Tests**
Camry	2	3	1	2	0	12
Civic	2	2	1	2	0	8
F-150	2	3	1.5	2	3	21
Sienna	2	3	1.5	2	0	18
Prius	2	2	1	2	0	8
Rogue	2	3	1.16	2	0	14
Tunnel Blanks				2		**2**
					Total	**83**

- Test all front and rear assemblies
- Pad materials: combo of OES, aftermarket organic, and aftermarket metallic
- Simulated vehicle weight: normal test weight for all vehicles; additionally at elevated weight for F-150, Sienna, Rogue
- Two replicates conducted for all tests in the matrix, except for the Reference test
- Reference test will be the OES front pad for the F-150. 5 total replicates performed throughout testing.

Setting CVS Flow Rate

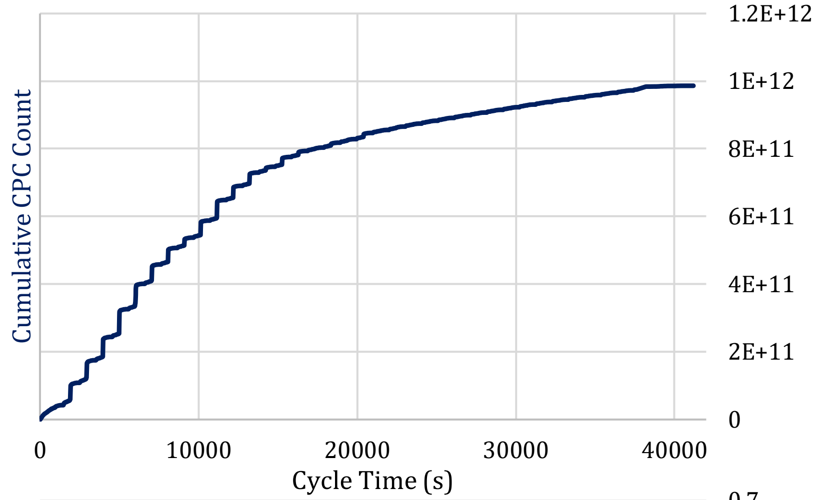
the PMP method worked on multiple vehicles, while the F150-FA was a challenge

FA- Front Axle
RA-Rear Axle

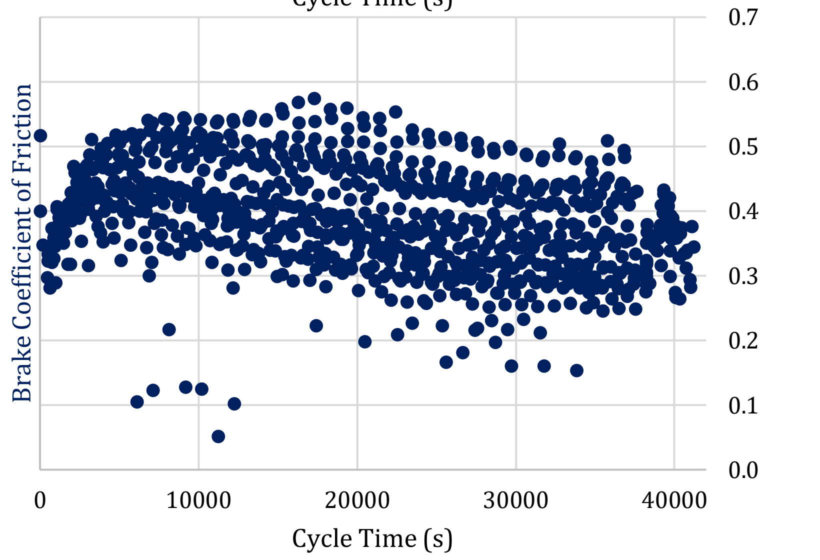


Evaluation of burnish procedure
Stable particle generation rates need a stable friction layer

Evaluated by Particle # Emission Rate – Camry Example



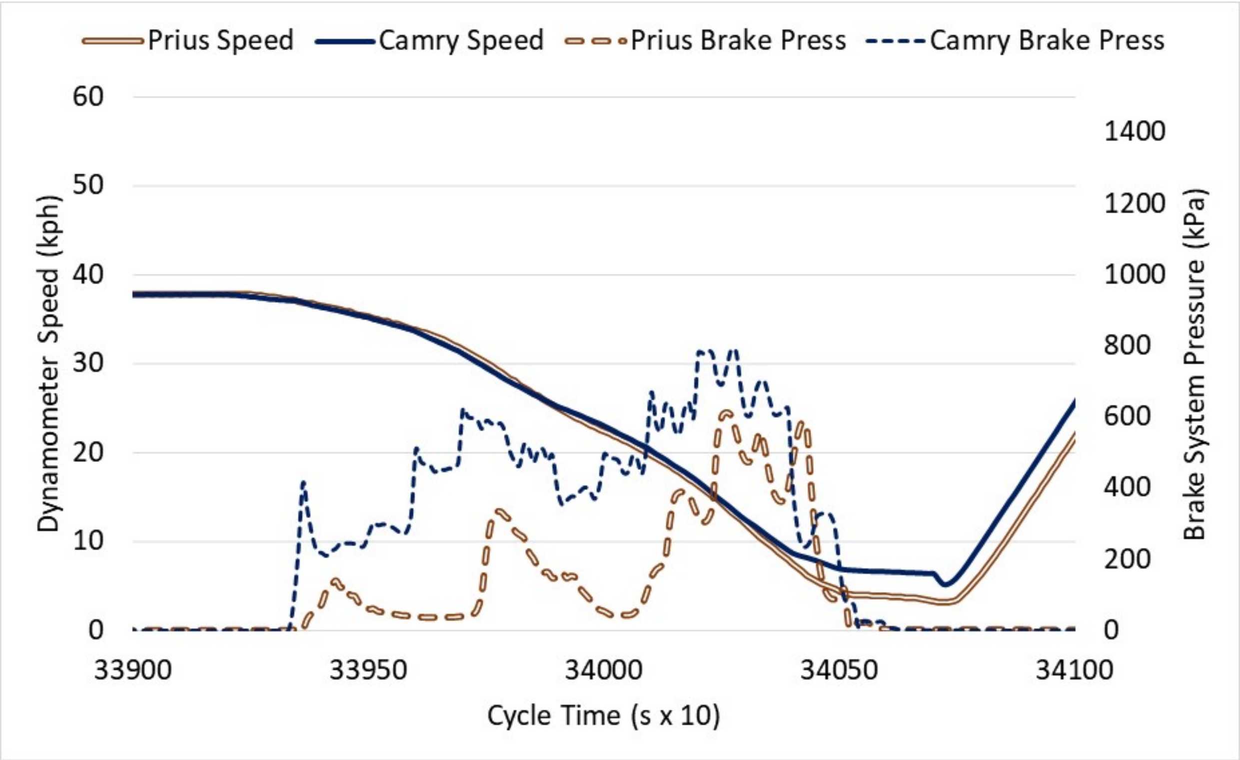
Evaluated by estimated coefficient of friction – F-150 Example



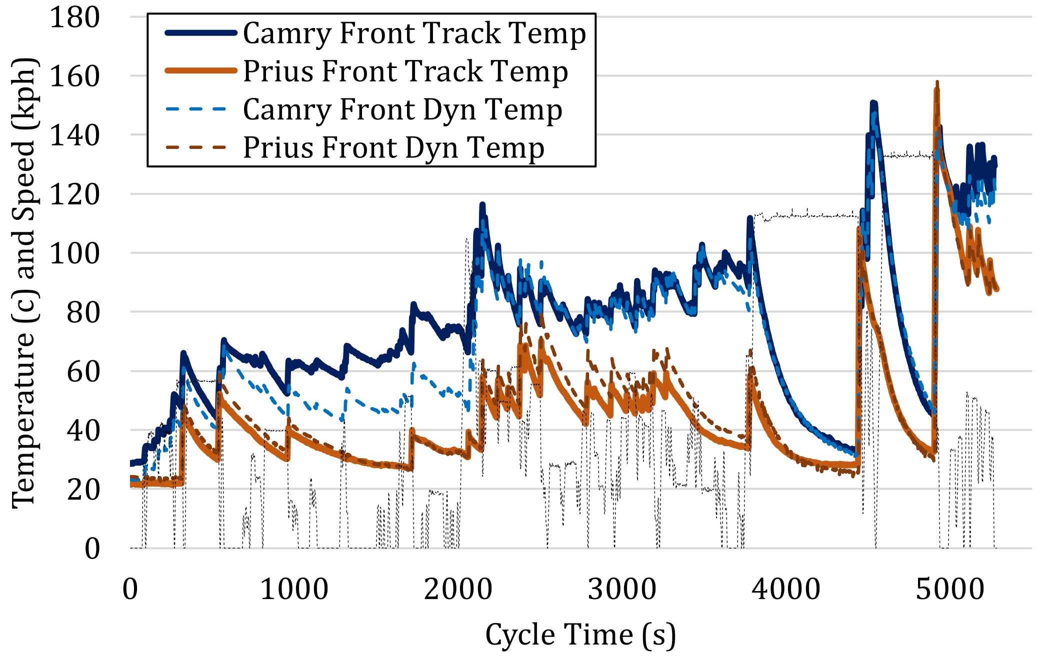
Evaluation of Prius Regeneration Simulation

Comparing Camry to Prius (similar vehicle mass)

Speeds/ Hydraulic Pressure



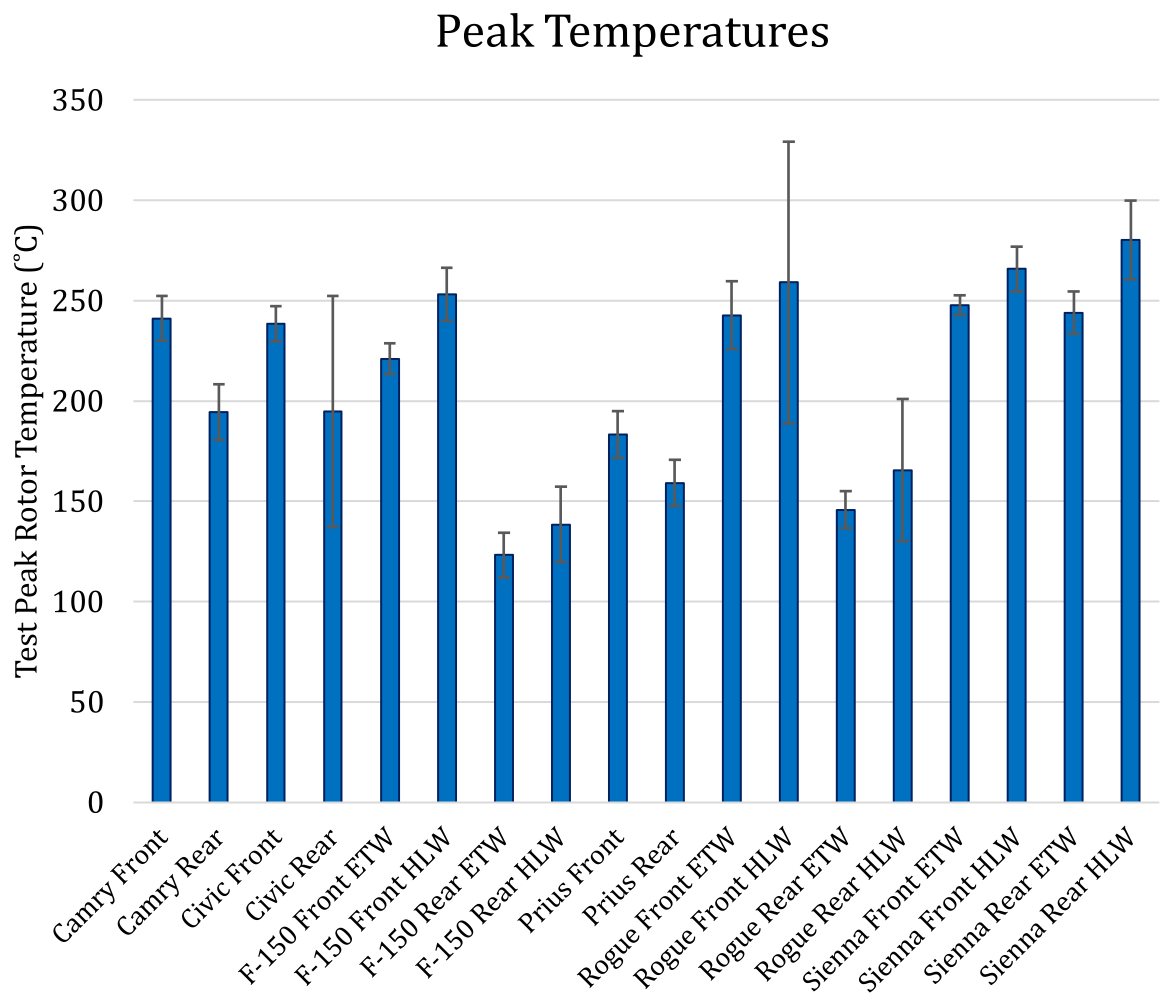
Temperatures

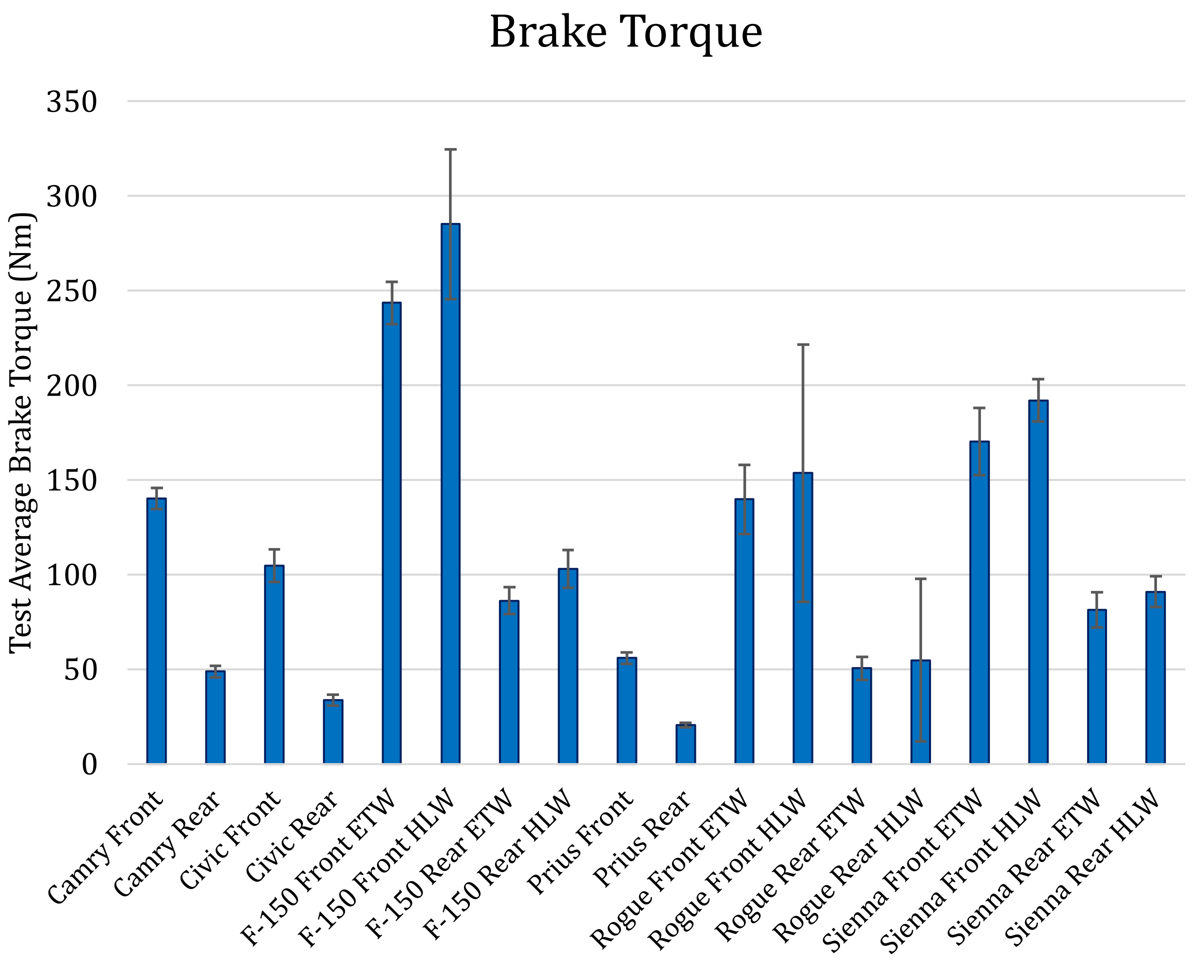


Results

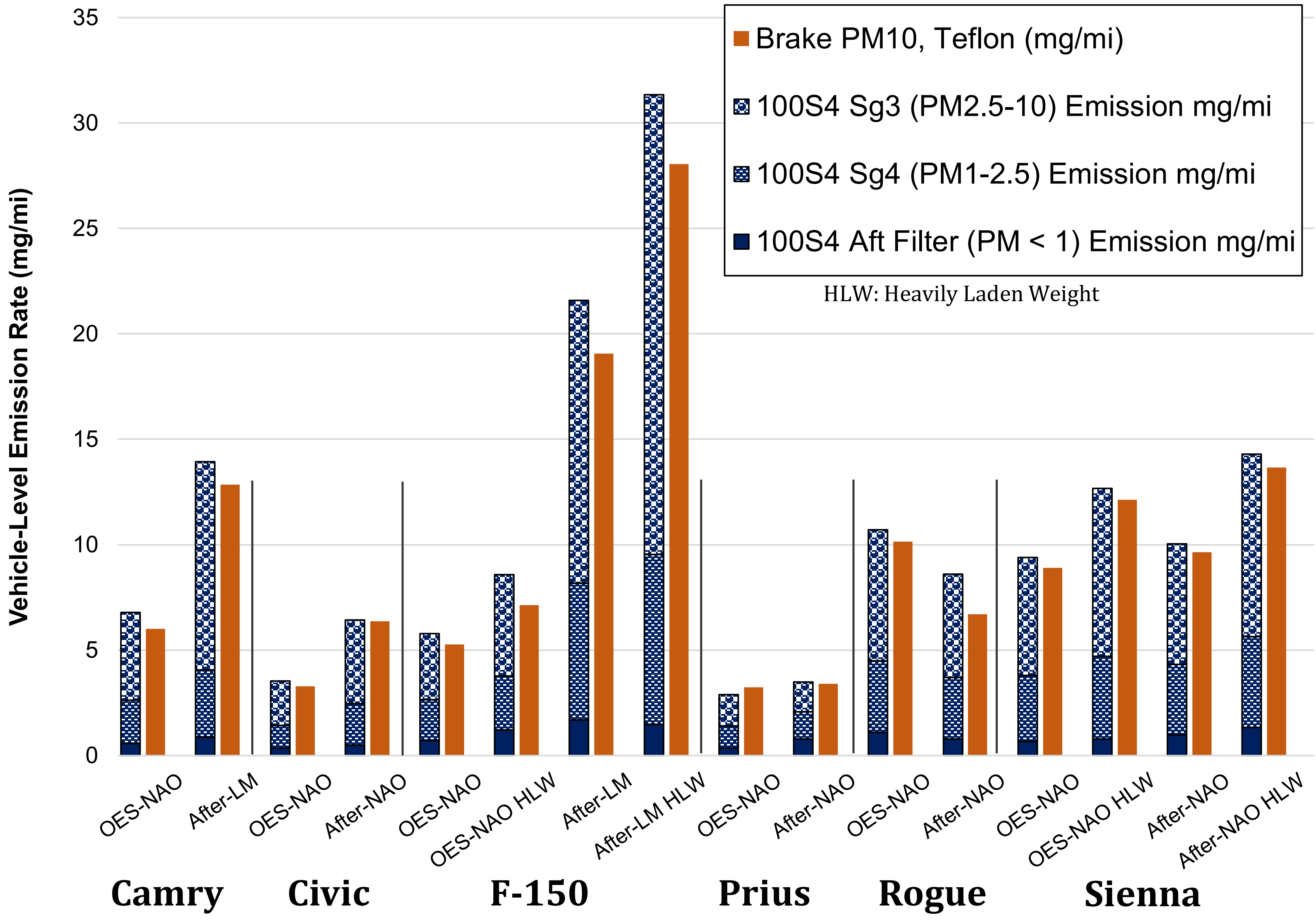
- Operational Parameters
- PM Mass
  - Test Level
  - Vehicle Level
- Speed Correction/Implementation in EMFAC
- Particle Size Distribution
- Comparison to Literature

Operational Parameters

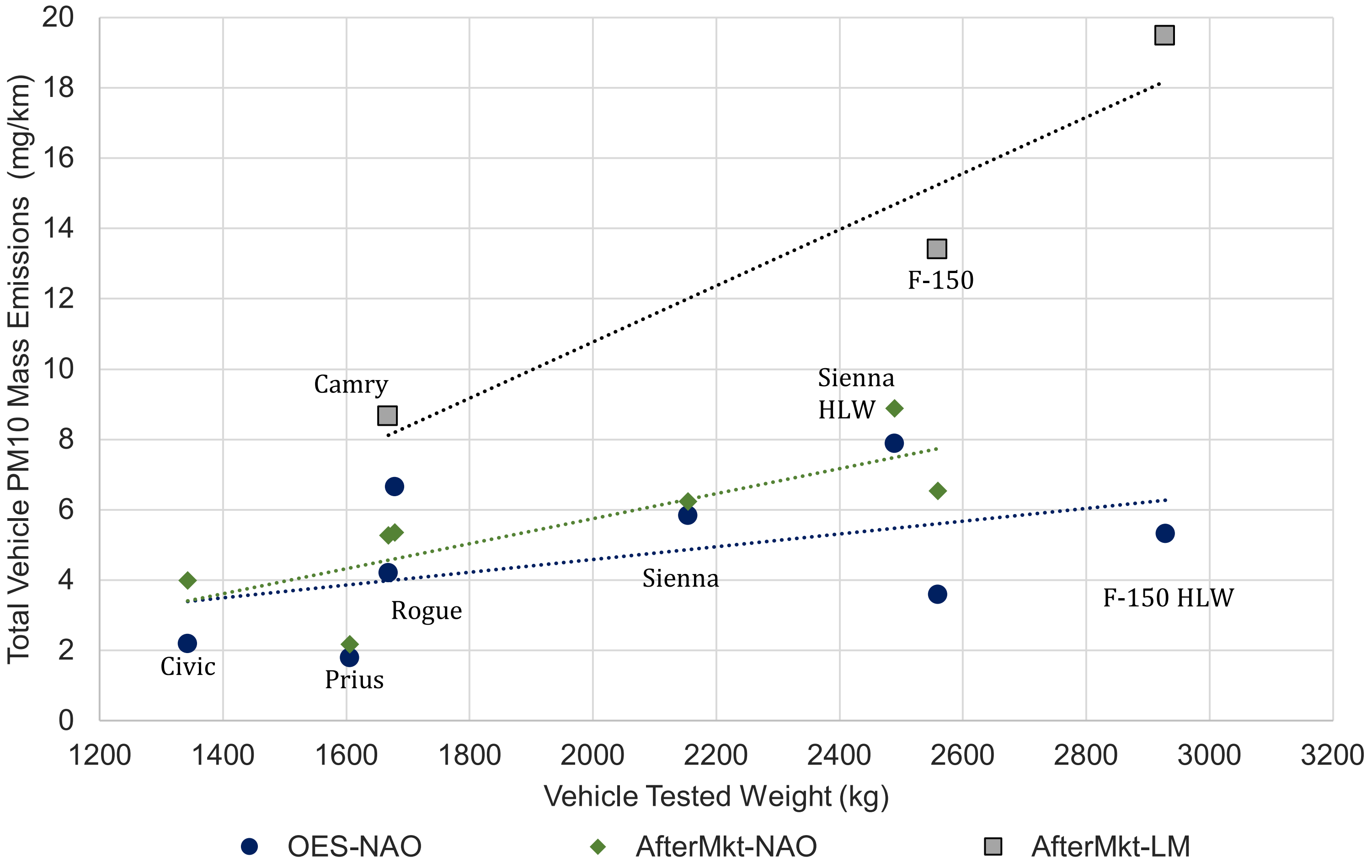




Results – PM Mass

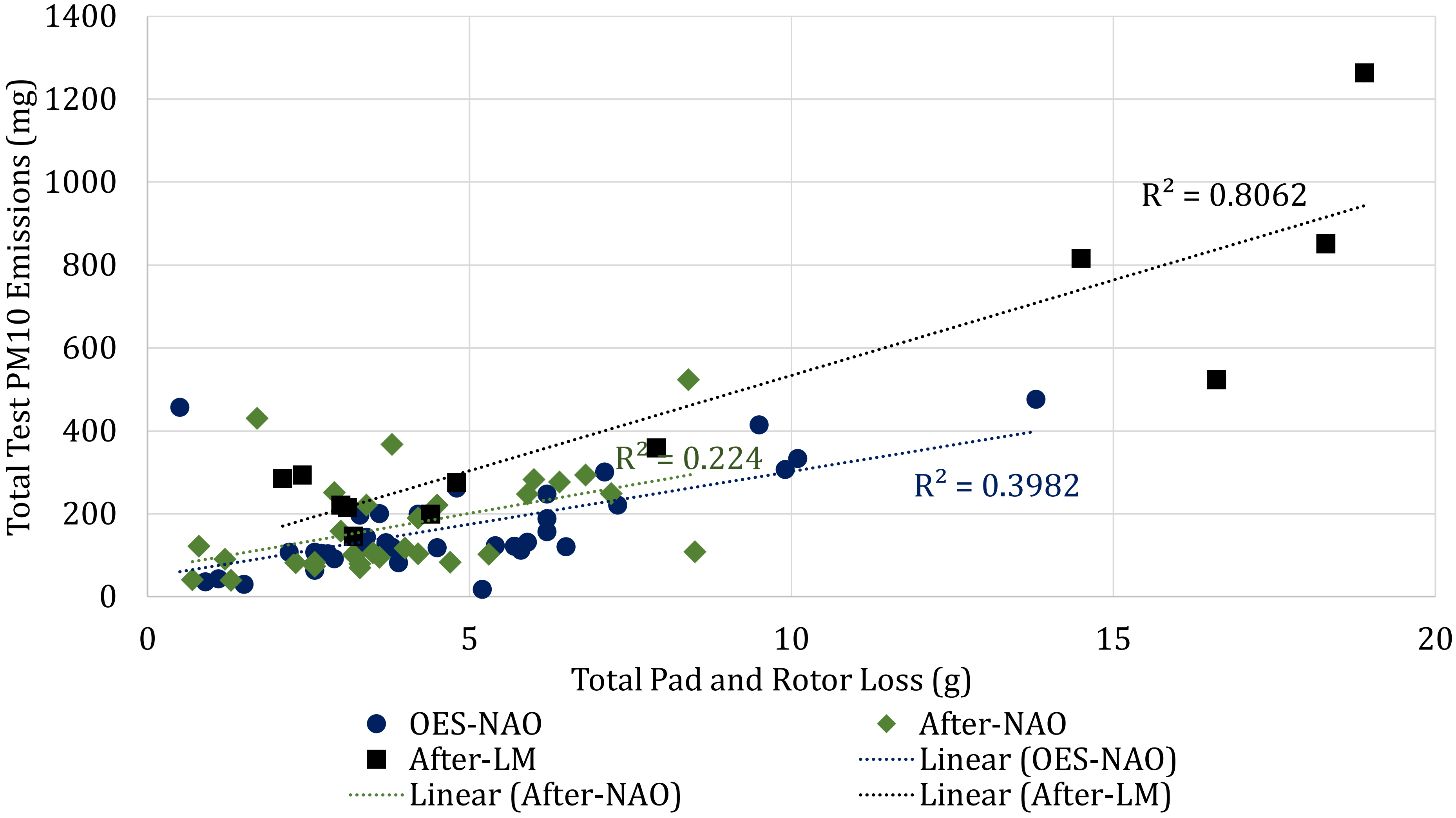


PM Mass Emission Rate vs Vehicle Mass and Pad Material Type

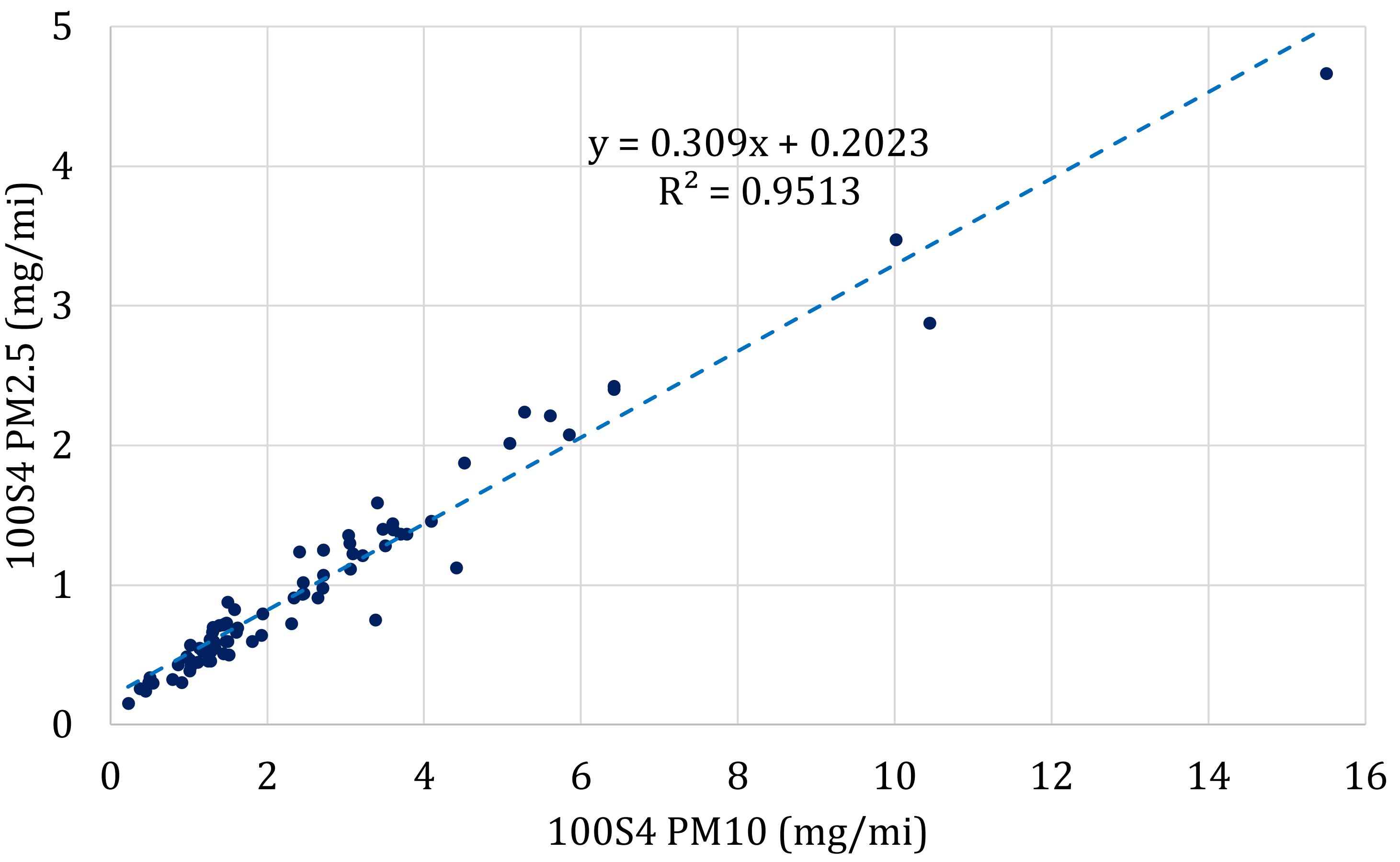


Measured PM10 v. Total Brake Component Wear

The observed trend is intuitive, but total wear rate is only an approximate predictor for PM10



PM2.5 vs PM10

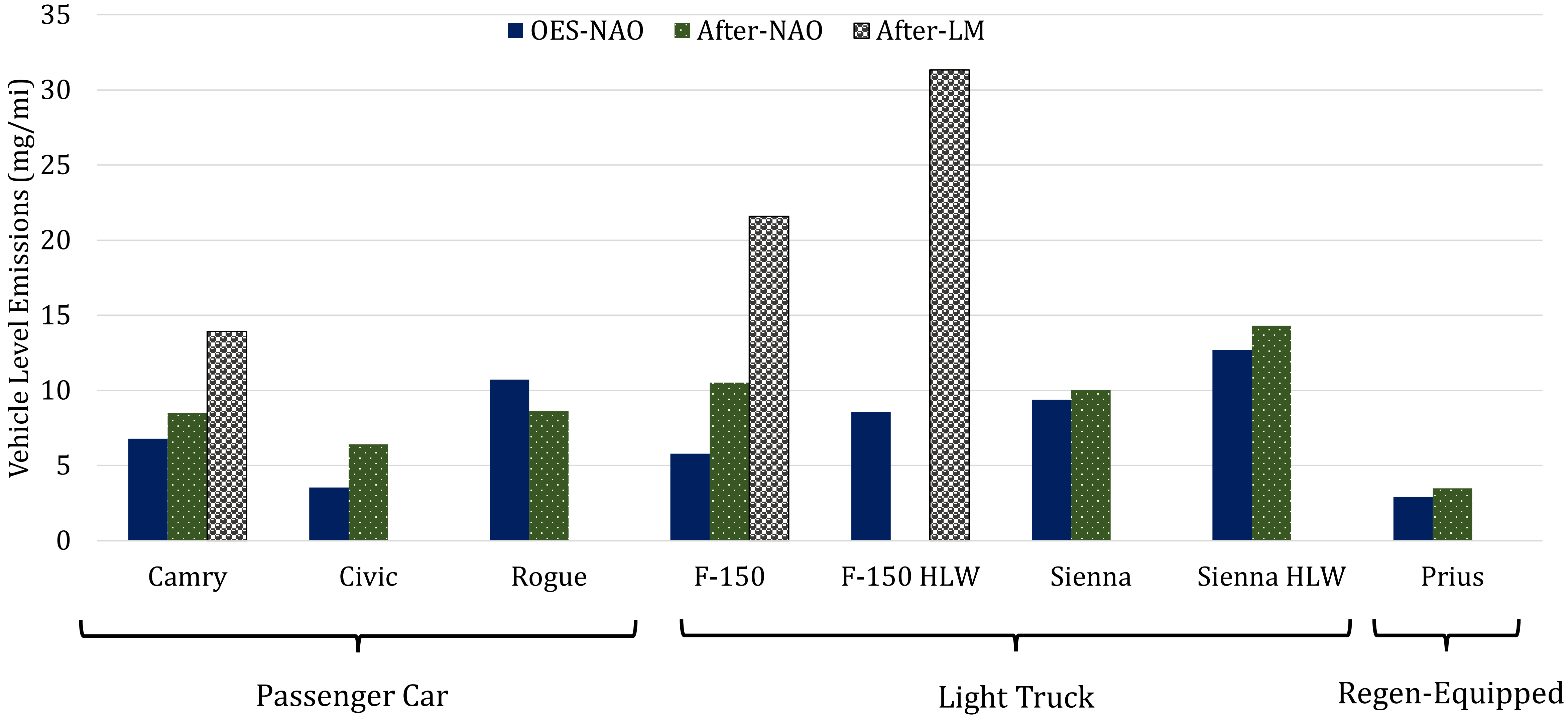


y = 0.309x + 0.2023
R² = 0.9513
100S4 PM2.5 (mg/mi)
100S4 PM10 (mg/mi)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16

Implementation of PM Mass in EMFAC

- Base Emission Rate (BER)
  - Overall cycle average speed is close to that of UC so consider overall cycle result to be BER
    - Conceptually similar to UC exhaust emission results
- Deterioration Factor (DF)
  - Based only on shift from OES materials to aftermarket
- Speed Correction Factor (SCF)
  - Generated from minute by minute QCM data vs associated source microtrip average speed

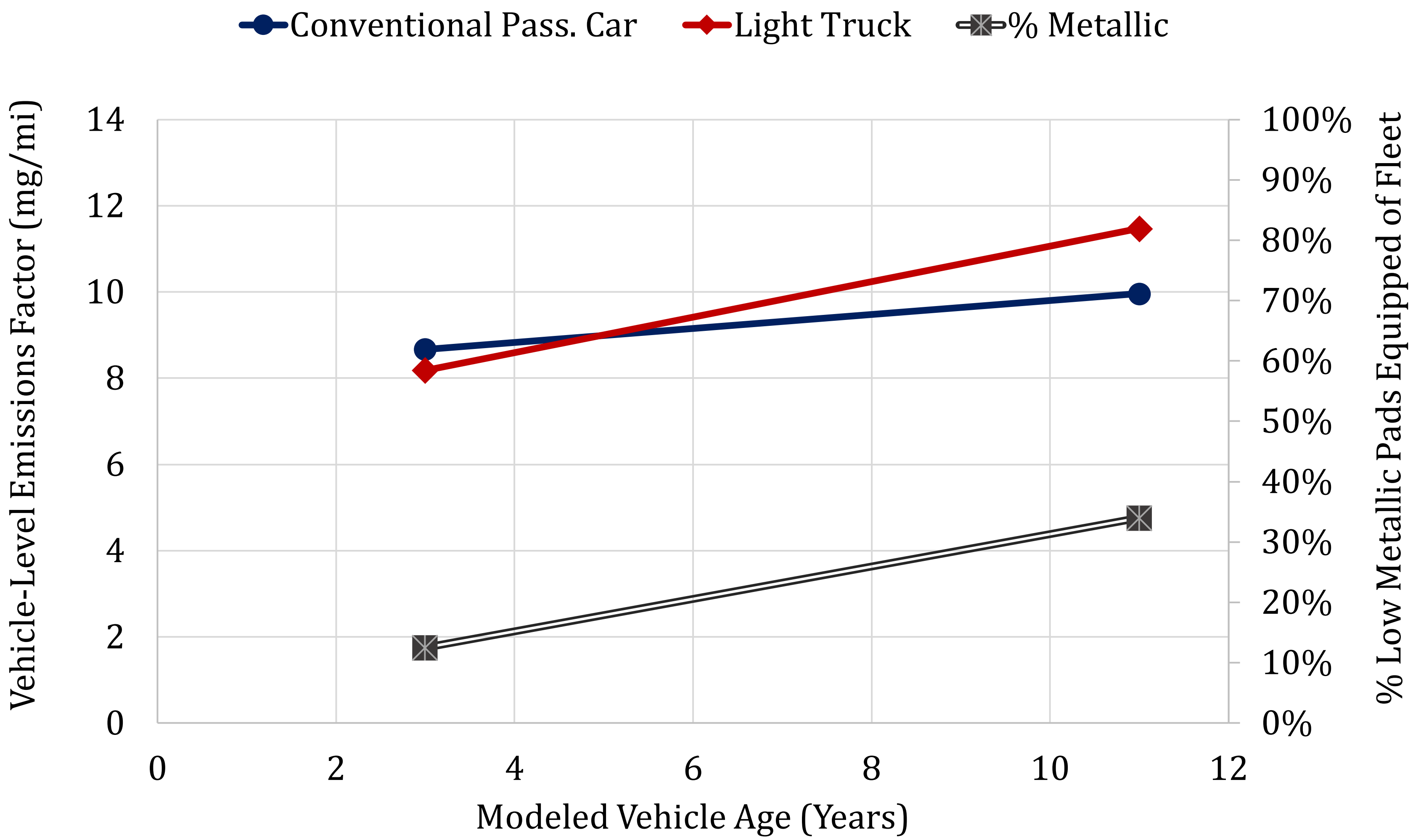
Vehicle Level Mass Emissions



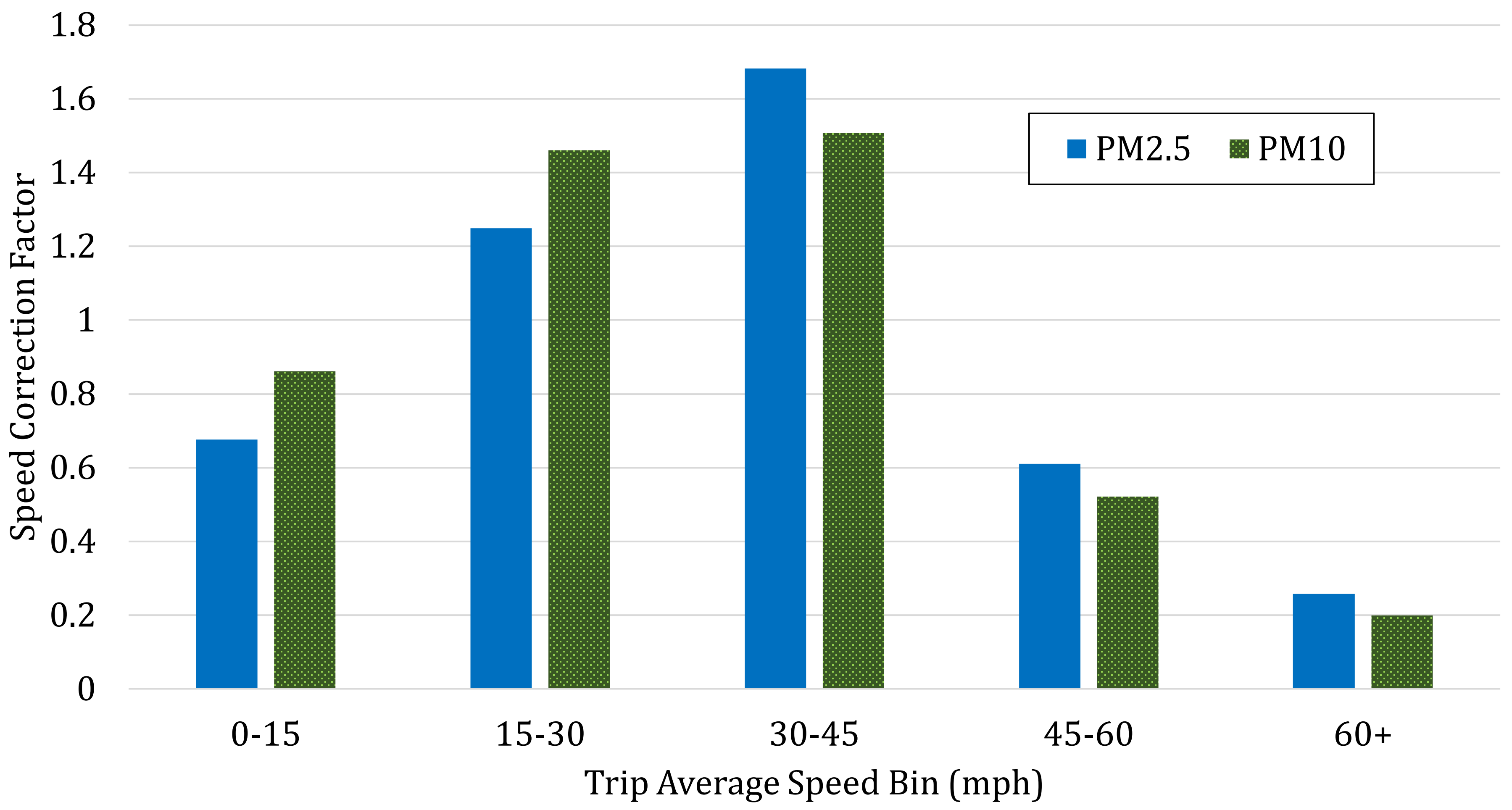
Base Emission Rate and Deterioration Rate

Vehicle Type	PM2.5 BER (mg/mi)	PM2.5 Additive deterioration per year of vehicle age, (mg/mi)	PM10 BER (mg/mi)	PM10 Additive deterioration per year of vehicle age, (mg/mi)
Conventional Passenger	1.62	0.01	8.18	0.16
Light Truck	1.54	0.07	6.94	0.41
Regenerative-equipped	0.93	0.003	3.30	0.005

PM 10 Base Emission Rate and Deterioration Rate



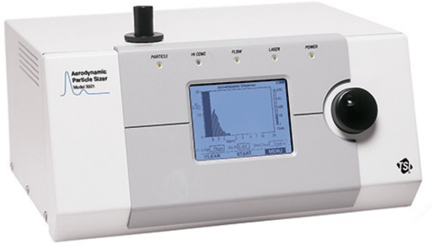
Speed Correction Factor



Particle Size Distribution Measurement

- Measurement types/size ranges
  - Engine Exhaust Particle Sizer (EEPS) - 5.6-560 nm

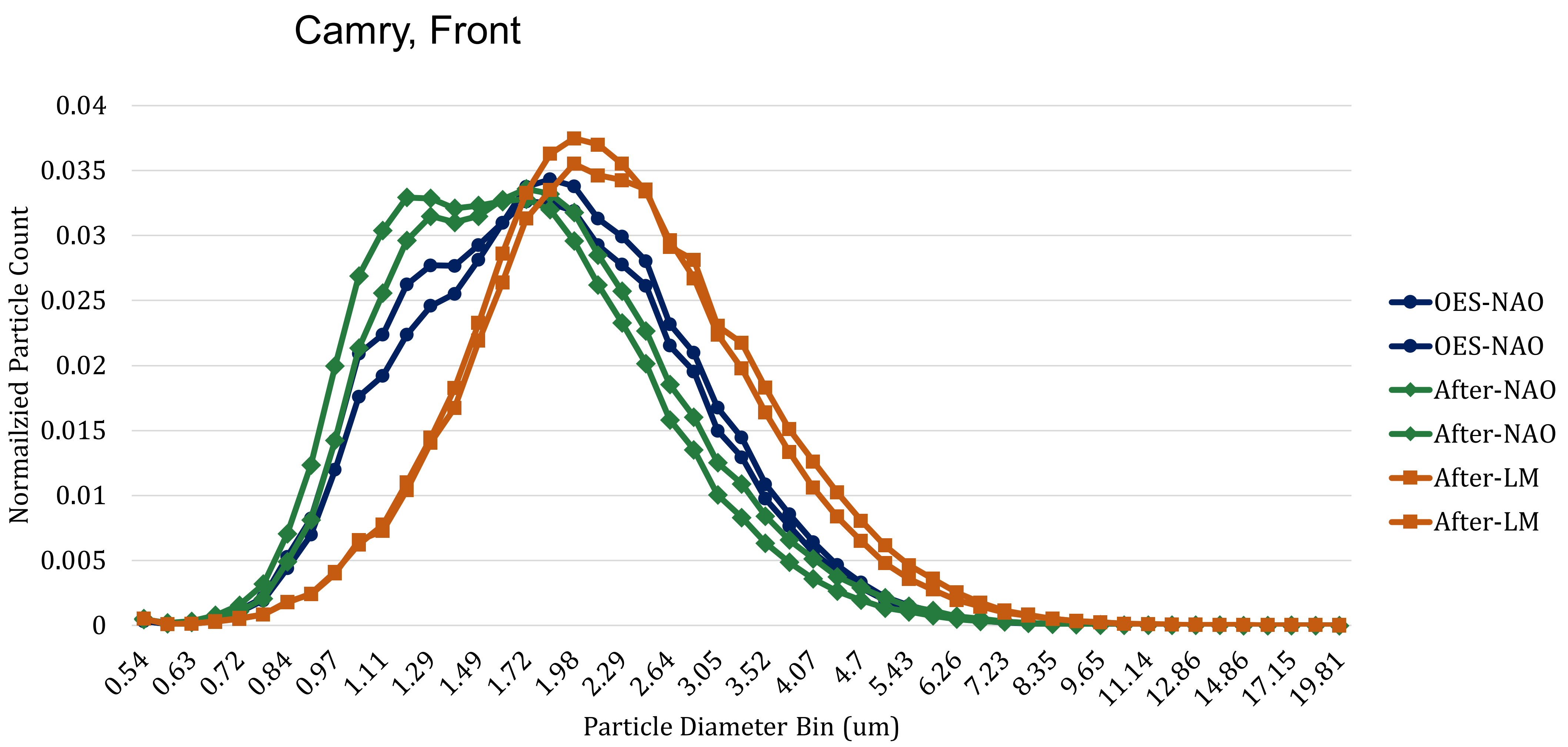
  - Aerodynamic Particle Sizer (APS) – 0.5-20 μm



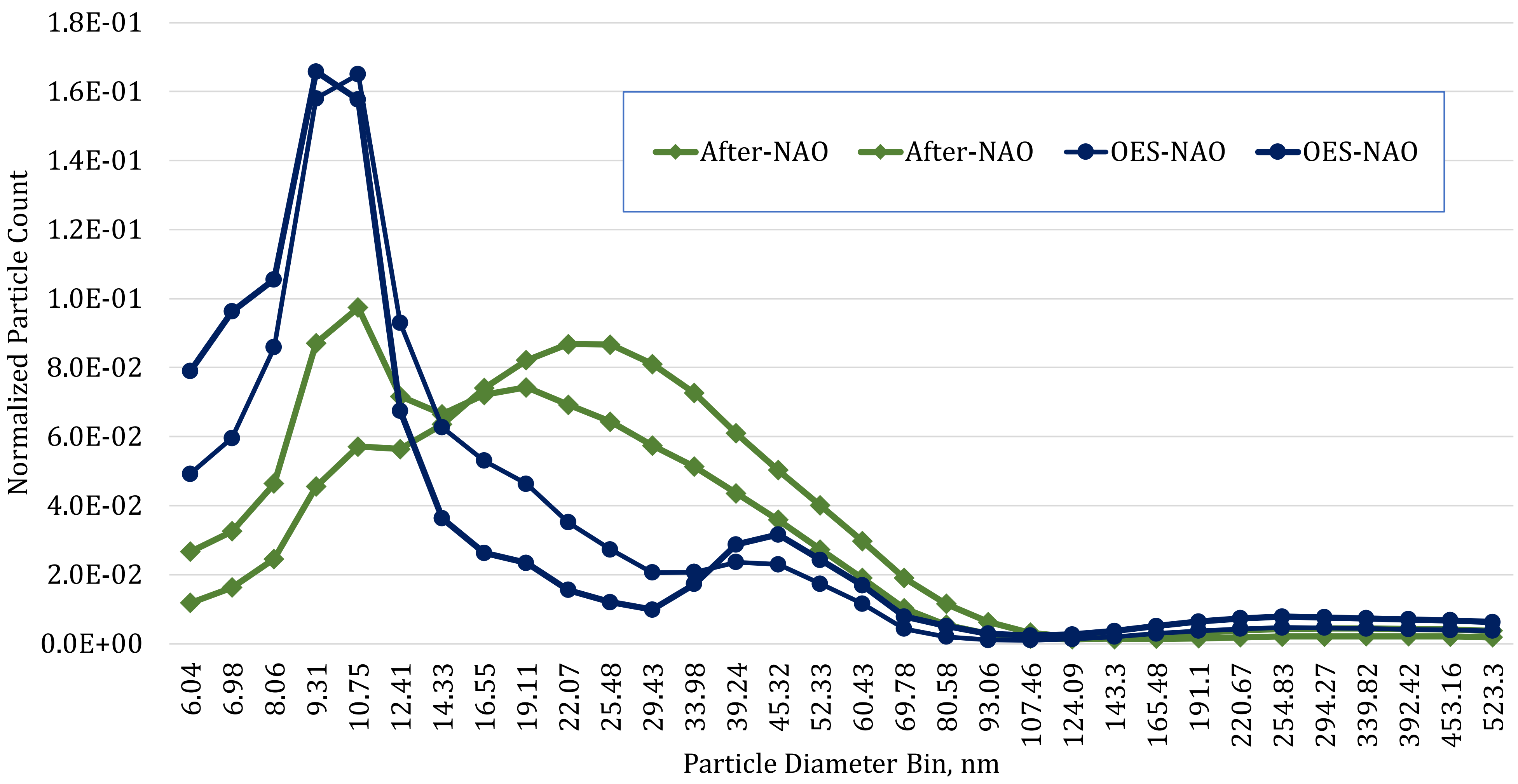
- Measurements are not on the same basis
- Presenting normalized data

Particle size distribution 0.5 – 18 µm

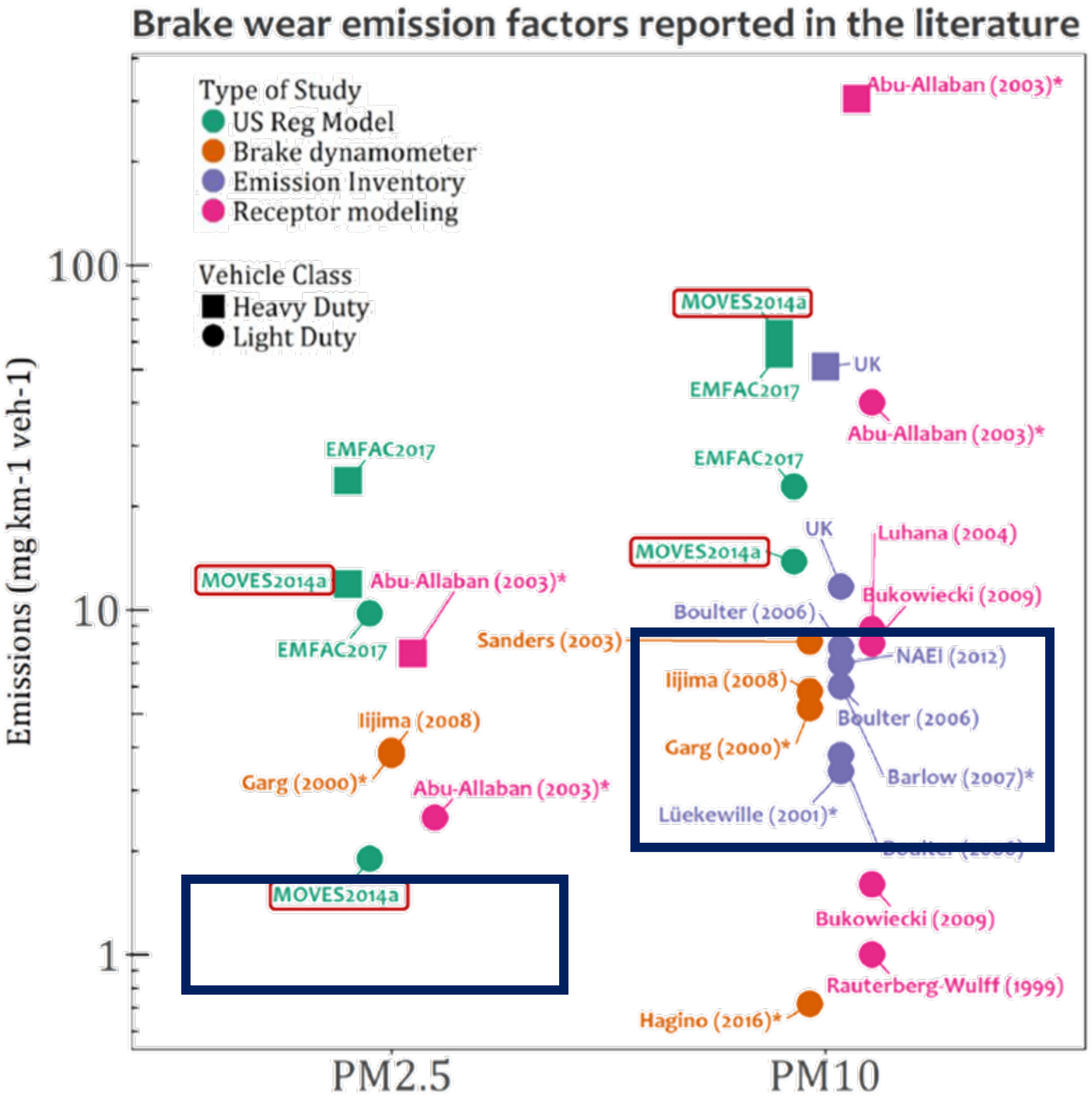
NAOs tend to give a bimodal response, while LM were predominantly unimodal



EEPS Example (Civic Front)



PM Mass Comparison to Literature



Sonntag et. al. *Modeling Brake and Tire Wear Emissions in Regulatory Models in the United States*, 2018 ISES-ISEE Joint Annual Meeting

Next Steps / Future Work

- Parallel study for heavy duty truck brakes funded by Caltrans
  - Various truck types and vocation duty cycles
  - Recently completed and used to update EMFAC HD PM emissions factors
- Determine fraction of particle settling on vehicle components/roadway
- Update chemical tracers for new ambient/roadside studies
- Continue to refine industry-accepted emissions measurement methods
- Environmental dilution and health effects – toxicity

LINK, CARB, and ERG Published a paper from this work:
SAE Paper 2020-01-1637
Brake Particulate Matter Emissions Measurements for Six Light-Duty Vehicles Using Inertia Dynamometer Testing

Thank You

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