CALIFORNIA
AIR RESOURCES BOARD

Numerical Analysis of Heavy-Duty Vehicle Activity and Brake-Wear PM Emissions to Assess Potential PM Reductions from Battery Electric Vehicles

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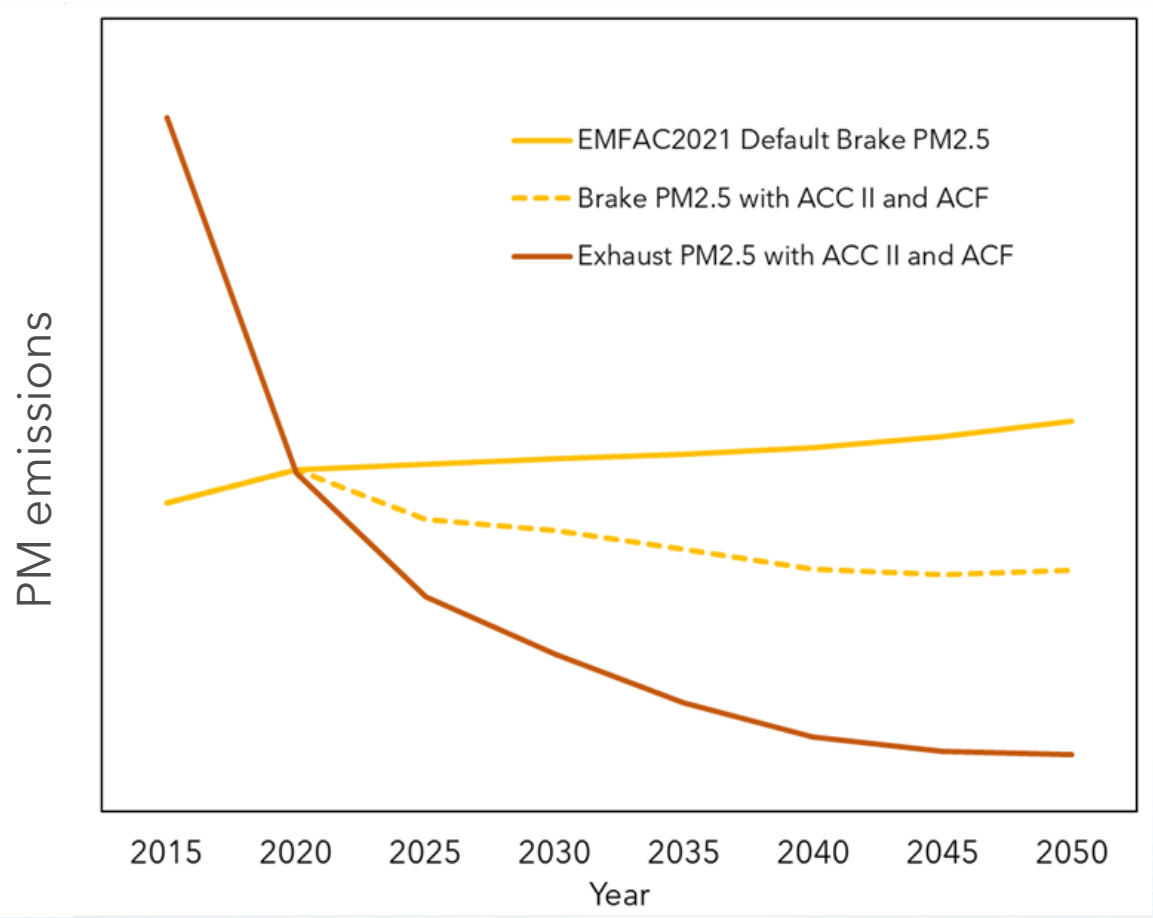
Background

California's mobile source programs

- Significantly reduced tailpipe emissions of air toxics and greenhouse gases
- Stringent emissions standards and transitioning to ZEVs
- Regenerative braking technology – potential to reduce brake-wear emissions

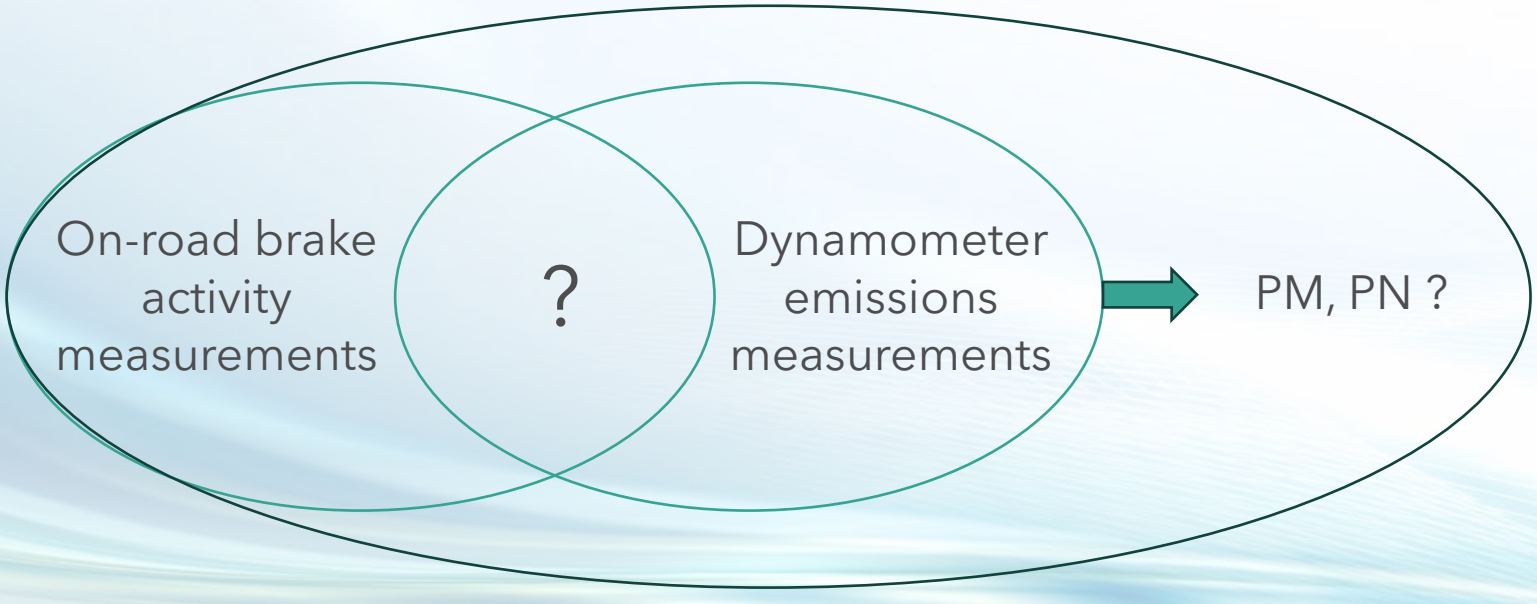
Laboratory brake dynamometer emissions testing

- Standardized procedures for light-duty vehicles (LDV) based on European regulatory procedures
- Heavy-duty vehicle (HDV) testing procedures need additional validation
- Estimating ZEV emissions reductions for HDVs especially uncertain

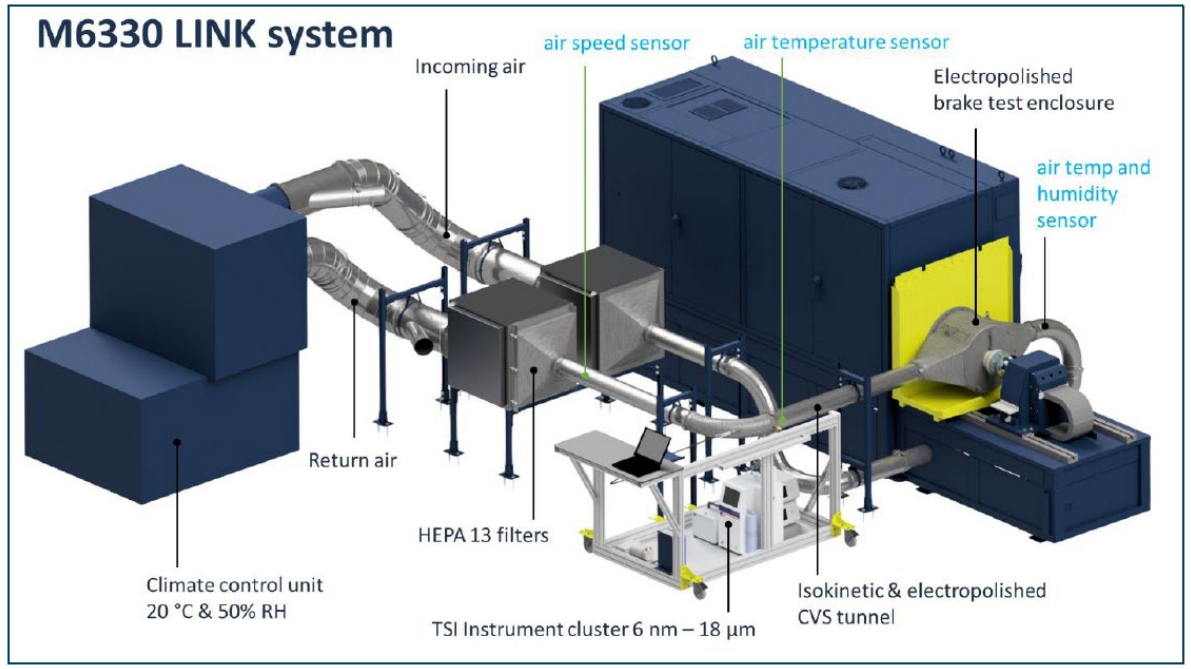


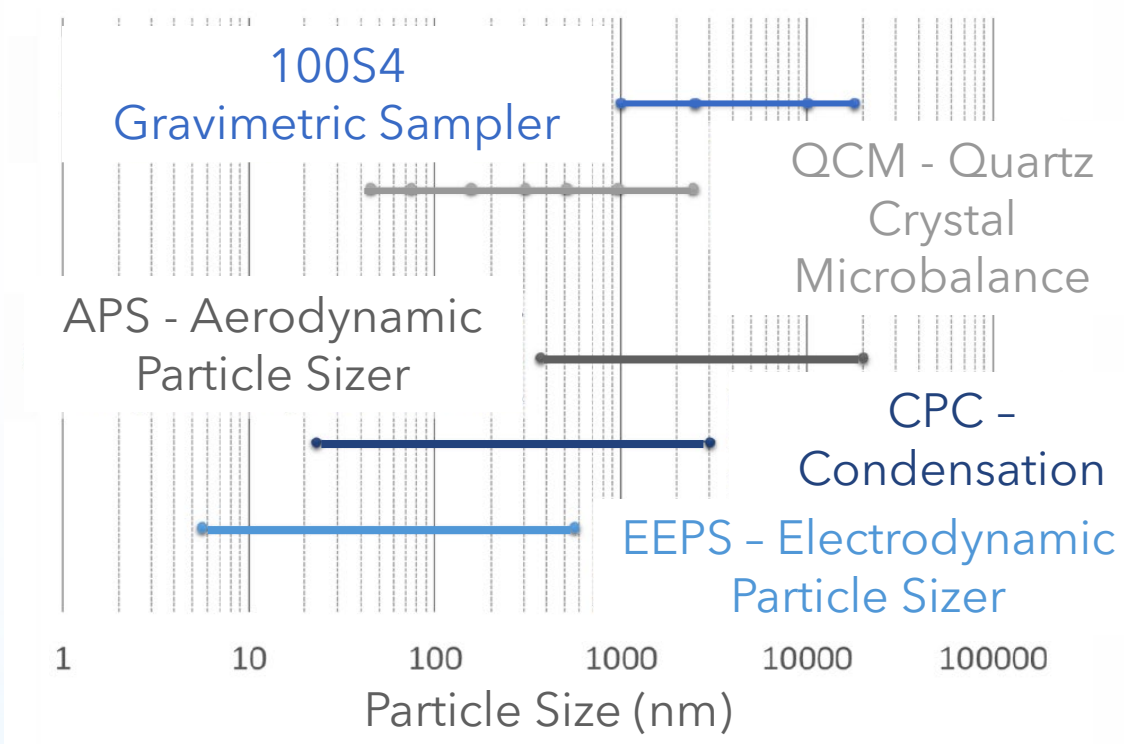
Research Questions

- Are there relationships between braking energy, temperature on emissions of PN and PM for HDVs? Particle size distributions?
- Do differences between HDV vocational brake cycles affect these relationships?
- Can they be leveraged to estimate emissions reductions from ZEVs?



Laboratory Brake Dynamometer Measurements





Real-time measurements:
Particle number
Particle mass
Rotor temperature
Dynamometer speed
Braking torque

Analysis:
Braking event duration
PN and PM Emissions
Kinetic energy = $\frac{1}{2}(m_{vehicle} v_{dyno}^2)$
Braking power = $\Delta ke/\Delta t$

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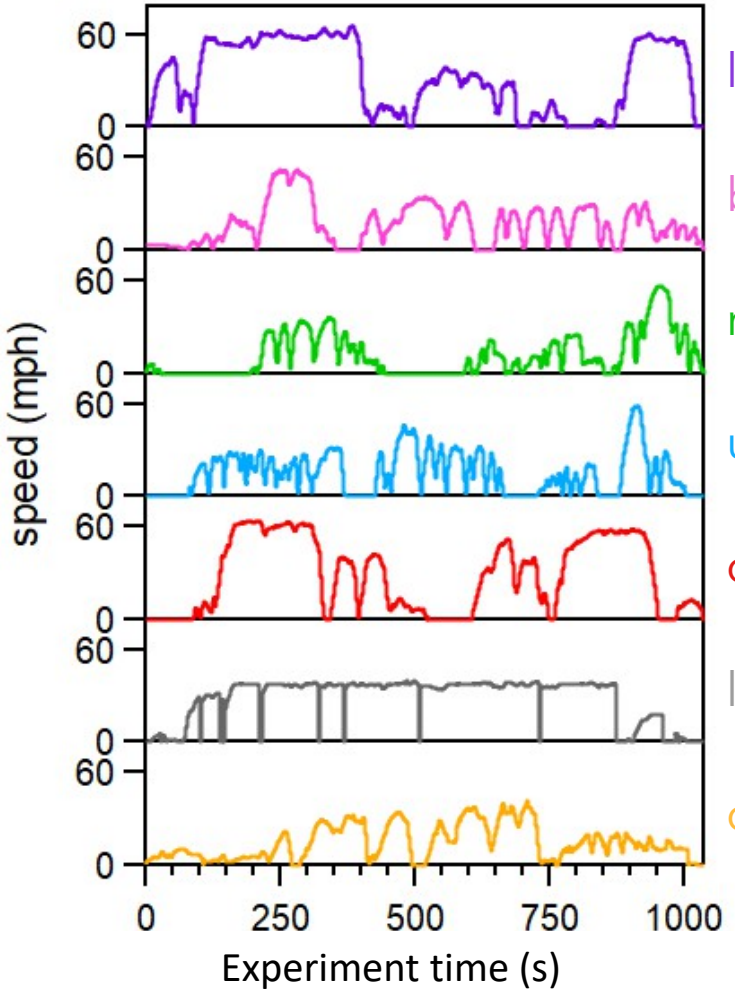
Brake Dynamometer Testing
Vocational Heavy-Duty Vehicle Cycles



local moving truck

beverage truck

refuse truck

urban bus

cement truck

line haul truck

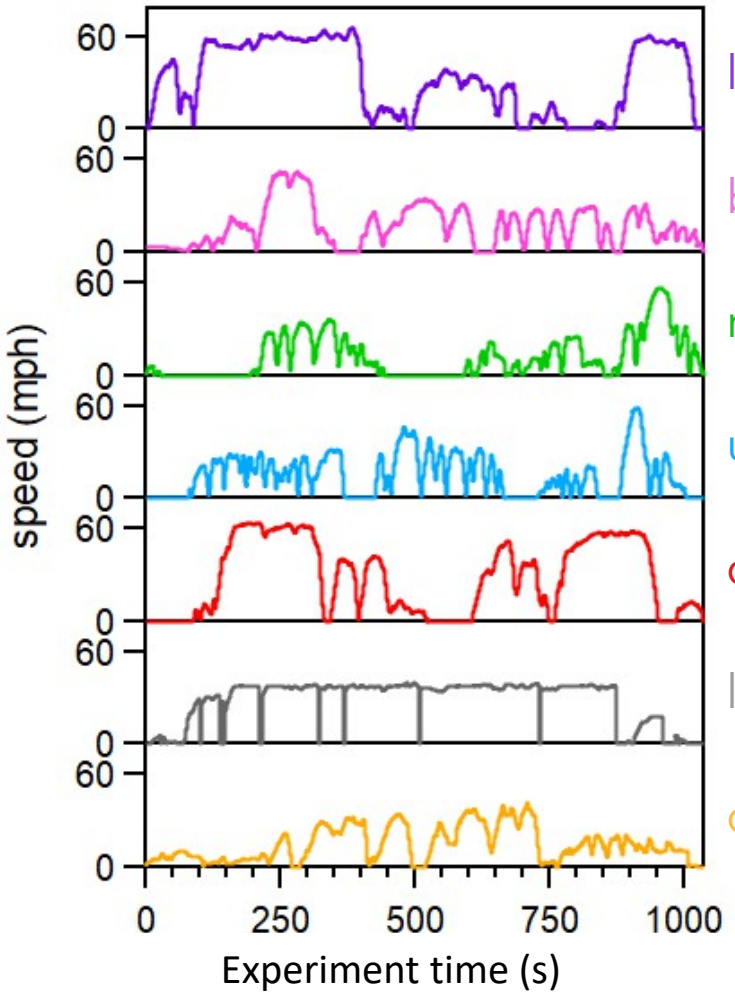
drayage truck

MHDVs

HHDVs

Class 8

Brake Dynamometer Testing
Vocational Heavy-Duty Vehicle Cycles



local moving truck

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urban bus

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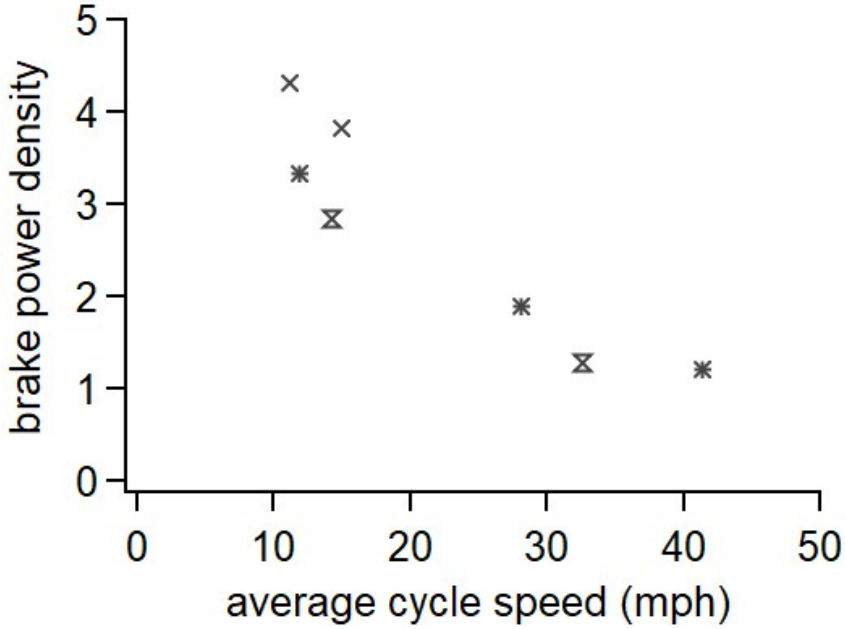


- Exhaust emission testing cycles for CA heavy duty fleet used to test brake-wear emissions
- Vocation specific
- Span a range of speed and braking power

Dynamometer Emissions Correlations

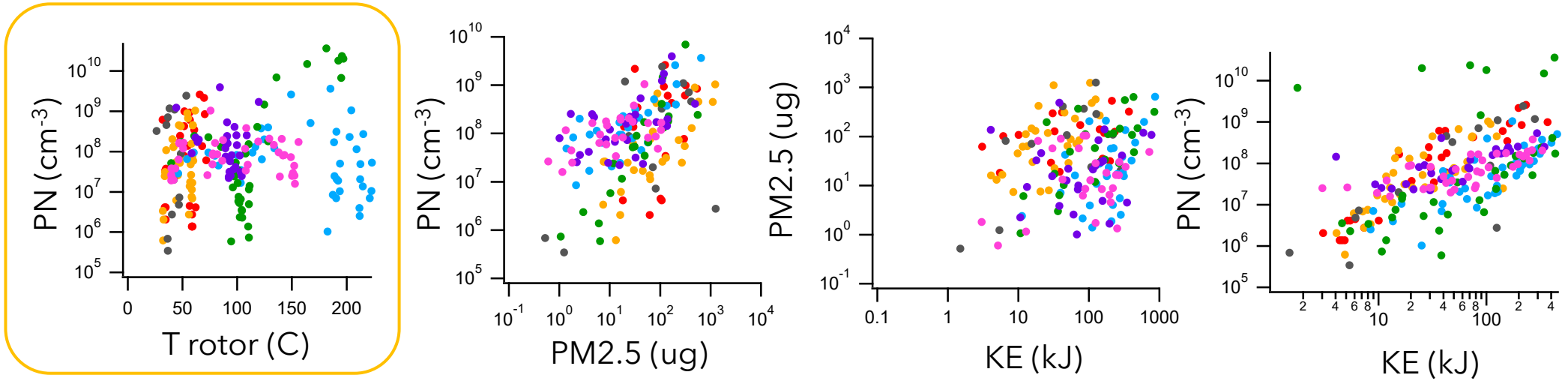
Particle number and rotor temperature

PM 2.5, PN, and kinetic energy

Particle number and braking kinetic energy

Correlation Strength

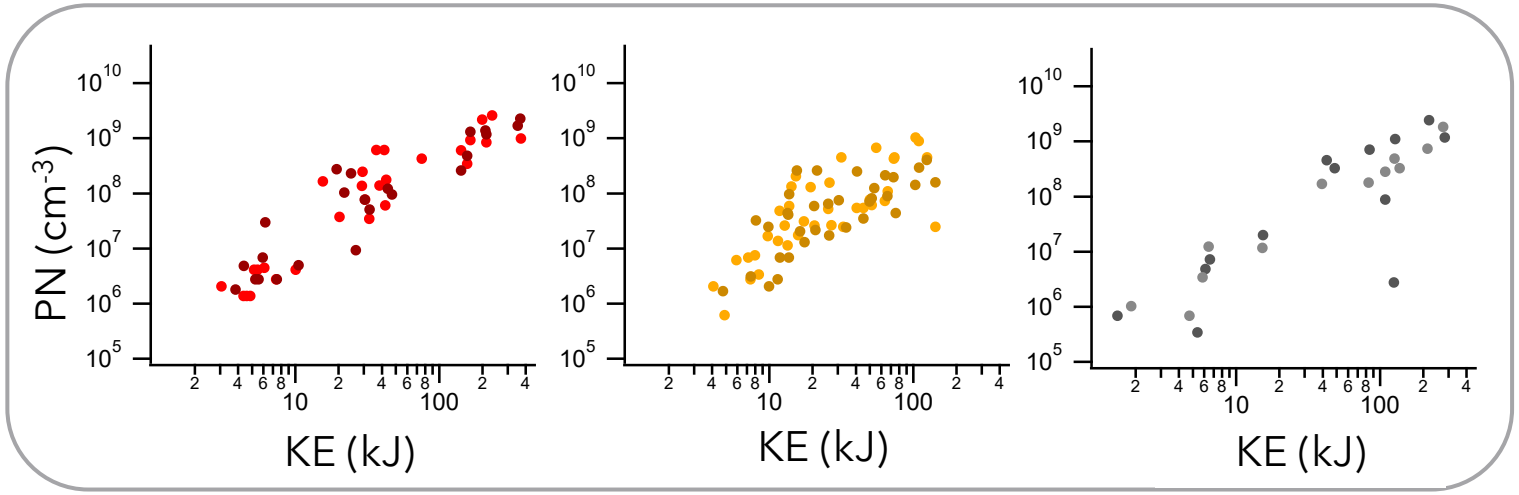
All HDVs



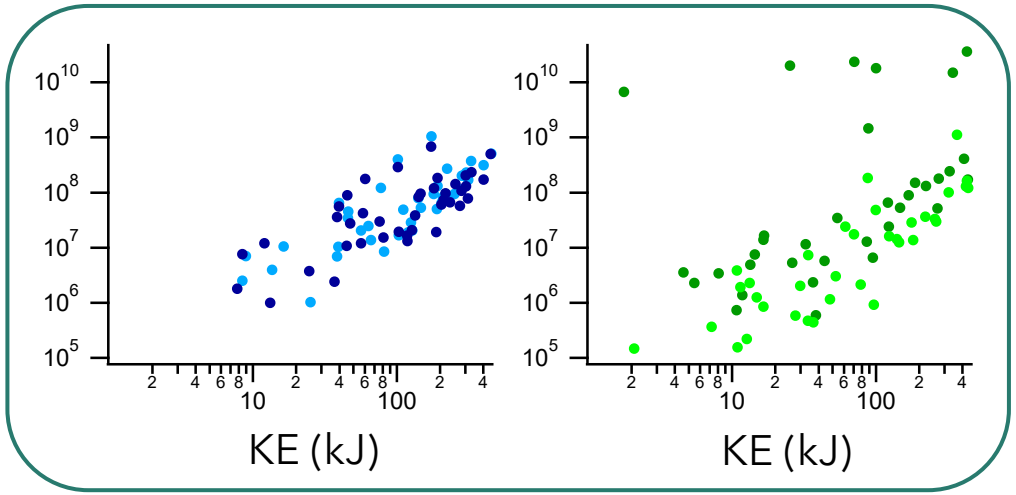
"M" shaped PN – Temperature correlations not representative of real world conditions.

Vehicle weight classes show similar speed-based PN emission behaviors with some variation due to vocational driving cycles

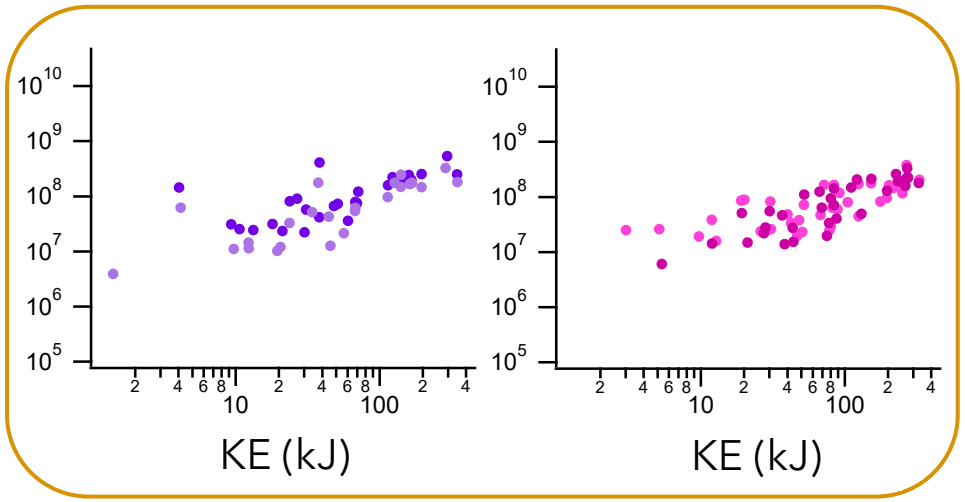
Class 8



- cement
- drayage truck
- line haul
- bus
- refuse truck
- local moving truck
- bev truck



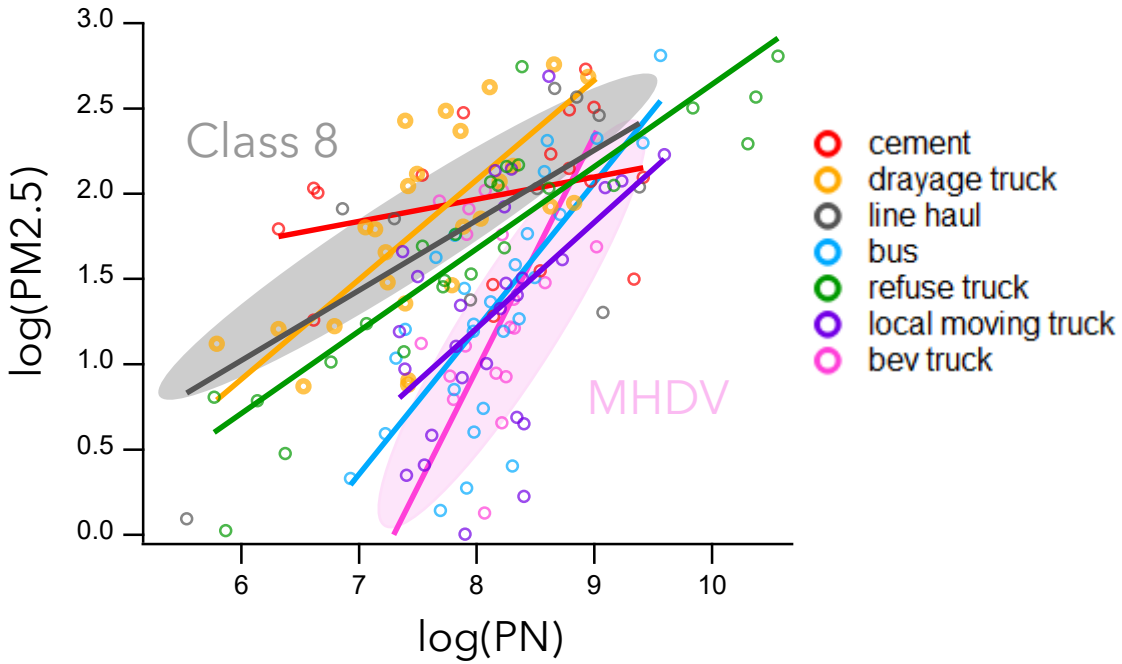
HHDV



MHDV

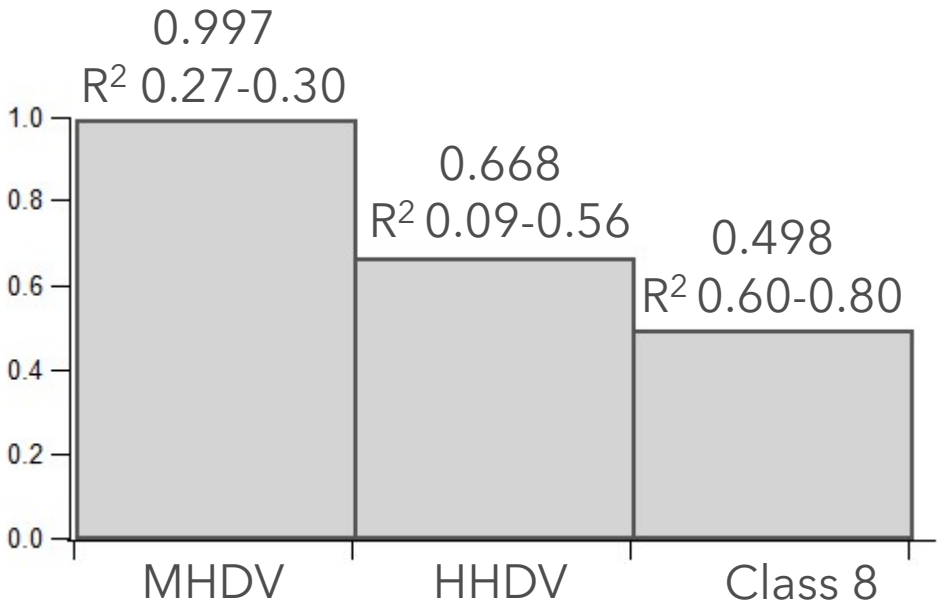
Vehicle weight and vocation effects on PN and PM2.5

Log(PM 2.5) vs Log(PN)



Particle number and mass emissions are similar for vehicles within the same weight class.

Slope of Log(PM 2.5) vs Log(PN)



As vehicle weight increases, more PN is produced, but less PN is PM2.5.

Difference in correlation strength between vehicle weights and vocations.

On-Road Brake Activity Data Collection – Drayage Trucks

- 17 drayage trucks operated in southern California instrumented with on-board diagnostic data logging systems
- 14 were BEVs and 3 were diesel vehicles
  - BEVs were pilot models
  - Routes were generally shorter in duration and range
  - No driver training was given to ZEV drivers

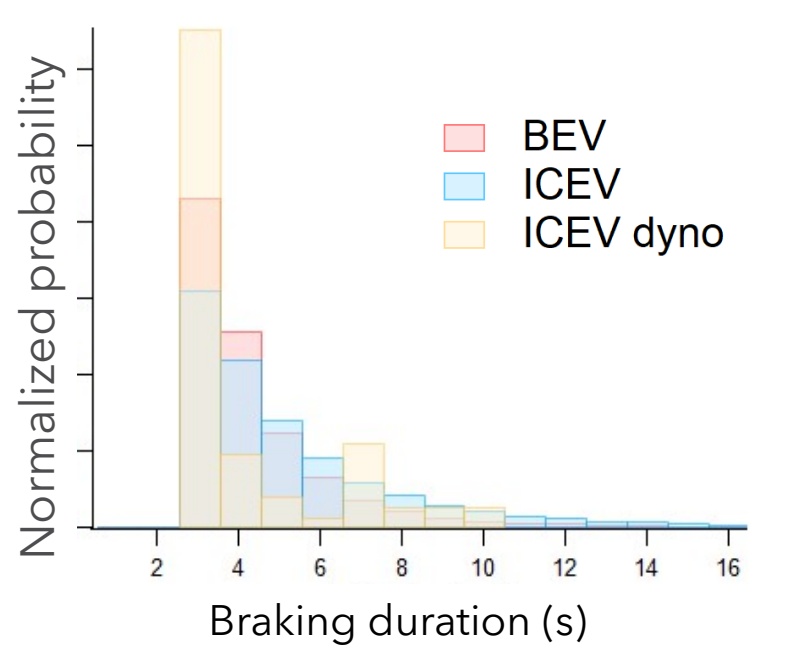
OBD Parameters recorded:

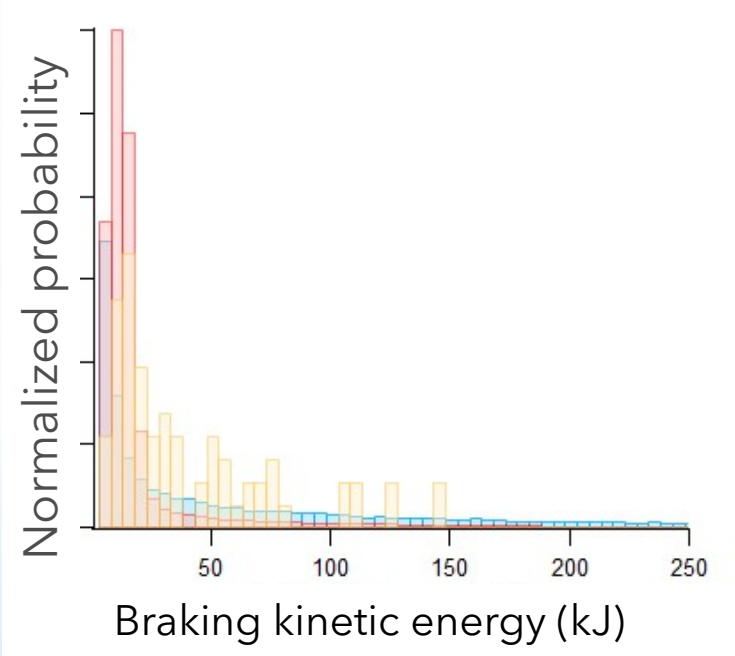
Brake switch (on/off)
Brake switch percent (BEV)
Vehicle Velocity
Battery current (BEV)

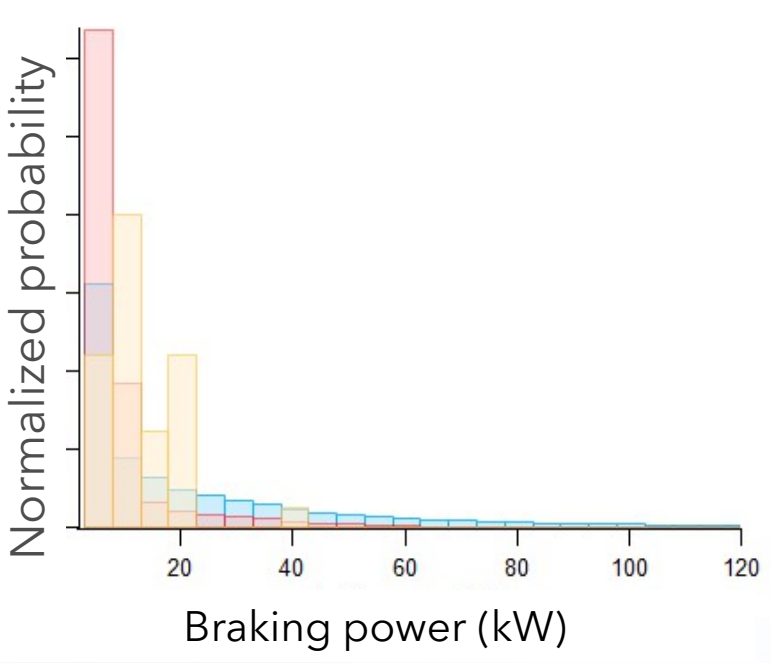
Analysis:

Braking Event Duration, brake switch > 0
Kinetic Energy = ½(mv^2)
Braking Power = $\Delta KE/\Delta t$
Regenerative Braking Periods, battery current < 0

Drayage Truck Dynamometer Cycle and On-road Braking Activity Comparison







Dyno braking shorter than BEV, BEV shorter than ICEV braking. Over half braking events under 4 seconds for dyno.

BEV most "gentle" braking. Dyno braking energy ~20% higher than on-road BEV.

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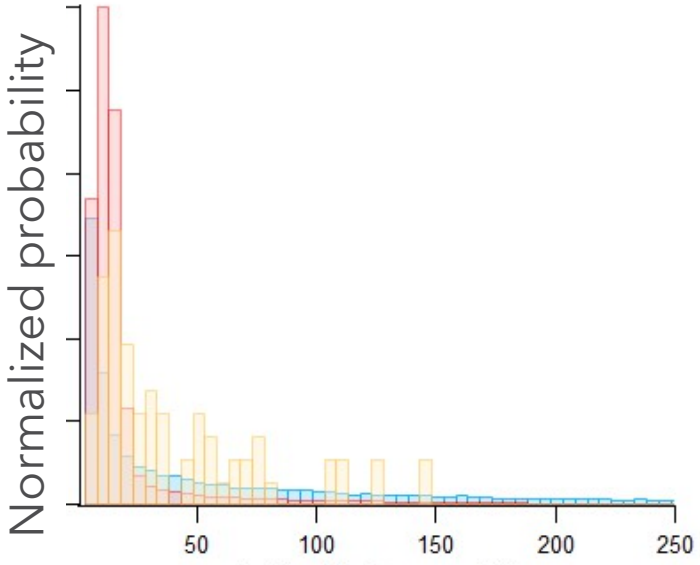
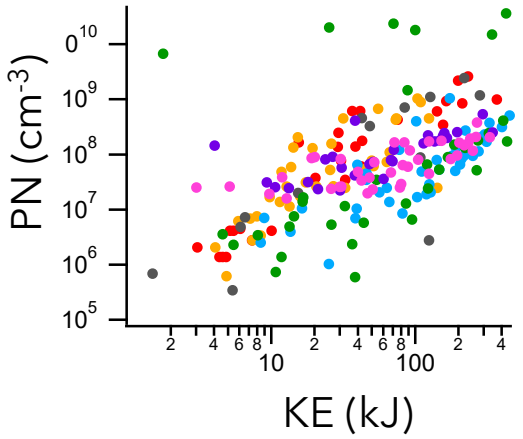
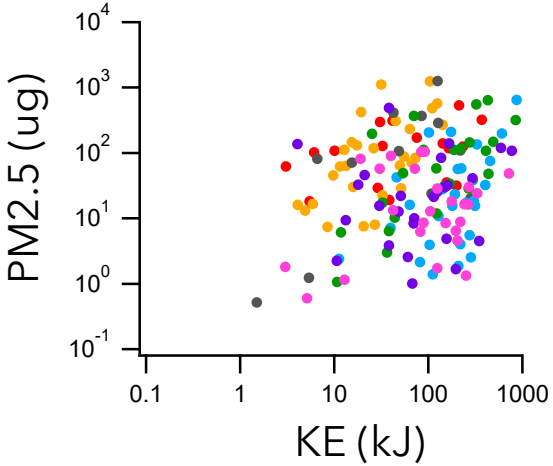
How can correlations between brake activity and brake-wear emissions be further characterized?



Braking kinetic energy (kJ)

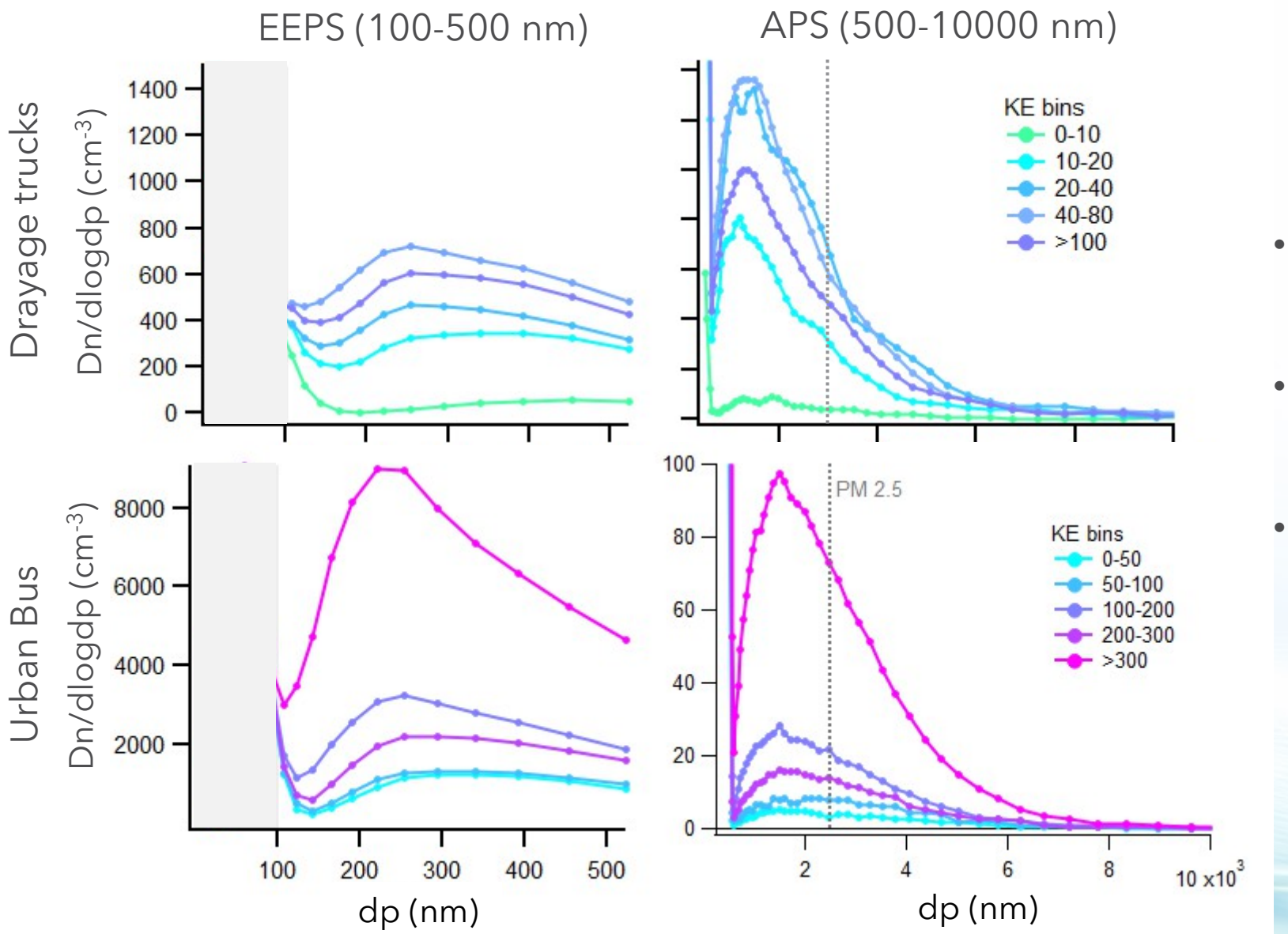
Do we need to fine tune HDV cycles to more closely align with measured braking activity, especially for EVs? Currently planned on-road measurements will help bridge these gaps.





Why does PN tightly correlate with kinetic energy, while PM and kinetic energy have a weaker correlation? Can particle size distributions help explain this difference?

Investigating size distributions of drayage truck and urban bus PM emissions



- Bimodal distribution for both vehicle types, range of KE is different
- Non-linear relationship between KE and measured particle size
- Implications for particle density and particle mass - further investigations needed

Takeaways

- Relationships between braking activity and brake-wear emissions present an opportunity to assess emission reductions from clean transportation programs
- Weight class affected emissions relationships with braking activity more than vocation
- Although PN correlations with KE are strong, PM correlations are weaker.

  Additional research areas for investigation:

  - Vehicle weight dependence of particle size.
  - Investigations of size distributions and particle density.
- HDV dynamometer cycles can be fine tuned to better represent temperature profiles and vocational braking activity for BEVs and ICEVs
  - Measurement gap from EVs, testing currently planned