WEBINAR:

Vehicular Non-Exhaust Emissions Research in California: Understanding the Characteristics of the Emissions

Dr. Seungju Yoon

September 18, 2024

CALIFORNIA AIR RESOURCES BOARD

CENTER FOR ADVANCING RESEARCH IN
TRANSPORTATION EMISSIONS, ENERGY, AND HEALTH (CARTEEH)
A USDOT University Transportation Center

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For a Seminar Hosted by the Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH)

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September 18, 2024

Seungju Yoon, Okjoo Park, Michelia Dam, and Jorn Herner

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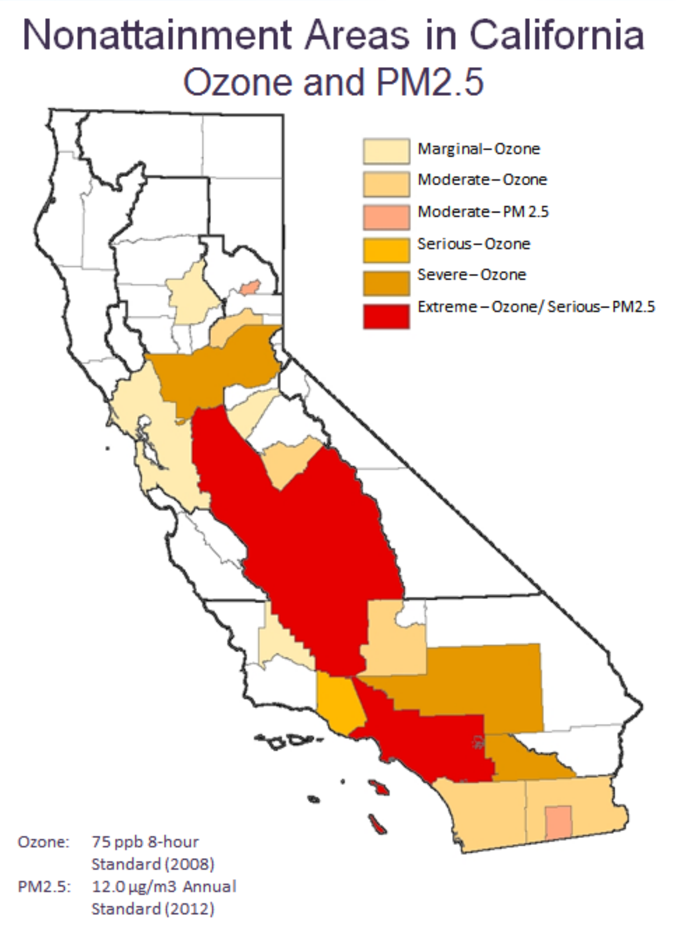
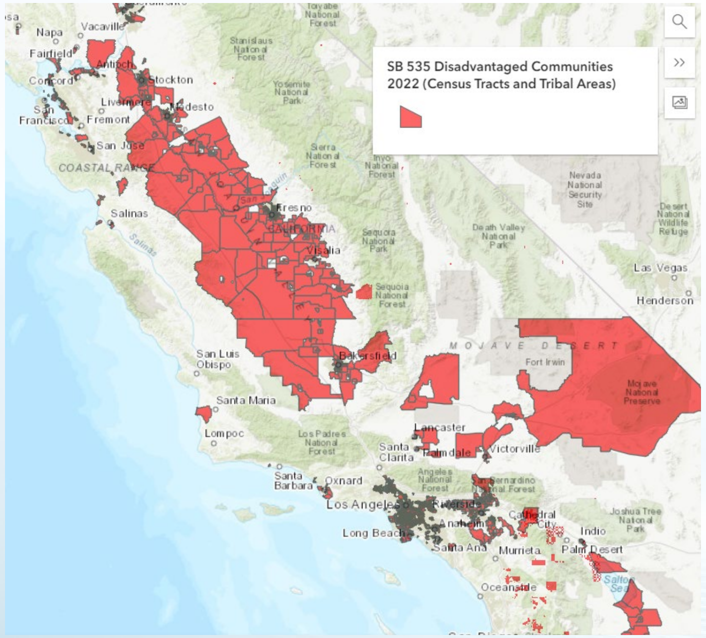
CARB leads California’s fight against air pollution and climate change, protects public health, and promotes clean, energy-efficient fuels and technology.

California needs to improve air quality regionally and locally and reduce greenhouse gas emissions

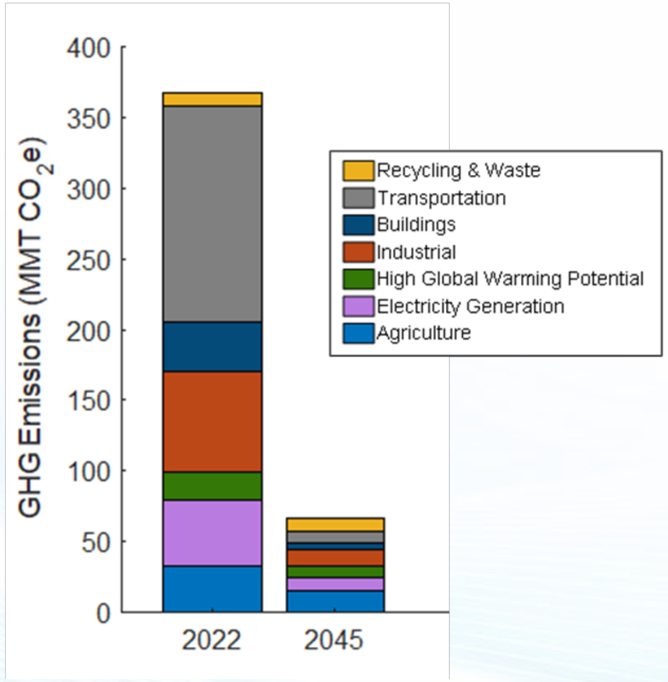


Disadvantaged Communities



(CalEnviroScreen Disadvantaged Communities)

Stringent Reductions at Source Reduce Greenhouse Gas Emissions By 85%



(California's 2022 climate change scoping plan)

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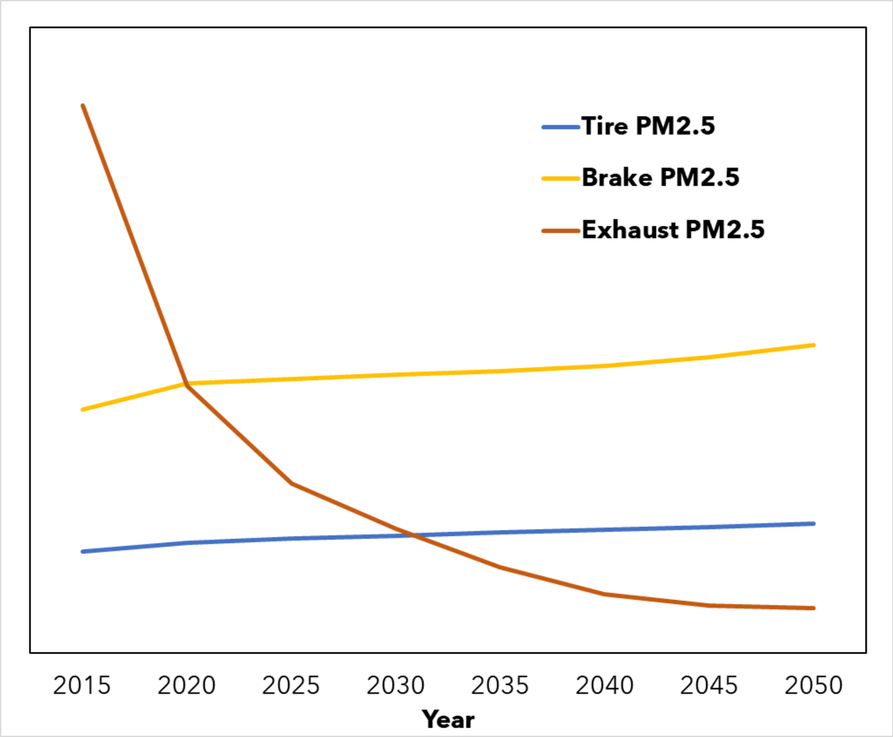
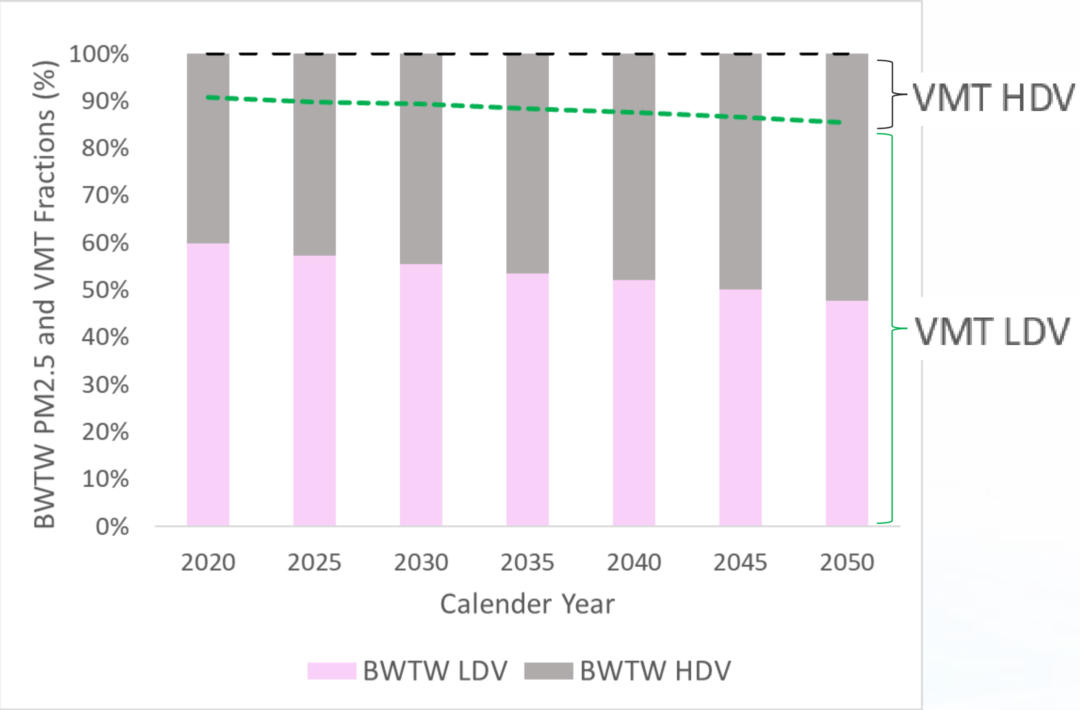
Non-exhaust is a dominant source of total direct PM2.5 for on-road vehicles



(EMFAC2021 default values before adjusting for the brake-wear PM benefits of clean transportation programs.)



Need to characterize non-exhaust PM with scientifically-robust, reproducible methods

Brakes and tires generate airborne particles that may be associated with adverse health effects

- Brake-wear PM
  - Mode: ~ 2.5 µm
  - Metal content: Ba, Fe, Cu, Zn, Ti, and others
- Tire-wear PM
  - Mode: 2.5 - 10 µm
  - Metal and micro-plastic content: Zn, Si, Al, Ca, Ti, Alkanes, NR, SBR, SBR, and others

Table 2 Individual effects of metals, estimated with Poisson regression, on cardiovascular mortality, respiratory mortality and lung cancer incidence adjusted for tobacco weekly expenditure, IMD and percentage of Asian and white population. Mean and lower and upper bounds of the credible intervals of the IDR RR

	Metal	RR (95% CI)
Cardiovascular mortality	Cu PM_{10}	0.994 (0.987 to 1.001)
	Fe PM_{10}	0.319 (0.037 to 2.779)
	Zn PM_{10}	1.073 (0.985 to 1.169)
	Cu $PM_{2.5}$	1.005 (1.001 to 1.009)
	Fe $PM_{2.5}$	0.042 (0.002 to 0.995)
Respiratory mortality	Cu PM_{10}	0.988 (0.978 to 0.998)
	Fe PM_{10}	0.649 (0.033 to 12.767)
	Zn PM_{10}	1.136 (1.010 to 1.277)
	Cu $PM_{2.5}$	1.003 (0.998 to 1.009)
	Fe $PM_{2.5}$	0.980 (0.013 to 72.673)
Lung cancer incidence	Cu PM_{10}	0.998 (0.912 to 1.091)
	Fe PM_{10}	0.973 (0.830 to 1.142)
	Zn PM_{10}	0.995 (0.910 to 1.089)
	Cu $PM_{2.5}$	1.092 (0.943 to 1.225)
	Fe $PM_{2.5}$	0.969 (0.889 to 1.057)

IDR, interdecile range; IMD, index of multiple deprivation; PM, particulate matter; RR, relative risk.

Note,
> 1 indicates an association with increased risk

(Aurore Lavigne et al., 2019)

Need to assess adverse health effects of non-exhaust emissions

CARB's research approaches and questions on non-exhaust emissions

- How to characterize non-exhaust emissions?
- What are their potential health effects: community exposure and regional air quality?
- Can our current programs and policies help reduce non-exhaust emissions?
- What are the impacts of new tire/brake materials and EV technologies?

CARB non-exhaust emissions research goals

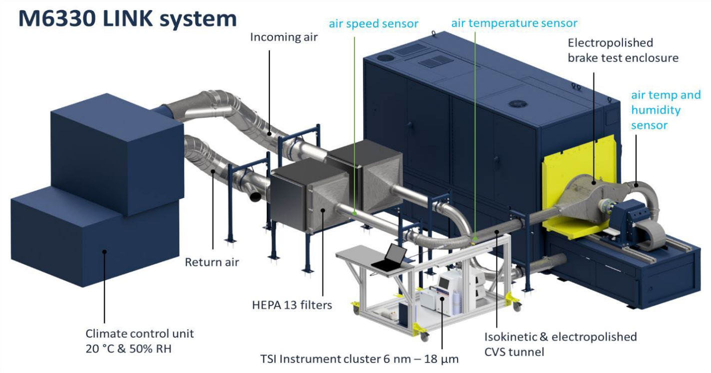
- Completed projects
- Current projects
- Planned/considered projects

FY17/18 · FY18/19 · FY22/23 · FY23/24 · FY24/25

Project	Objectives
17RD016: Brake-dyno tests for 6 LDVs (1HEV)	• Develop California Brake-Dyno (CBD) cycle and brake-dyno testing protocol • Develop brake-wear PM emission factors for EMFAC • Understand chemical characteristics of the PM through CARB and USEPA internal efforts
Caltrans/US EPA: Brake-dyno tests for 1 EV and 6 HDVs	
17RD012: Health impacts of brake/tire PM	• Characterize oxidative potentials (OP^{OH}) and exposure associated with brake/tire-wear PM
18RD017: Roadside measurement of non-exhaust PM	• Estimate contribution of brake/tire-wear PM to near-road communities
22RD002: On-road BWTW PM measurement	• Develop on-road brake/tire-wear measurement methods • Characterize EF, chemical profiles, and near-road exposure levels
CARB RL-SHED tests for brake/tire PM from EV regen-braking	• Assess brake-wear PM reduction potentials from EV regenerative braking compared to gasoline vehicles in consideration of duty cycles
23RD008: Characterization of tire-wear gaseous emissions under real-world driving conditions	• Measure on-road tire-wear gaseous emissions and profile emission chemical compositions • Derive EF for tire-wear gaseous emissions
23RD007: Assessing EV Technologies Associated with Improving Energy Efficiency or Reducing Brake- and Tire-Wear Emissions	• Assess EV system and component technologies associated with improving energy efficiency or reducing brake- and tire wear for passenger cars, trucks, and off-road vehicles.
23RD010: Train BWWW PM measurement	• Develop train BWWW measurement methods • Characterize EF, chemical profiles, and near-road exposure levels
FY24/25: Exposure and health impacts of non-exhaust particles in a region	• Conduct a regional assessment of the exposure and health risks for BWTW PM in a region with overburdened communities in the San Joaquin Valley
FY24/25: Off-road BW PM measurement	• Develop California off-road brake dyno testing protocol • Off-road BW EF for EMFAC • Understand chemical profiles from off-road BW

Brake-wear PM was measured at a brake-dyno laboratory

- Applied a similar concept to the EU brake-wear testing protocol
  - Developed and used braking activity cycles that represent California fleet
- Selected California fleet representative vehicles
  - 5 gasoline, 1 hybrid, and 1 full electric vehicles
  - 7 diesel trucks and buses
- Characterized brake-wear emissions and chemical compositions



(Brake Dynamometer System)

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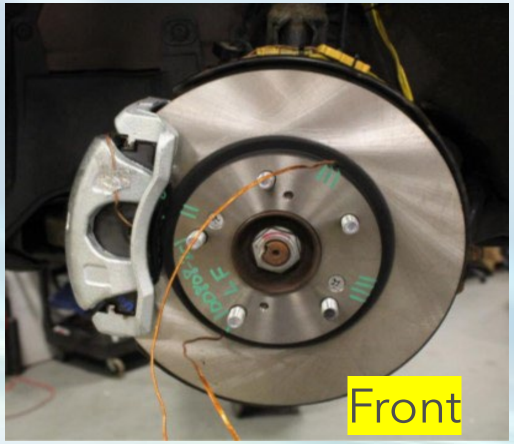
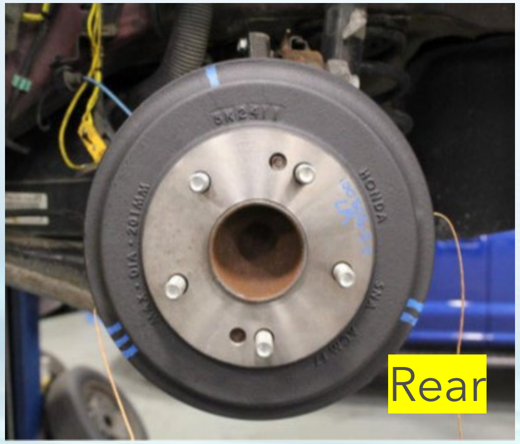
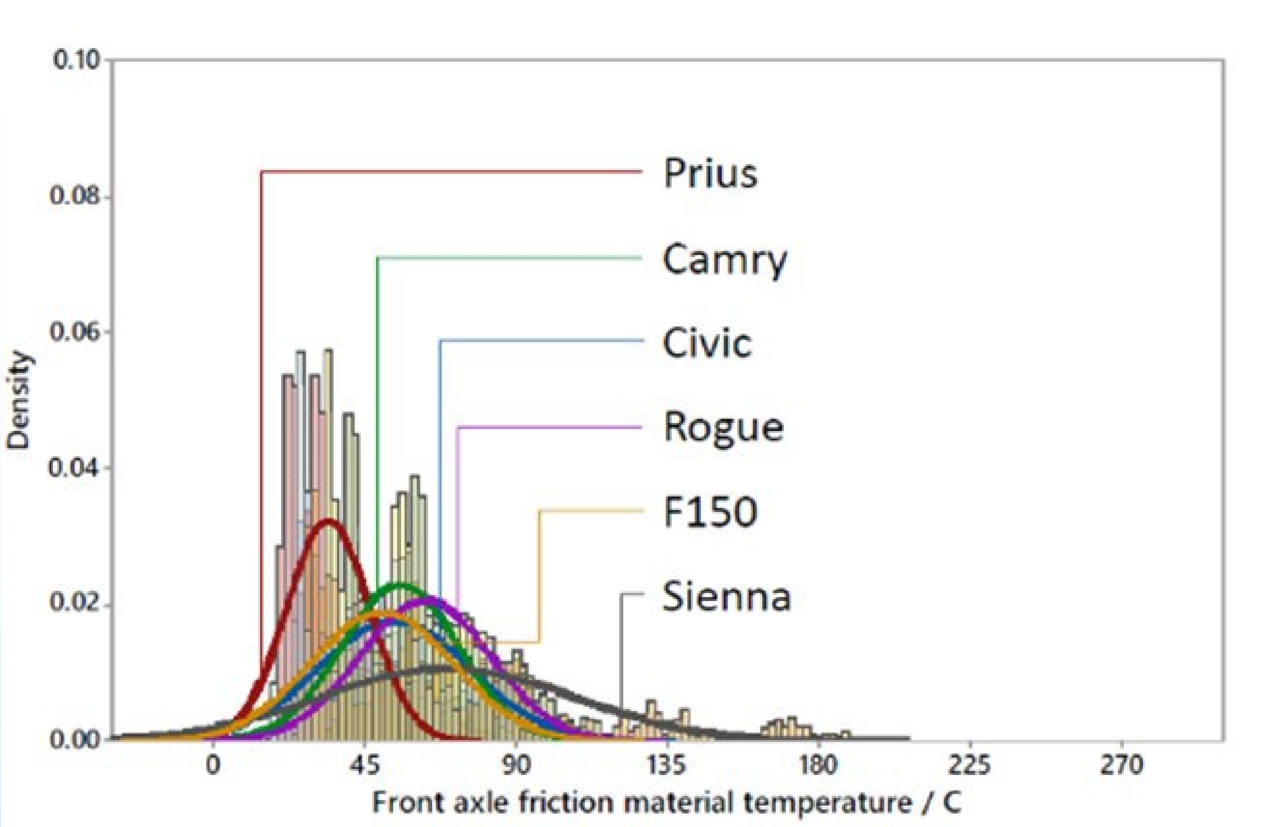
Brake temperature profiles were developed for each vehicle through on-road track tests







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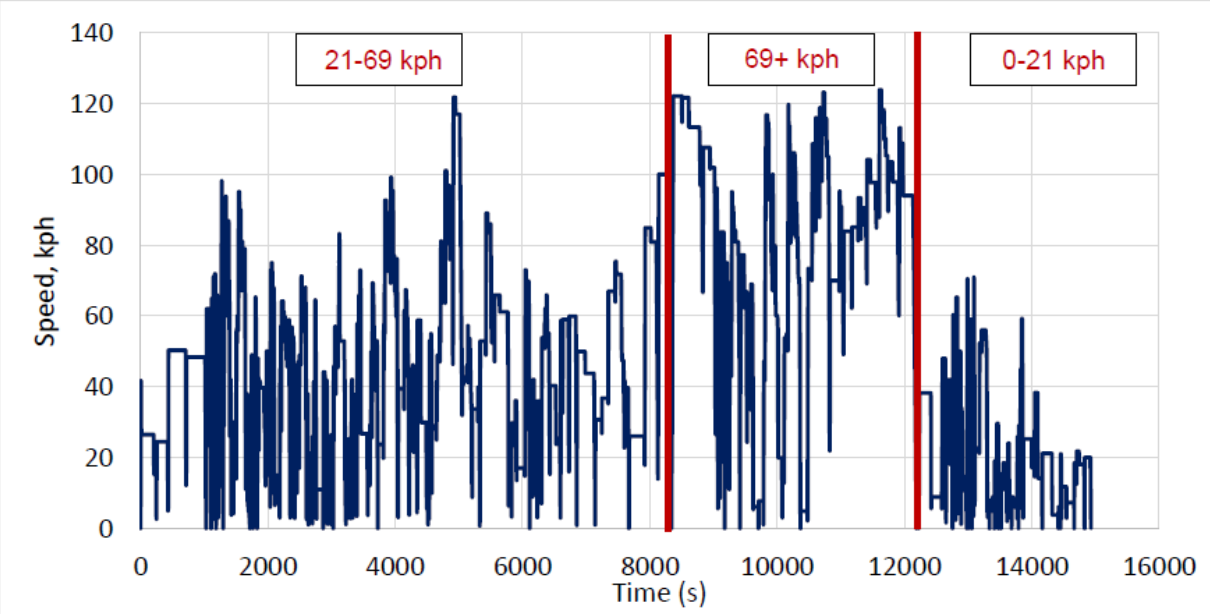
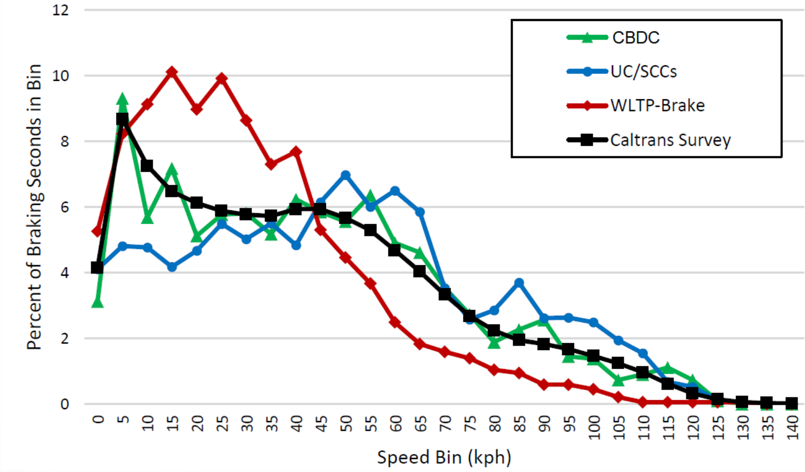
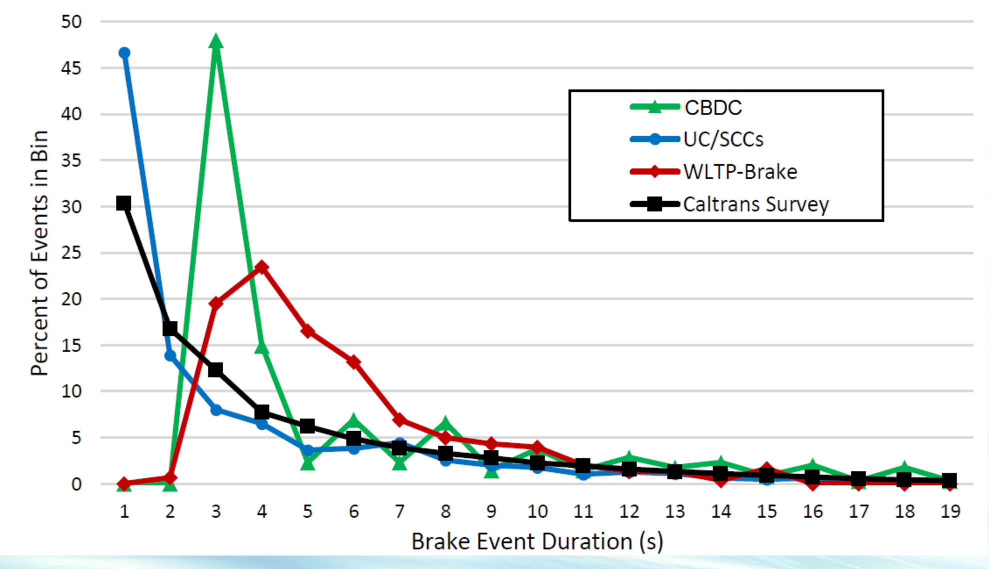
A brake-dyno test cycle was developed considering deceleration rate, braking duration and brake temperature, and speed







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

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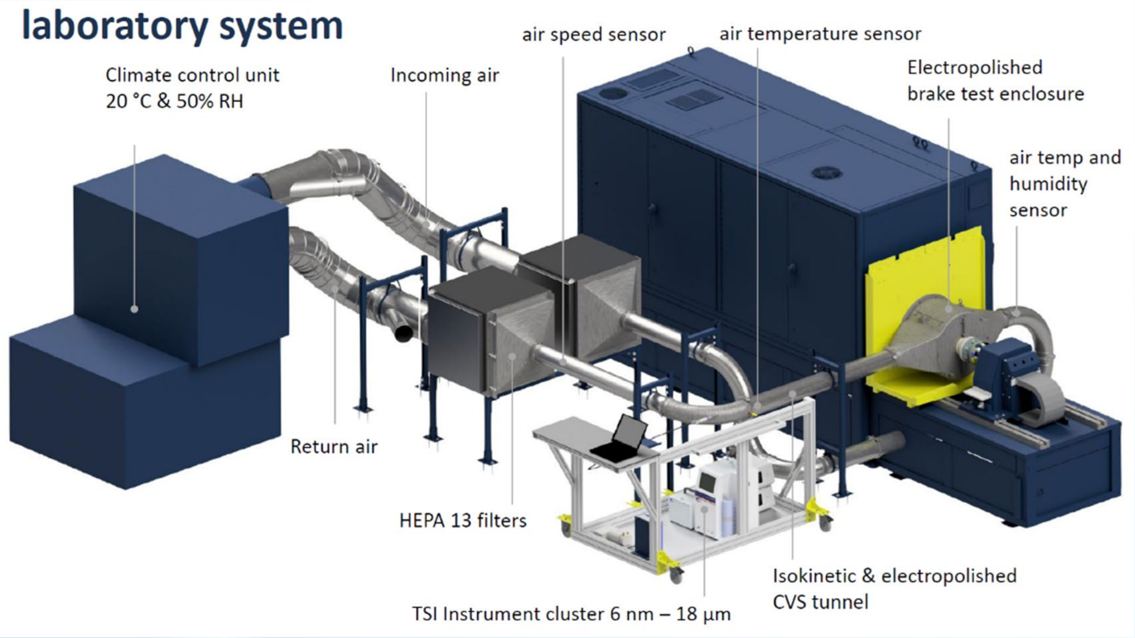
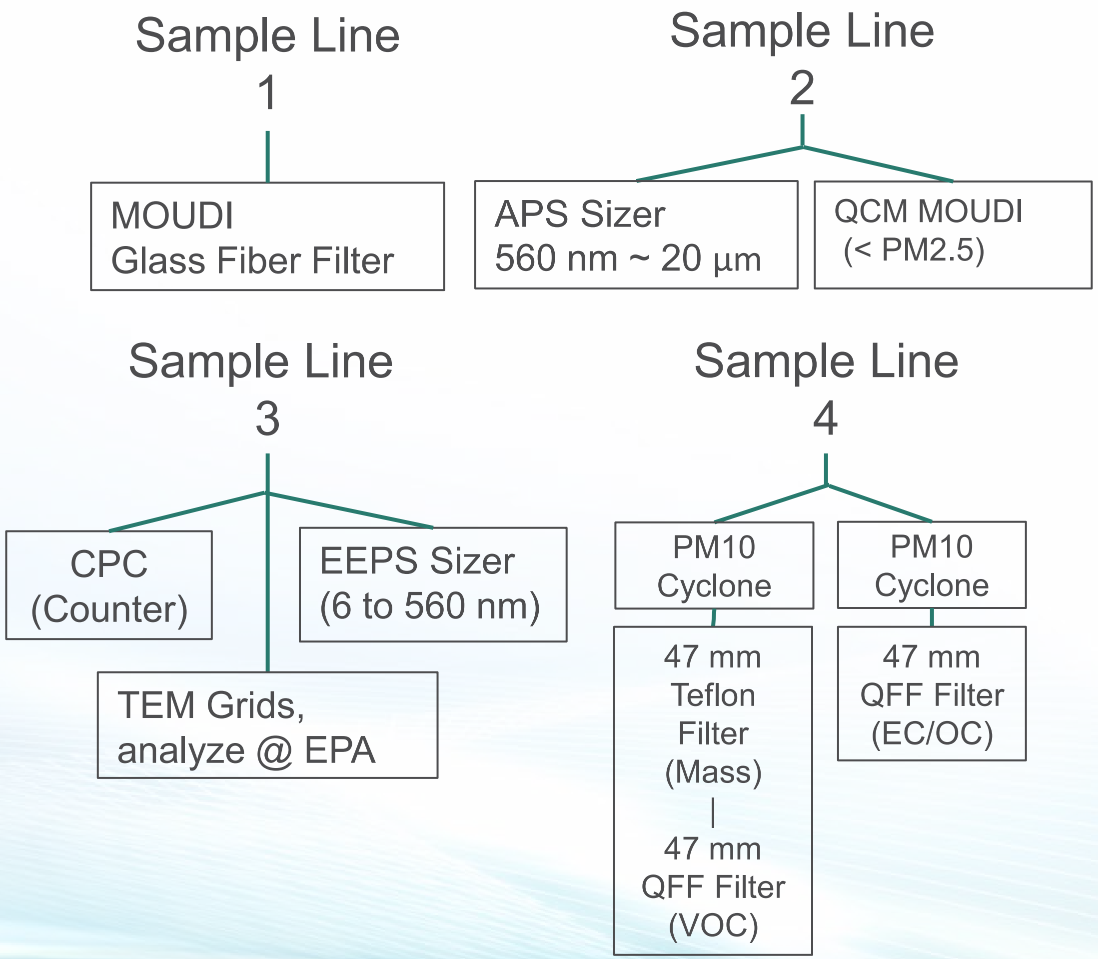
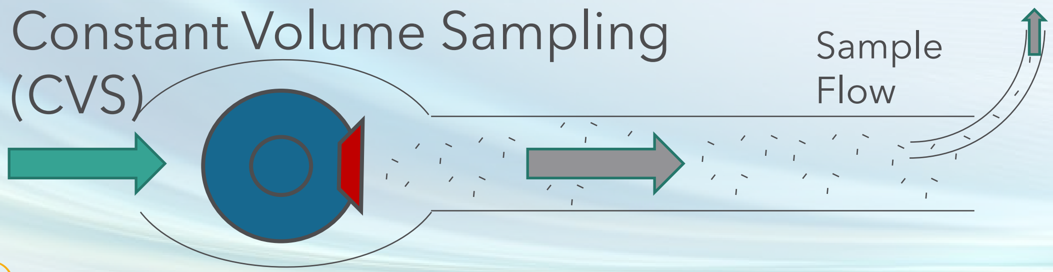
Brake-dynamometer and CVS experimental setup

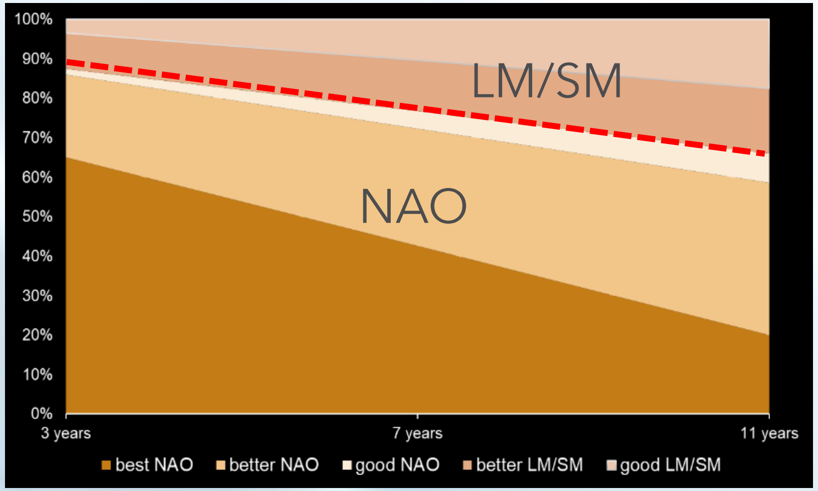




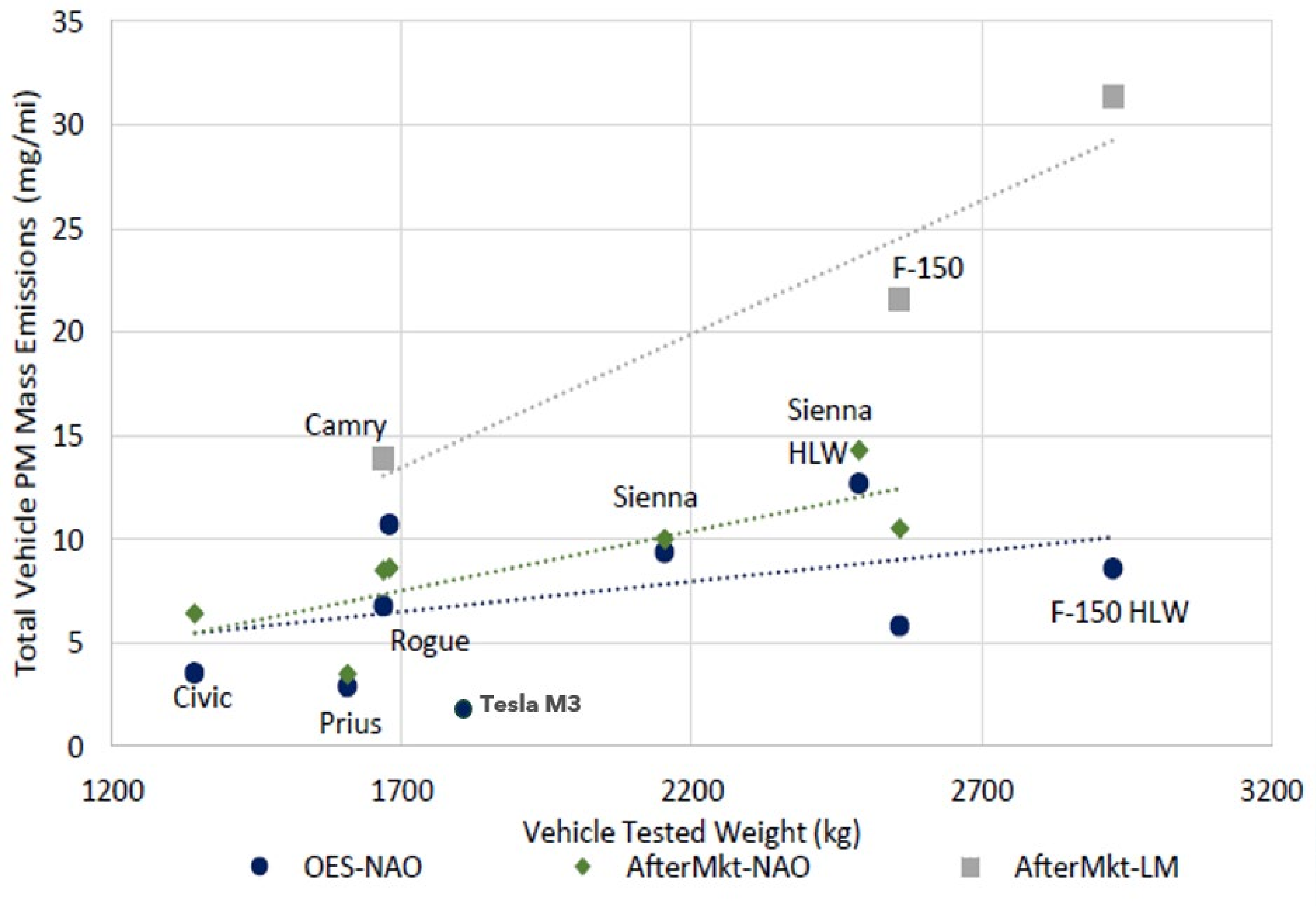


PM10 mass by vehicle weight and brake pad type

Brake pad type distribution



NAO: non-asbestos organic
LM: low metallic
SM: semi-metallic



(Details are available from CARB's research report, 2021)

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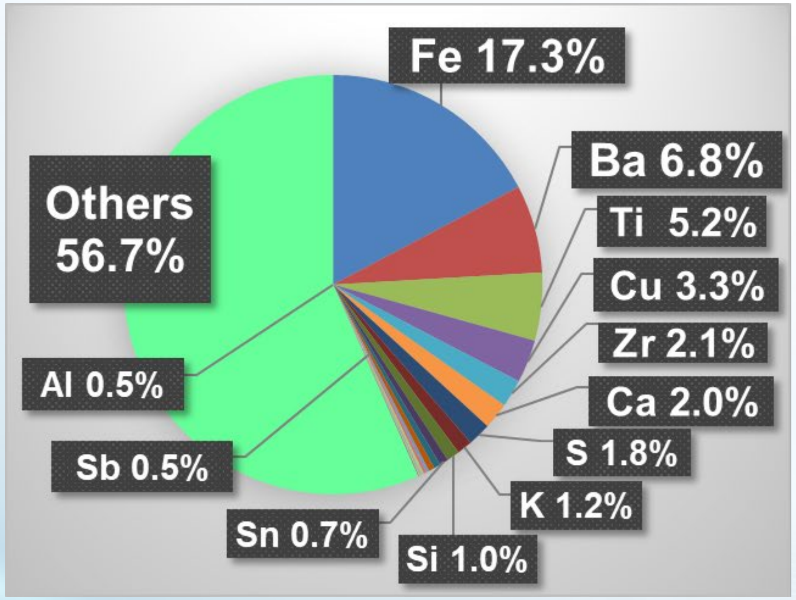
Chemical speciation profiles for California brake pads in 2018

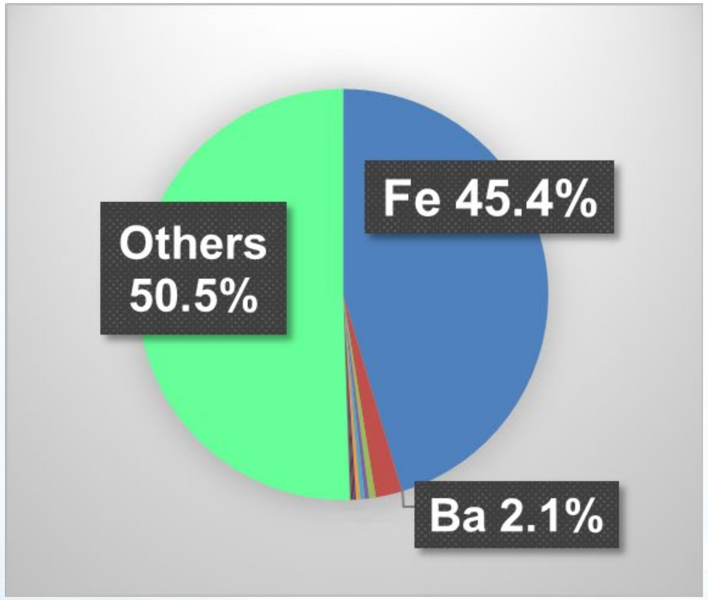
Average % of PM

NAO brake pad



n= 20

LM brake pad

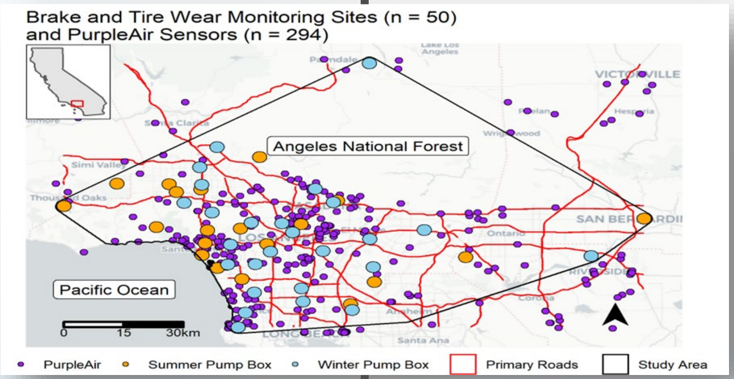


n= 6

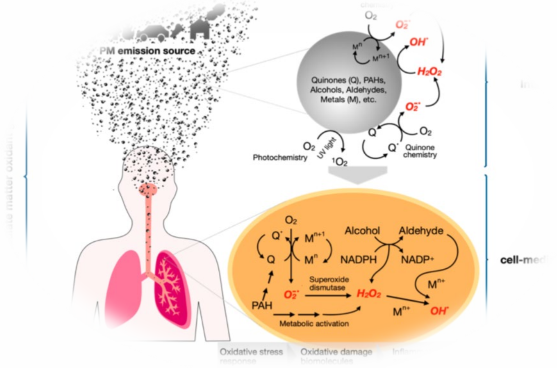
(Note that California has regulated heavy metal contents since 2014)

Health effects of brake and tire wear PM was studied in the greater Los Angeles area

- Understand potential health effects of brake and tire wear PM using ambient PM samples
  - Characterize spatial variations in PM2.5 metal concentrations
  - Integrate exposure model into health studies

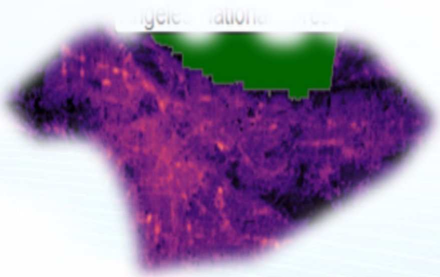


Health effects



Molina et al. (2020)

Exposure map



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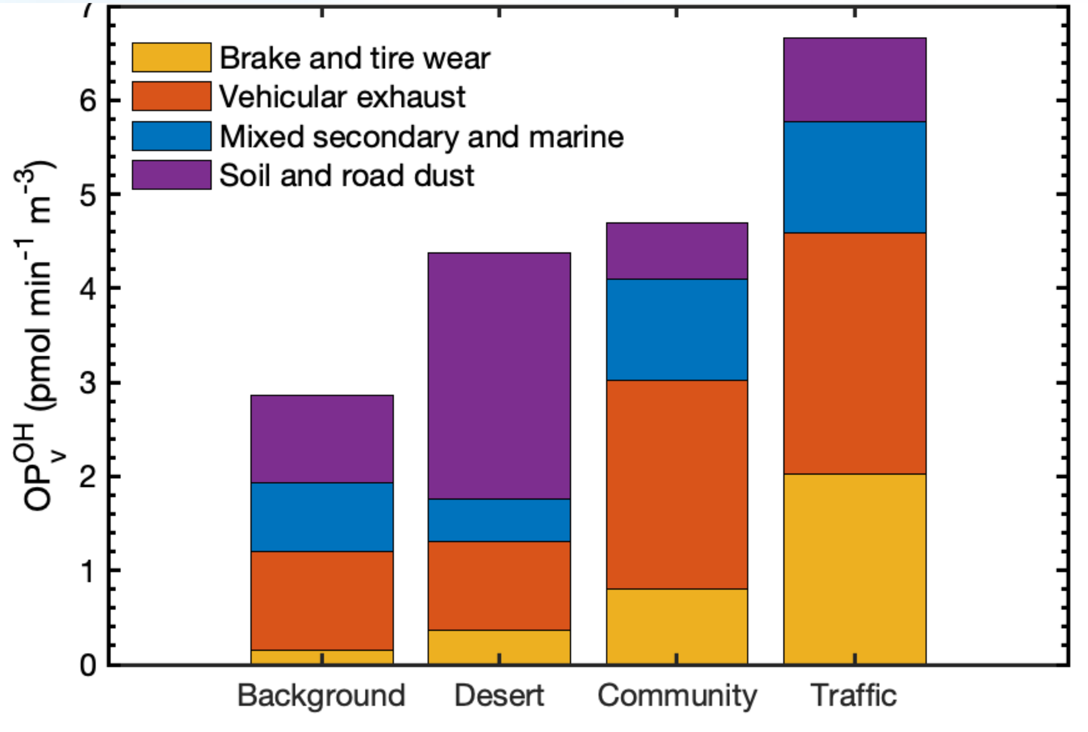
PMF source-apportionment analysis results for oxidative potential (OP^{OH})



- Tailpipe emissions are still the dominant source of the oxidative potential
- Brake and tire wear is an important contributor to the oxidative potential

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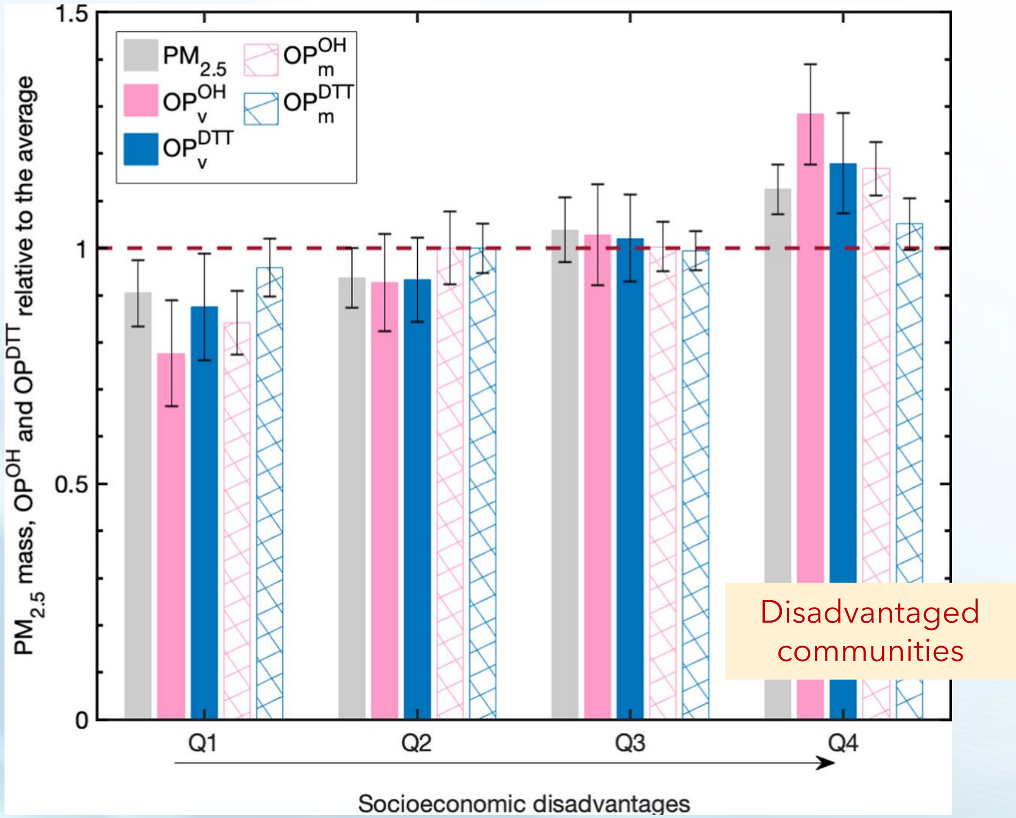
Disadvantaged communities exposed to higher oxidative stress potentials



(Jiaqi Shen et al, ES&T 2022 56 (24))

- Lower SES groups measured by CalEnviroScreen exposed to
  - higher particle mass concentrations
  - particles with higher toxicity due to higher oxidative stress potential of particles
- Lowest SES group exposed to particles with 62% higher oxidative stress

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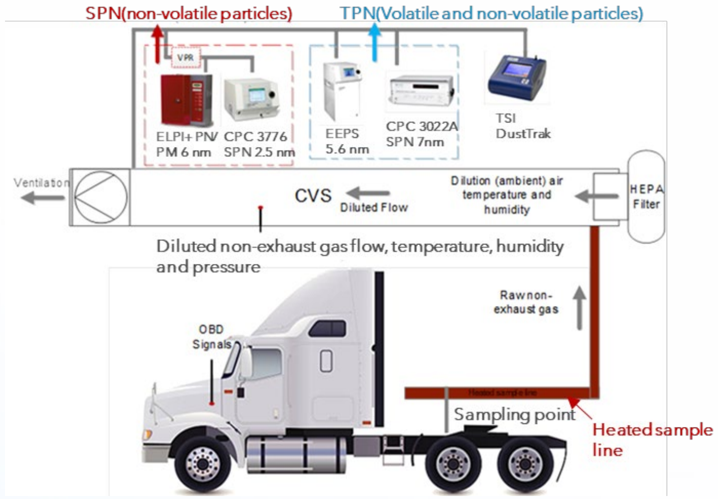
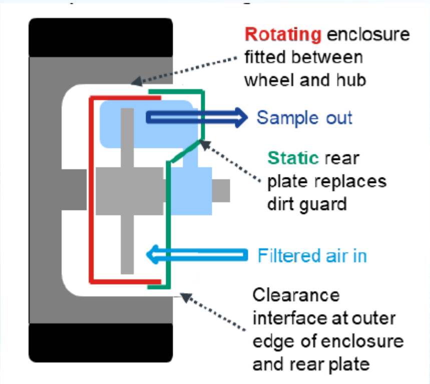
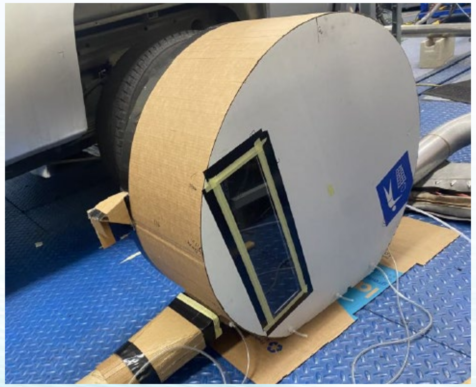
Current projects (1):
Characterize in-use non-exhaust emissions

- On-road brake/tire-wear (BWTW) PM measurement
  - Measure real-world BWTW emissions for LDVs and HDVs
  - Compare on-road BW PM to brake-dyno BW PM
  - Assess near-road community exposure level
- Tire-wear gaseous emission characterization
  - Measure real-world TW emissions of gaseous organic compounds for LDVs
  - Characterize gaseous pollutants and assess their air quality impact at community and regional levels





(Enclosed BW sampling)



(TW sampling in design)

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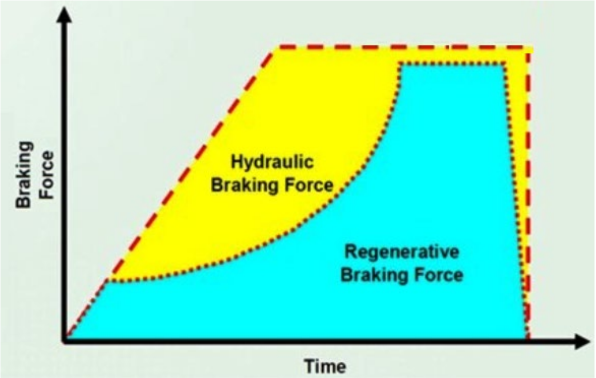
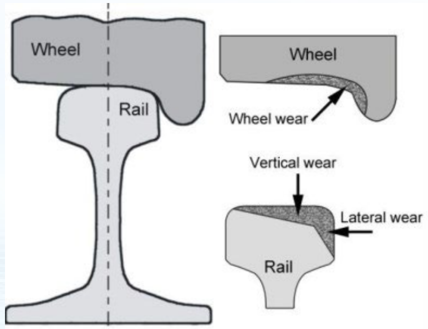
Current projects (2):
Assess EV technologies and characterize train non-exhaust emissions

- Assessing technologies that reduce brake/tire wear for EVs
    - Evaluate energy-efficient technologies for EVs and estimate impacts on brake and tire-wear
- Train brake/wheel/rail-wear (BWWW) PM measurement
    - Measure train BWWW PM emissions
    - Develop chemical profiles of train BWWW PM
    - Assess potential enhancement of near-railway community exposure to BWWW PM





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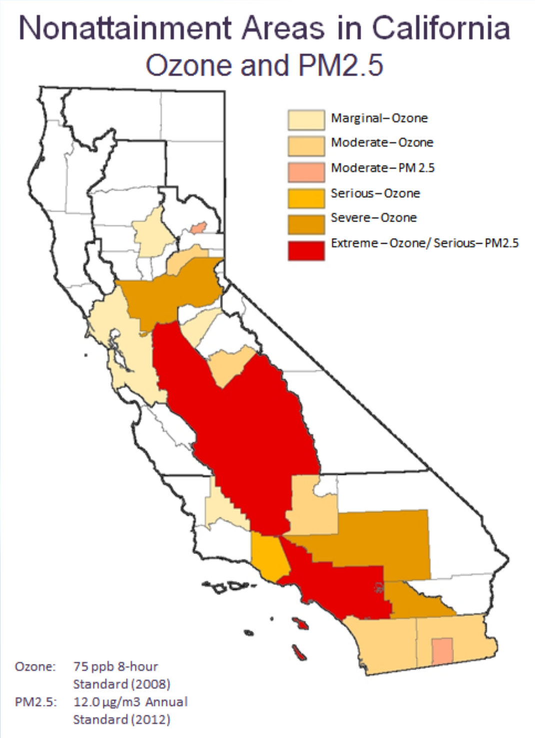
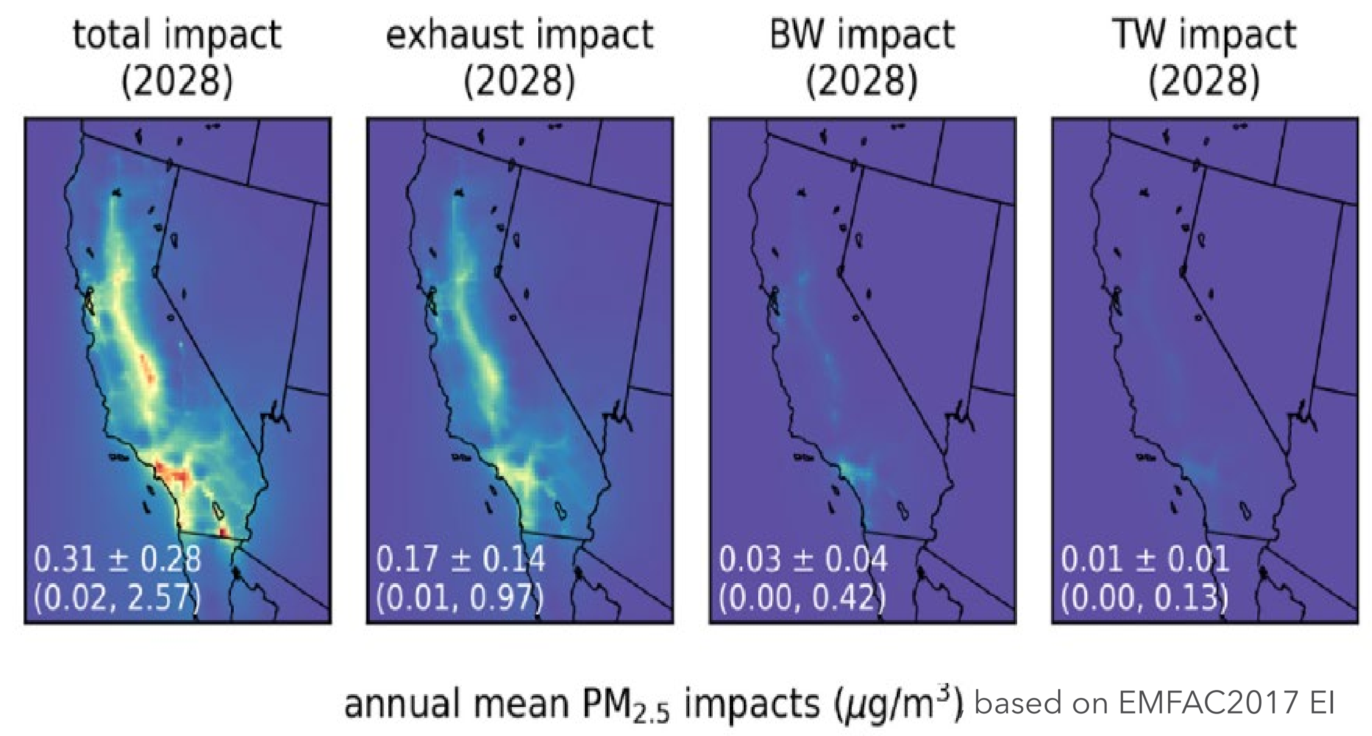
Remaining research area (1): Evaluate the contribution of both PM and gaseous non-exhaust emissions to regional air quality





(Skipper et al., 2023)

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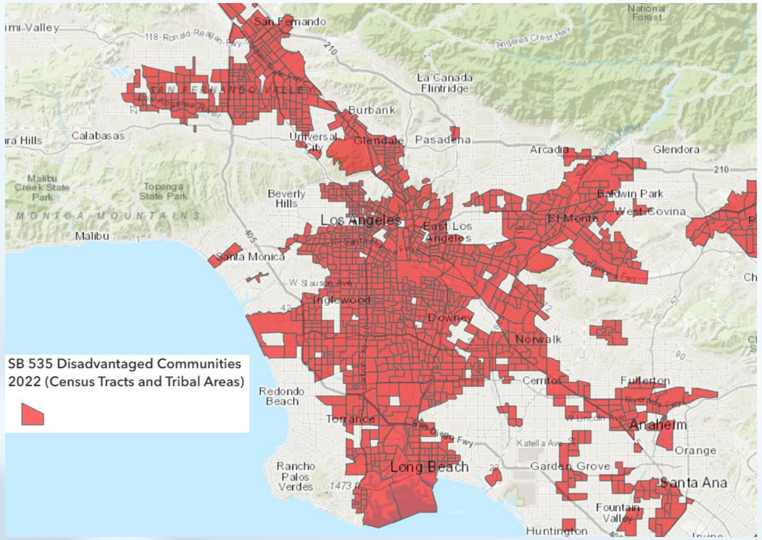
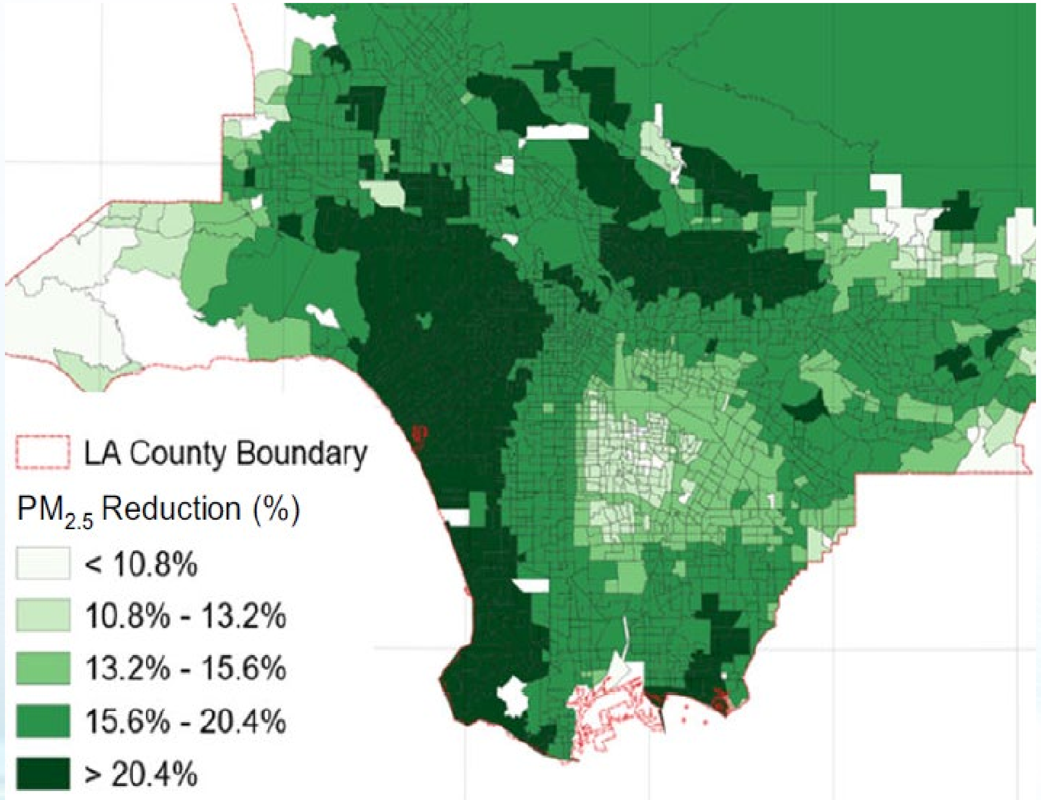
Remaining research area (2): Assess NEE health effects and exposure disparities between communities

Disadvantaged communities in LA area



2035 projected PM reduction with clean transportation programs in LA area



(Yu et al., 2023)

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Remaining research area (3): Explore non-exhaust emission reduction opportunities through clean transportation programs

Executive Order N-79-20

100% ZEV sales by 2035

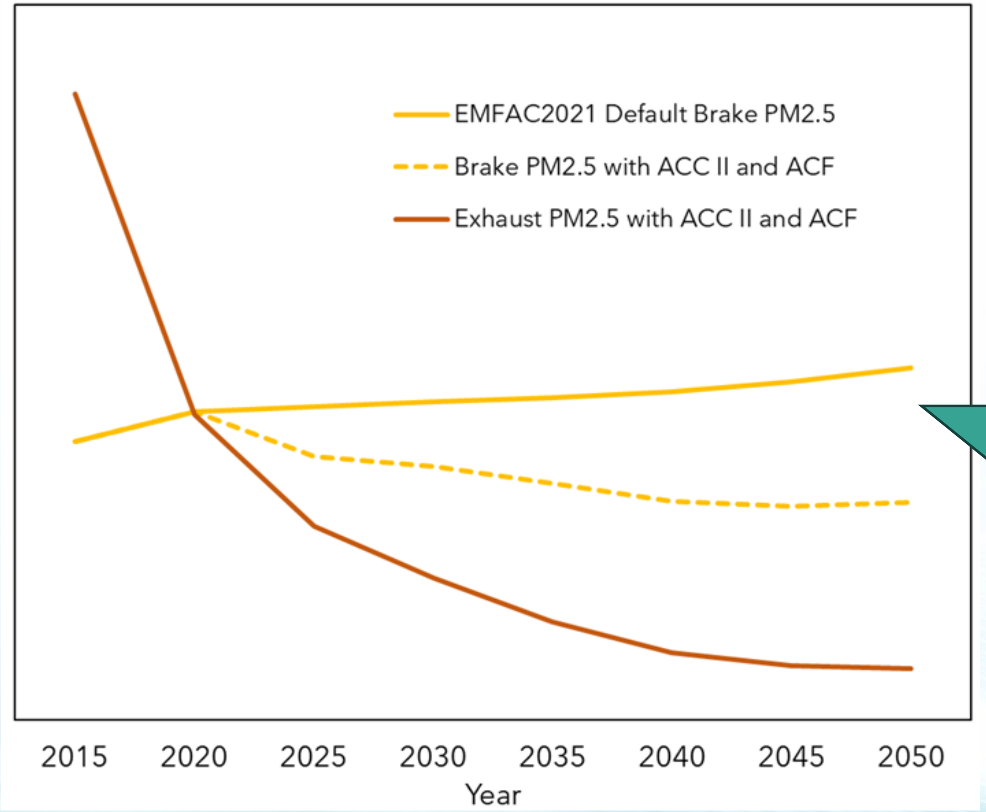
Full transition to **ZEV short-haul/drayage trucks** by 2035

Full transition to **ZEV buses** & **heavy-duty long-haul trucks** by 2045*

Full transition to **ZE off-road equipment** by 2035*

*where feasible

Projected emissions with Advanced Clean Cars II and Advanced Clean Fleets programs



Brake-wear PM for electric vehicles is 50% lower than conventional vehicles

Summary and Next Steps

- Brake- and tire-wear PM is a dominant source of total direct $PM_{2.5}$ emissions in California.
- Brake-wear PM was characterized using a standardized and reproducible scientific testing method.
  - California's low-carbon transportation programs help reduce brake-wear PM at community and regional levels.
- Non-exhaust emissions could be associated with adverse health effects.
- Characterizing non-exhaust emissions and their health effects by source type needs to be continued.
  - Assess air quality impact locally and regionally
  - Assess exposure to non-exhaust emissions near road/railway communities

Supplemental information

- California regulatory programs relevant to non-exhaust emissions
- What are non-exhaust emissions?
- Brake-dyno testing approach and results for HDVs
- Brake and tire wear PM exposure maps

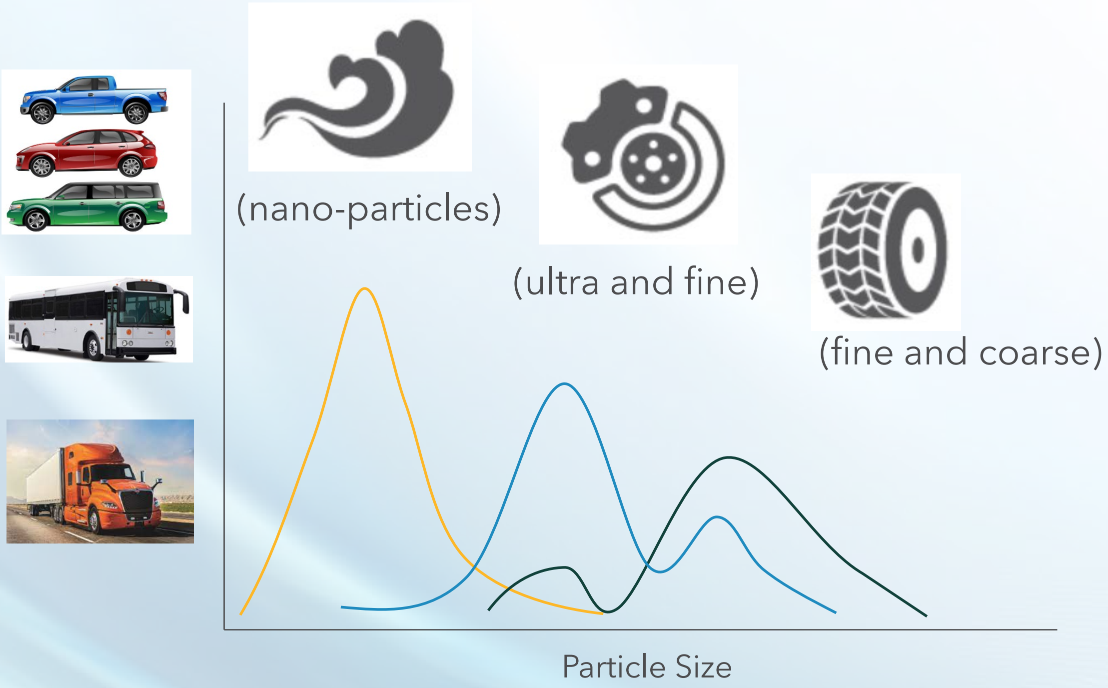
California regulatory programs relevant to non-exhaust emissions

- California Energy Commission (CEC) regulates replacement tire efficiency
  - o Requires tire efficiency rating and a minimum efficiency performance standard of 9.0 rolling resistance coefficient (N/kN)
- Department of Toxic Substance Control (DTSC)
  - o Limits metal contents in brake pad
  - o Requires tire manufacturers for sales in California to evaluate safer alternatives to 6PPD

Pollutant	Estimated Potential Reduction in 2035
NOx (Tons)	1485
$PM_{2.5}$ (Tons)	239
Million Metric tons (MMT) CO_2 equivalent	5.4

Brake-Wear Metal Content by	Not to exceed by weight (%)
1/1/2014	Cd < 0.01 Hg < 0.1 Cr (VI) < 0.1 Pb < 0.1 Asbestos <0.1
1/1/2021	Cu < 5%
1/1/2025	Cu < 0.5%

What are non-exhaust emissions?



- On-road brake-wear
  - PM size < 2.5 µm
  - Metal content: Ba, Cu, Zn, Ti, and others
  - NOx, CO, and VOC
- On-road tire-wear
  - PM size < 10 µm
  - Metals and micro-plastics: Zn, Al, Ca, Ti, NR, SBR, and others
  - Tire additives: 6PPD, silica, and others
  - VOC, PAHs, alkanes, and others
- No non-exhaust emissions info for:
  - Potential discrepancy between lab vs. in-use
  - Complete chemical profiles
  - Gaseous tire-wear emissions
  - Off-road vehicles and trains

HDV: fleet representative chassis-dyno cycles were identified for track testing

Usage pattern	Vocation Cycle	Cycle Distance (miles)	Brake Power Density (unitless)	Average Speed (mph)
Long haul	Long haul - out of state	21.1	0.66	48.6
Long haul	Long haul - in state	18.5	1.21	41.3
Pick-up & delivery	Airport shuttle	7.5	2.60	15.0
Pick-up & delivery	Refuse	5.2	4.32	11.1
Pick-up & delivery	Food distribution	17.8	0.88	36.1
Pick-up & delivery	Beverage distribution	5.6	2.85	14.2
Pick-up & delivery	Local moving	15.3	1.28	32.6
Pick-up & delivery	Urban buses	7.1	3.82	14.9
Pick-up & delivery	Express buses	14.5	1.50	30.2
Service	Utility - repair	11.3	2.19	22.7
Service	Public - freeway work	10.9	2.06	24.5
Service	Public - sweeping	8.5	1.49	18.2
Service	Public - municipal work	13.6	1.87	28.6
Service	Public - towing	16.8	1.59	36.8
Short haul	Drayage - Northern CA	4.3	3.33	11.9
Short haul	Drayage - Southern CA	9.4	1.94	19.3
Short haul	Agriculture - Southern	18.3	0.85	44.8
Short haul	Construction	15.4	1.44	32.3
Short haul	Cement mixers	11.6	1.89	28.1

$$Brake\ Power\ Density_{cycle} = \frac{\sum_{t=1}^{duration}[(Speed_{t-1}^2 - Speed_t^2) \div (Deceleration\ Rate)]}{Cycle\ Distance}$$

Vehicle/Configuration	Load	Vocation Cycles					
		Drayage Northern California	Beverage Distribution	Long Haul In-State	Towing	Refuse	Urban Bus
Class 8 All-Disc Tractor + Drum Trailer	Full Load (80,000 lbs)	•	•	•			
	Unloaded (37,500 lbs)	•					
Class 8 All-Drum Tractor + Drum Trailer	Full Load	•	•				
	Unloaded	•	•				
MD Hydraulic disc	26,000 lbs		•		•		
Refuse truck simulation: Class 8 All-Disc Tractor + Actuators representing refuse + Unbraked 28' Control Trailer	Full Load (over tractor king pin)					•	
Bus Coach	37,500 lbs						•

Class 8 truck used for drum, air disc, refuse track tests

Class 6 truck used for hydraulic disc track tests

Bus coach used for urban bus air disc track tests

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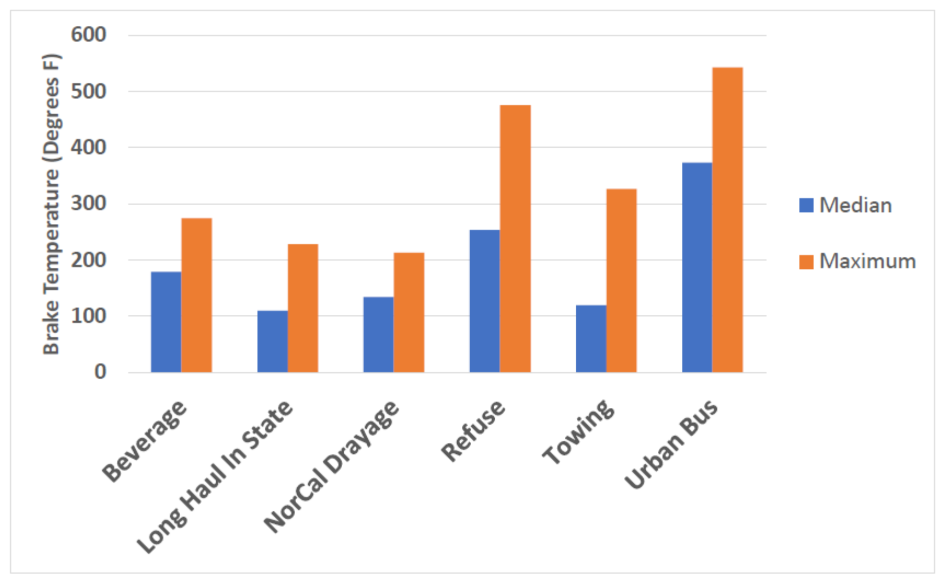
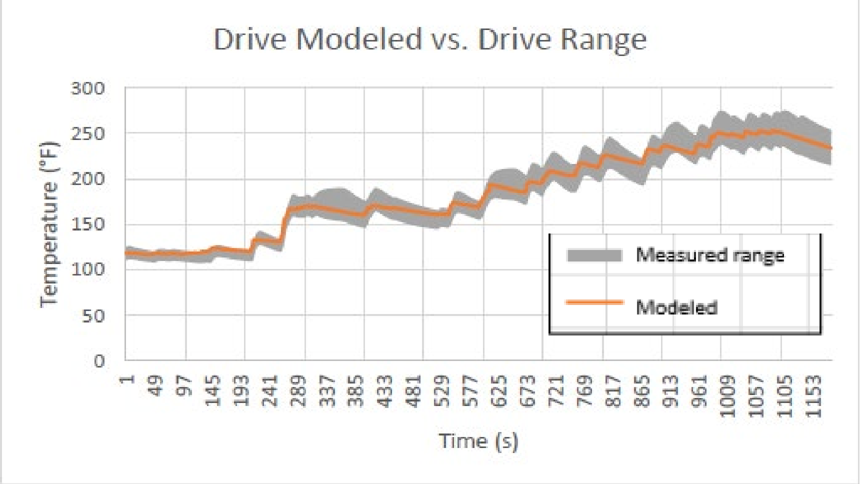
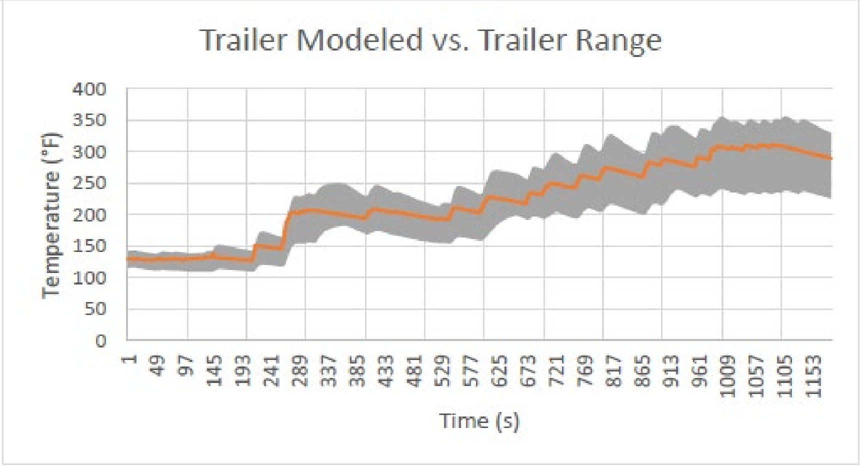
HDV: temperature profiles were developed and applied for brake-dyno testing

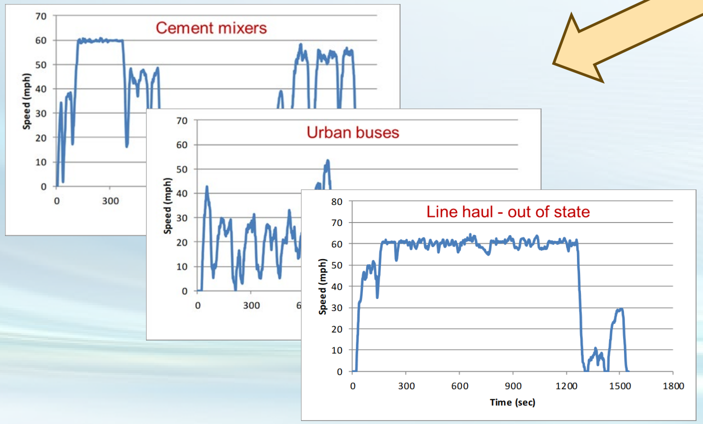


Brake Temperature Model

$$T = T_i e^{-t/\tau} + \left(\left(\frac{HP_B}{h(v)}\right) + T_a\right)(1 - e^{-t/\tau})$$

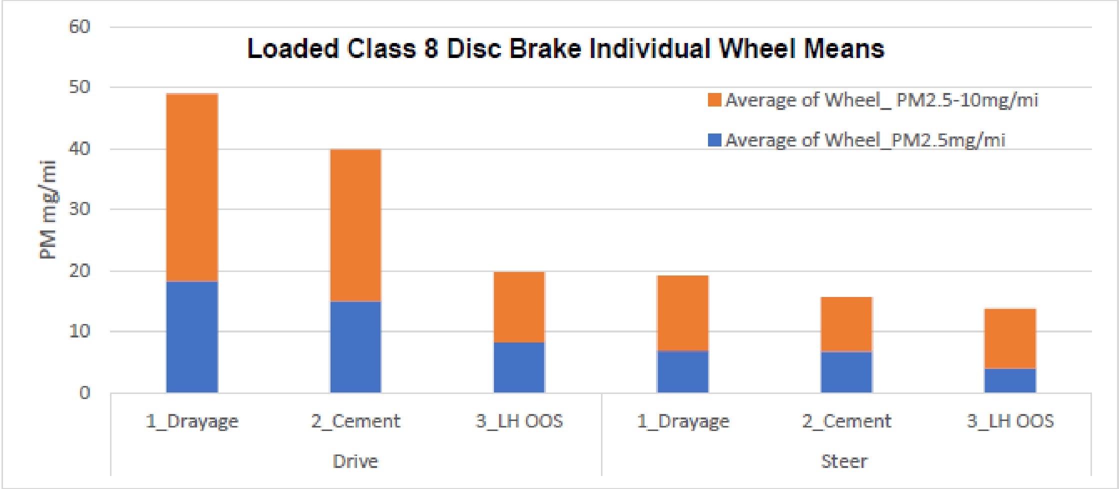


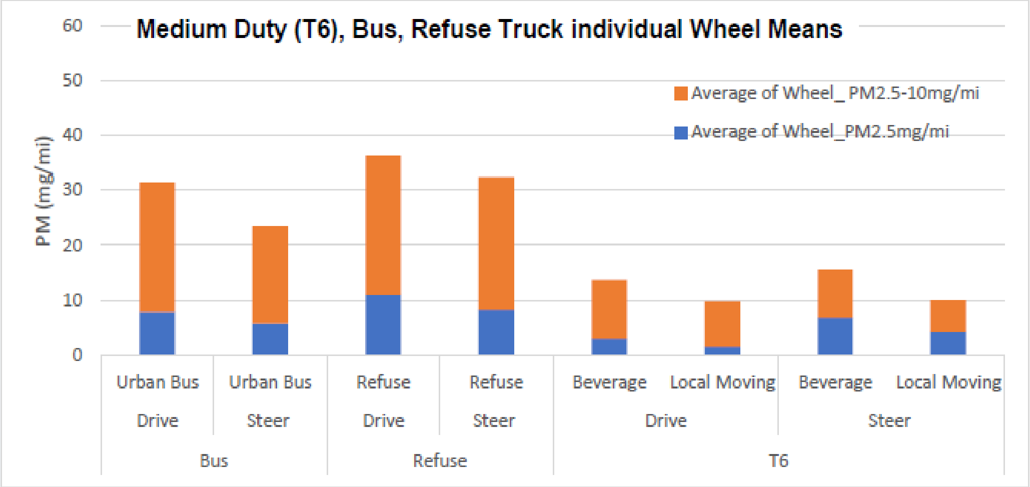


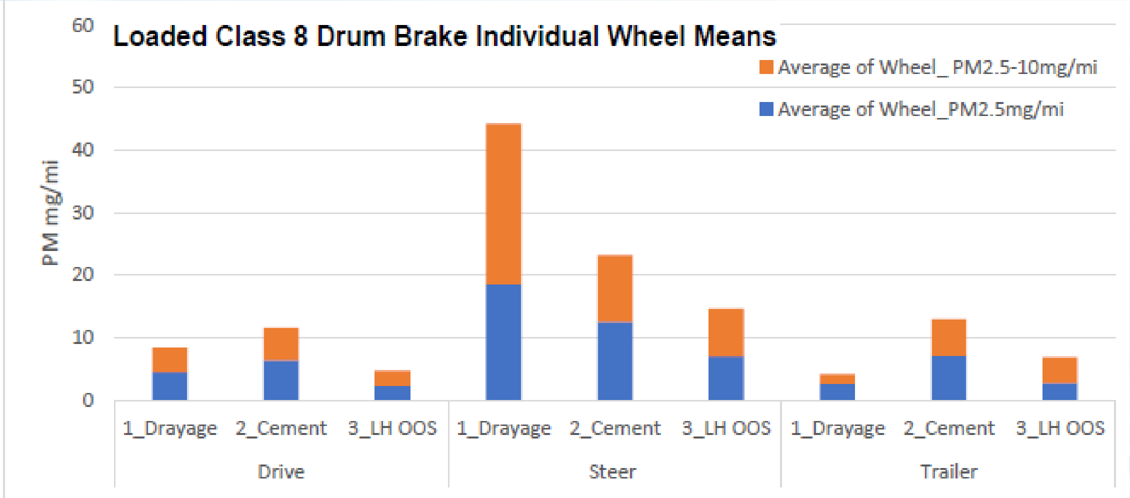


CARB

HDV: brake-wear PM emission rates of individual wheels for loaded trucks

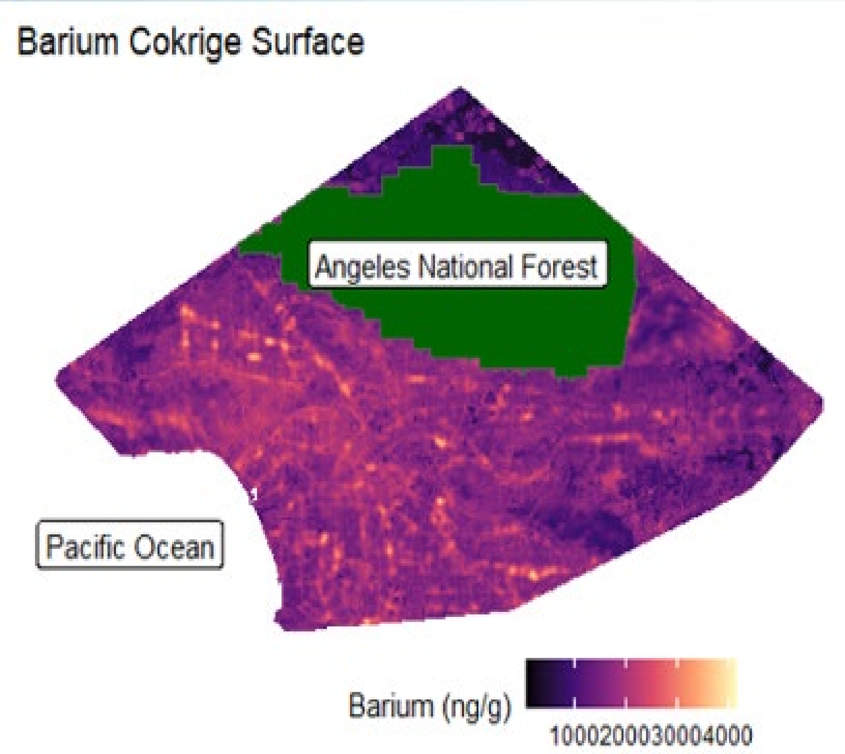




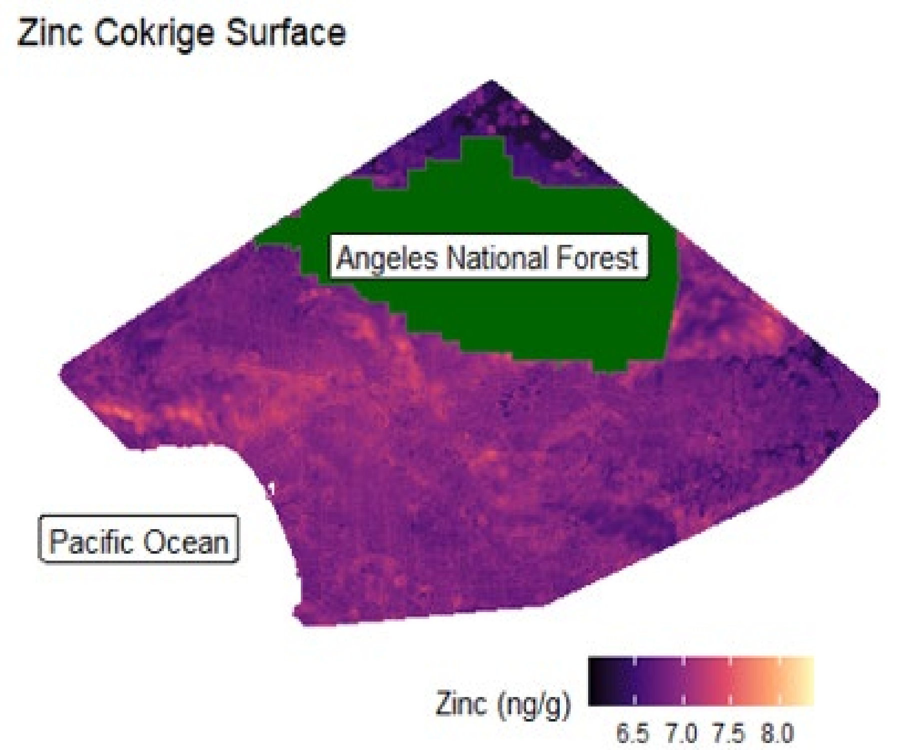


(Details are available from Caltrans' research report, 2021)

Brake and tire wear PM exposure maps from the CARB's Health effect study



(Barium is a primary tracer for brake-wear PM)



(Zinc is a primary tracer for tire-wear PM)