CALIFORNIA
AIR RESOURCES BOARD

Assessment of Energy Recuperation and Brake-Wear Particulate Matter Emissions Over Chassis Dynamometer Test Cycles

Okjoo Park, Michelia Dam, Seungju Yoon, Yilin Ma, Wilson Chau, Shishan Hu, Tao Zhan, Georges Saliba, Steven Magbuhat, Gary Mikailian, Jorn Herner

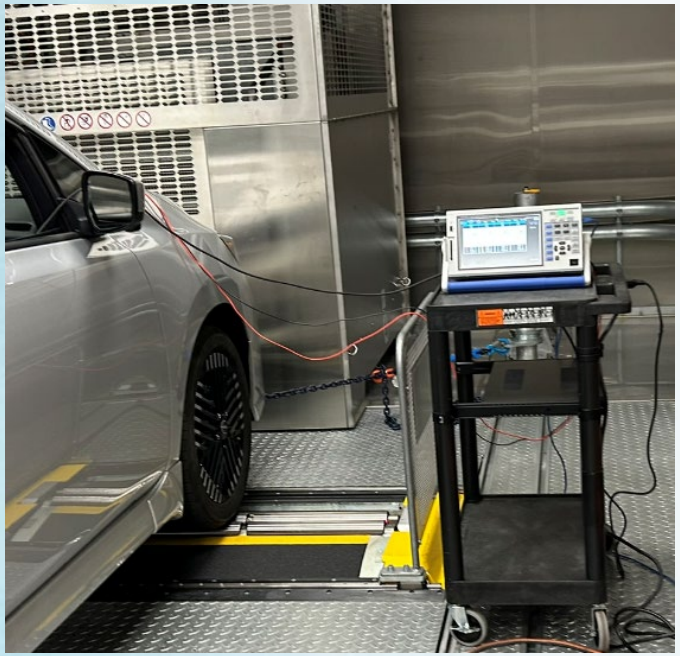
Background/Motivation

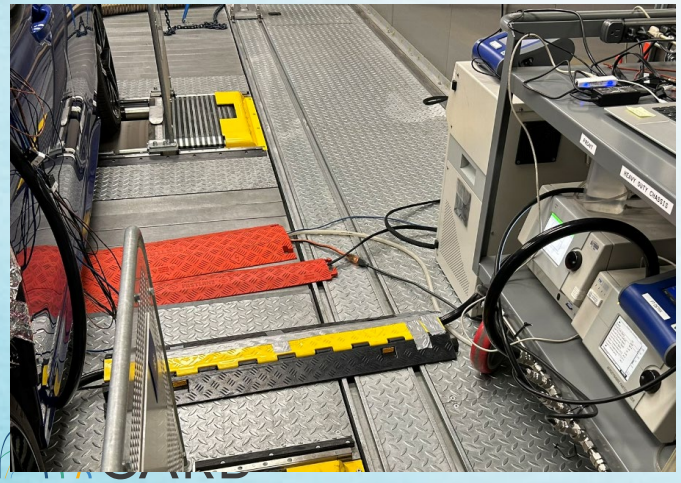
- Growing concerns on non-exhaust particulate matter (PM) emissions
  - As exhaust PM are controlled, Brake-wear (BW) and tire-wear (TW) account for an increasing fraction of mobile-source PM
- Potential co-benefit of transitioning to EVs in California
  - Correlation of regenerative braking energy with vehicle specs, operations, and emissions
  - Level of braking energy depending on vehicle electrification
- Considerable knowledge gap
  - Impact of driving cycles, brake and tire technologies and materials, and regenerative technologies on non-exhaust emissions
  - Measure potentials of EV regenerative technologies in reducing BW emissions

Objective

- Measure Brake wear PM emissions
- Characterize the energy recuperated by regenerative braking technologies
  - Investigate how regenerative braking technology is applied in EV
  - Assess the level of braking energy recovery over chassis dynamometer test cycles
- Characterize BW reduction potentials from electric vehicles
  - Explore the correlation between braking energy recovery and brake-wear particulate matter reduction

Testing Facility and Instrumentation



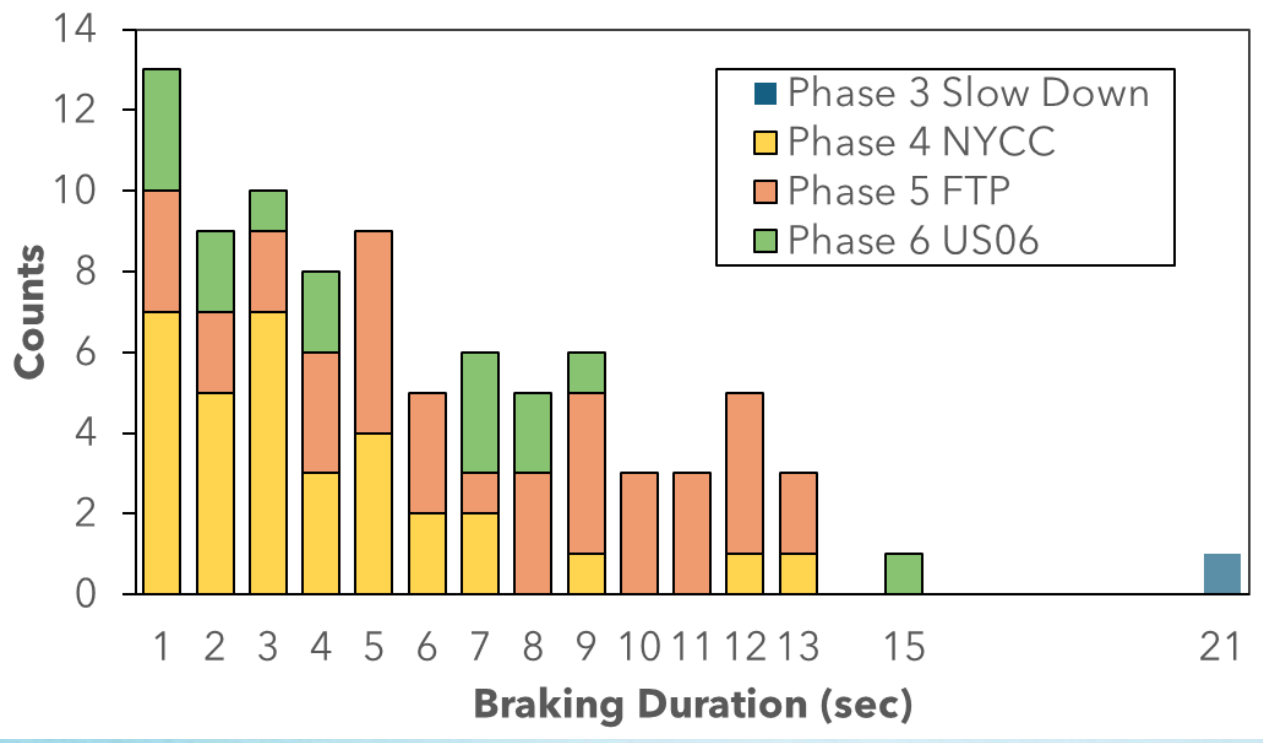


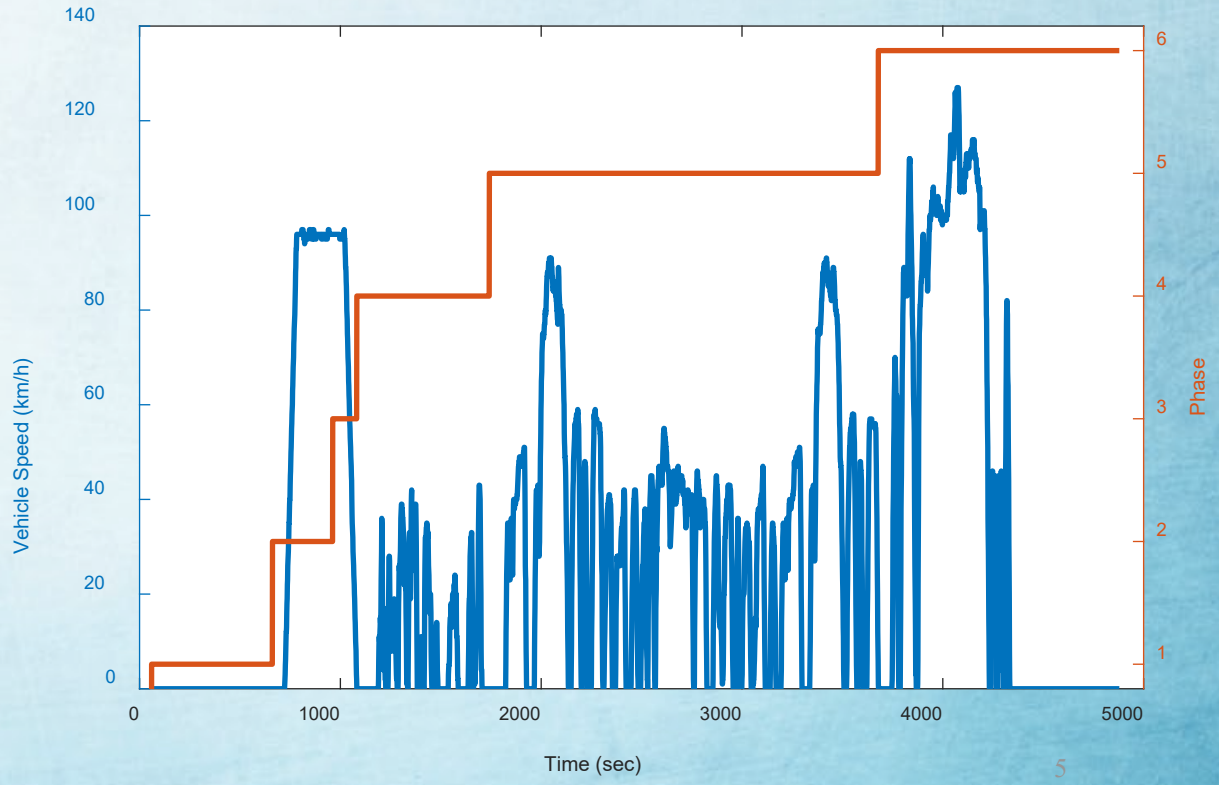
- Running-Loss Sealed Housing for Evaporative Determination (RL-SHED)
  - Chassis Dynamometer:
  - 48” roll, 4 wheels x 2 motors
- Hioki Power Meter
  - Battery voltage and current
- ECU data logger
  - Battery current/voltage
  - Brake switch, regen torque, etc.

- Real-time PM and PN instrument
  - EEPS, APS, CPC, DustTrak
- Thermocouples for brake pad temperature

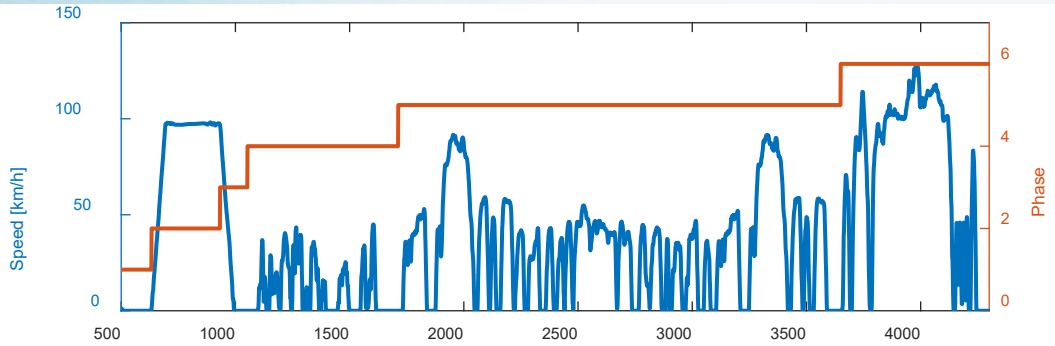
Test Cycle Braking Events

Phase	1	2	3		4		5		6		Total
Cycle	Idle	Speed-up	Slow Down	idle	NYCC	Idle	FTP	Idle	US06	Idle	
Duration (s)	600	300	60	60	600	60	1877	60	600	600	~1.32 hrs
Distance (km)		7.2			1.9		17.8		12.9		39.8 km

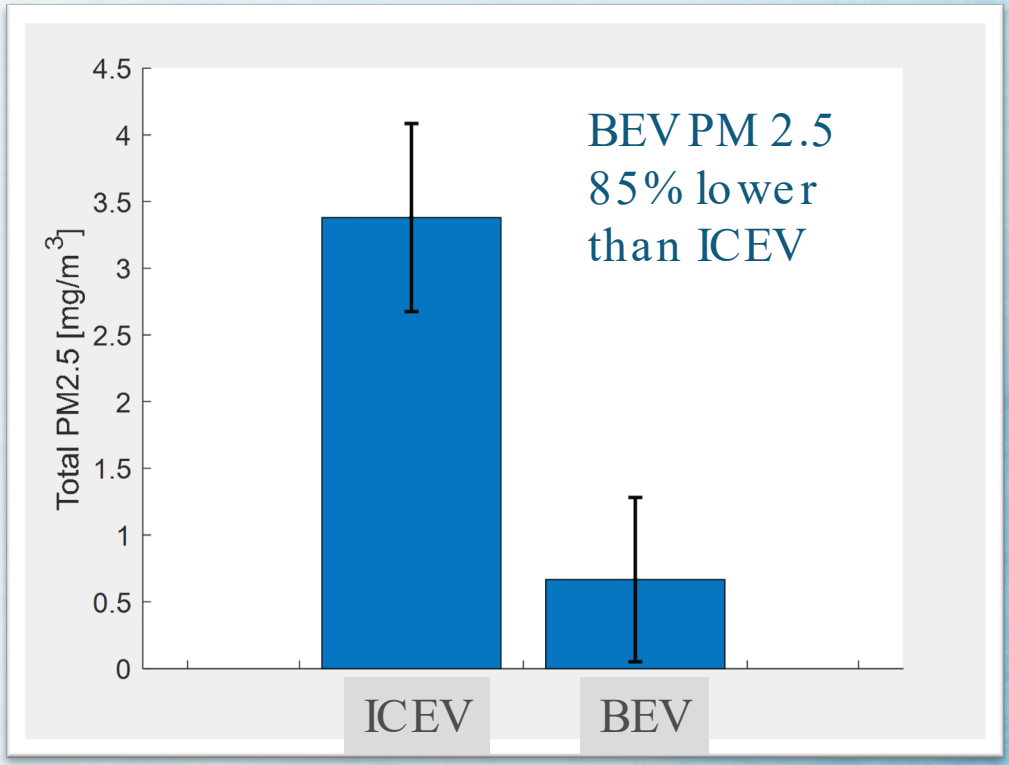




ICEV vs. BEV Comparison



- ICEV: 2023 MY, Sedan, 3610 lbs
- BEV: 2023 MY, Compact, 4080 lbs



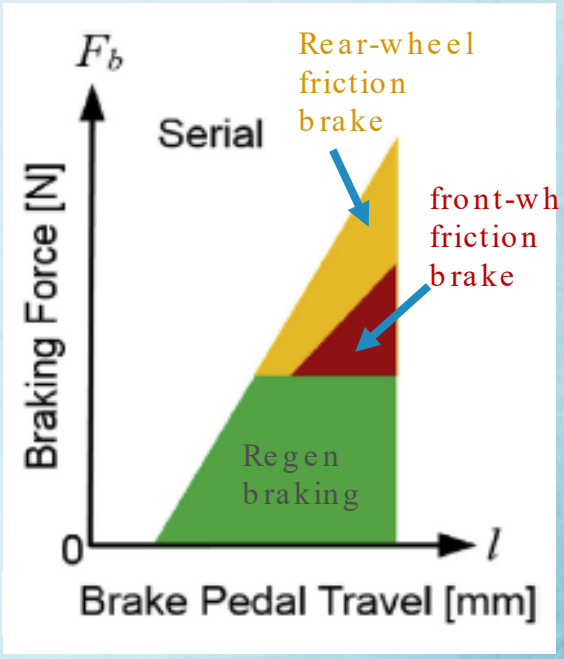
ICEV: Internal Combustion Engine Vehicle
BEV: Battery Electric Vehicle

Test Vehicle's Braking System

- Test Vehicle : 2023 MY, Compact, 4080 lbs

A serial regenerative braking system with a blended braking approach

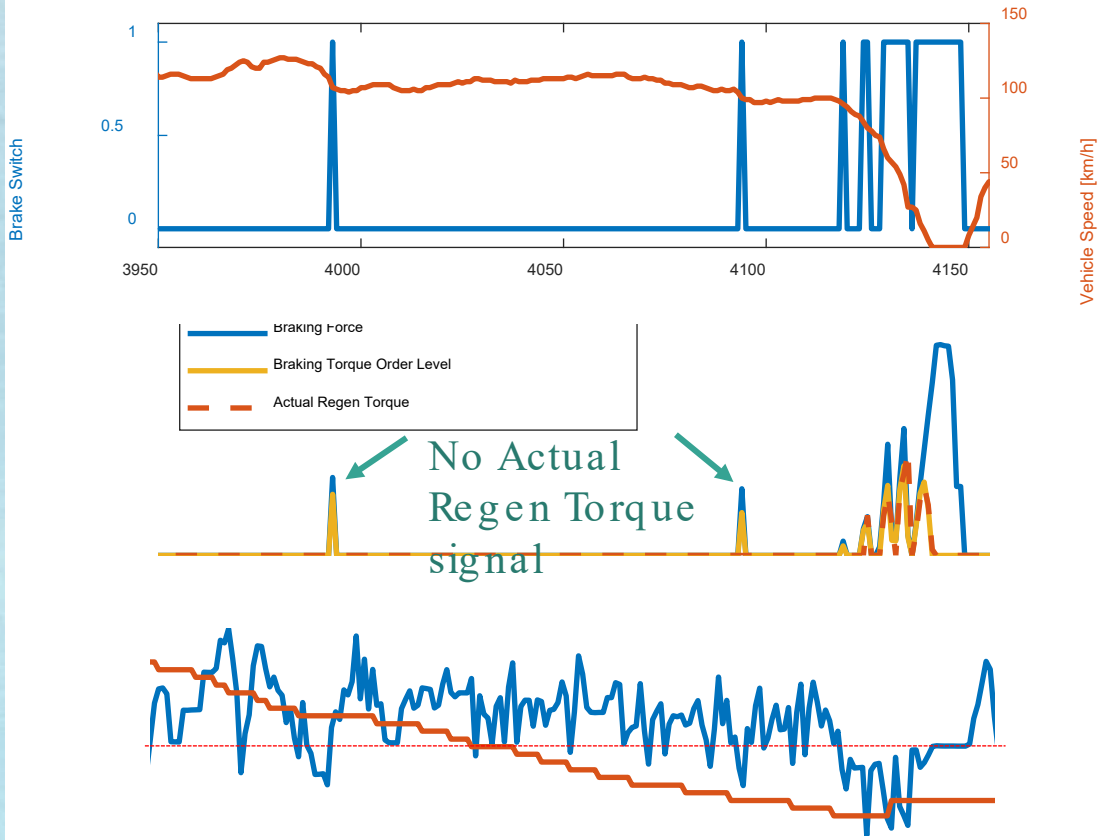
- Serial Regenerative Braking
  - The Electric Motor as a primary braking force until its maximum regenerative capacity is reached
  - The friction brakes engages to achieve the desired deceleration
  - In most driving, regenerative braking provides the majority of braking force
- Blended Braking System (friction braking + regen braking)
  - If additional braking force is needed (e.g., hard braking, low speeds when regen is less effective)
- One-pedal Driving
  - Engages strong regenerative braking when the drive lifts off the accelerator, allowing the car to slow down significantly
  - Maximize energy recuperation



C. Qiu, G. Wang, M. Meng, and Y. Shen, "A novel control strategy of regenerative braking system for electric vehicles under safety critical driving situations," *Energy*, vol. 149, pp. 329–340, Apr. 2018

Test vehicle driving mode was default/basic mode (no enhanced regen braking mode)

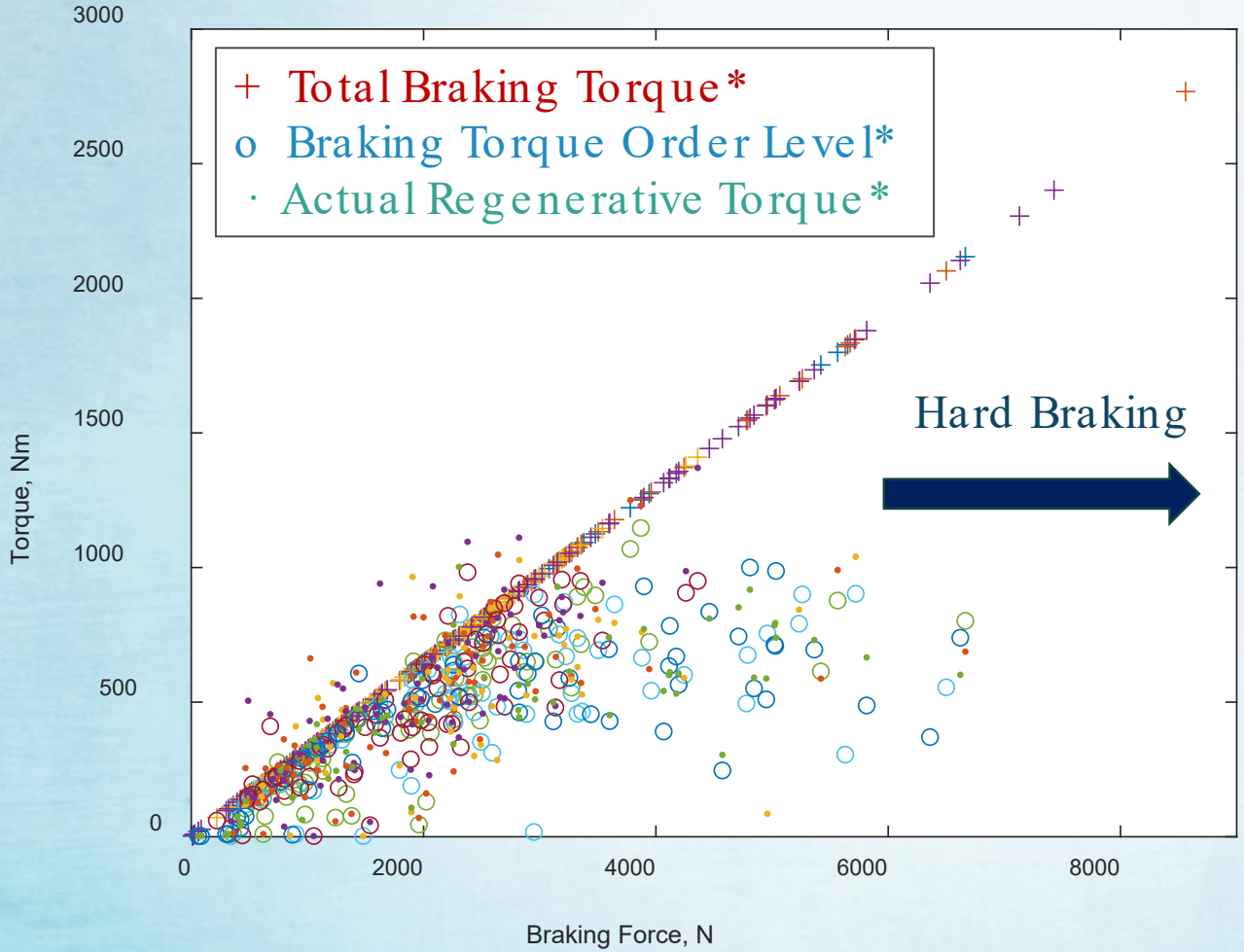
Braking and Regeneration



- Parameters
  - Vehicle Speed
  - Brake Switch Status
  - Braking Force
  - Braking Torque Order Level
  - Actual regenerative braking torque applied
  - Battery Current
  - Battery Voltage
  - State of Charge

- Negative battery current during the regenerative braking periods

Braking and Regeneration



Total Braking Torque = Braking Force* · r_{eff}

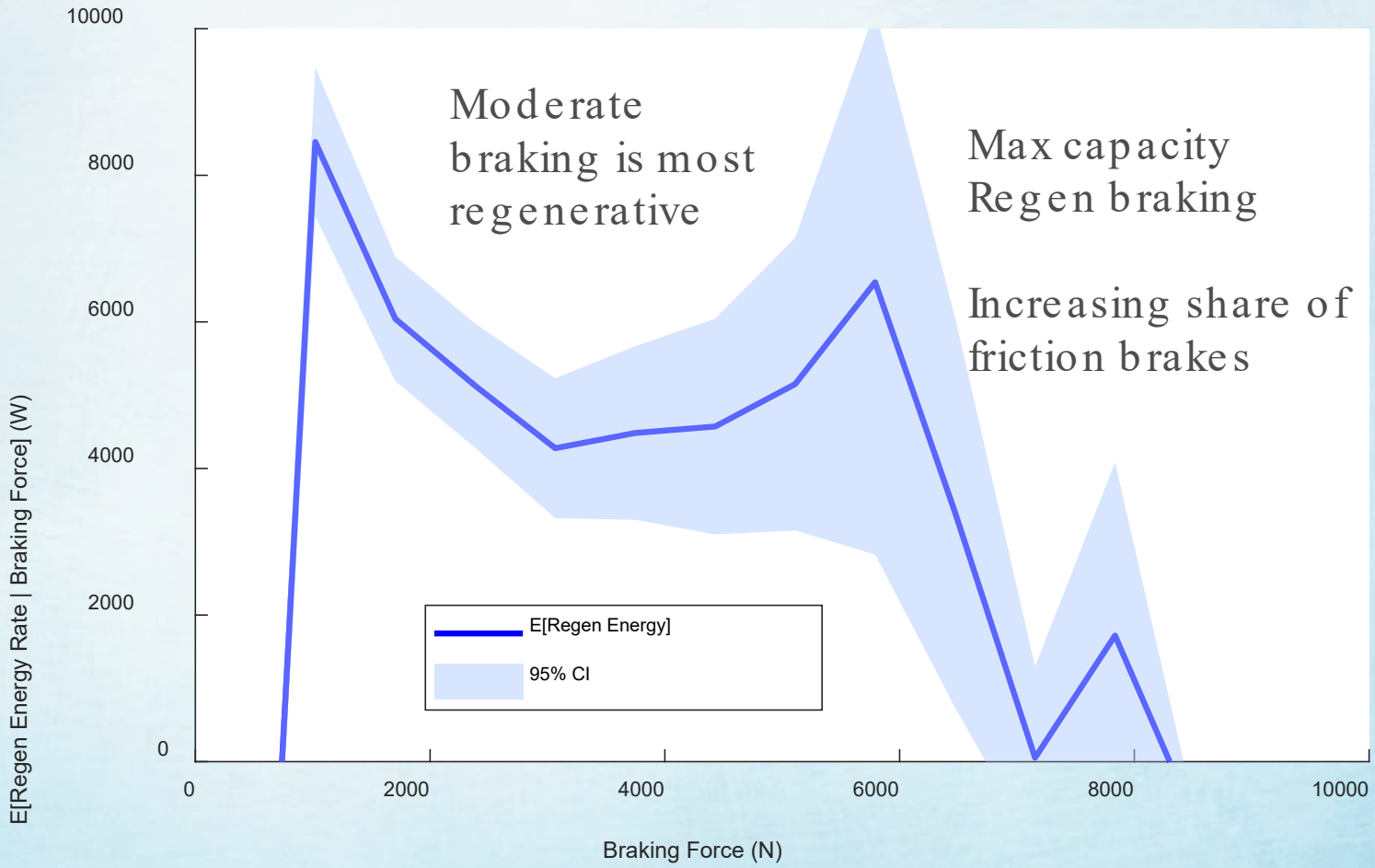
- Effective Wheel Radius (r_{eff}) : ~0.324m
- *ECU data
  - Braking Force
  - Braking Torque Order Level
  - Actual Regen Torque

- Factors affecting Regenerative Torque
  - Battery State of Charge (SOC)
  - Speed and Driving Conditions
  - Battery Temperature
  - Braking Mode

CARB

Braking and Regeneration

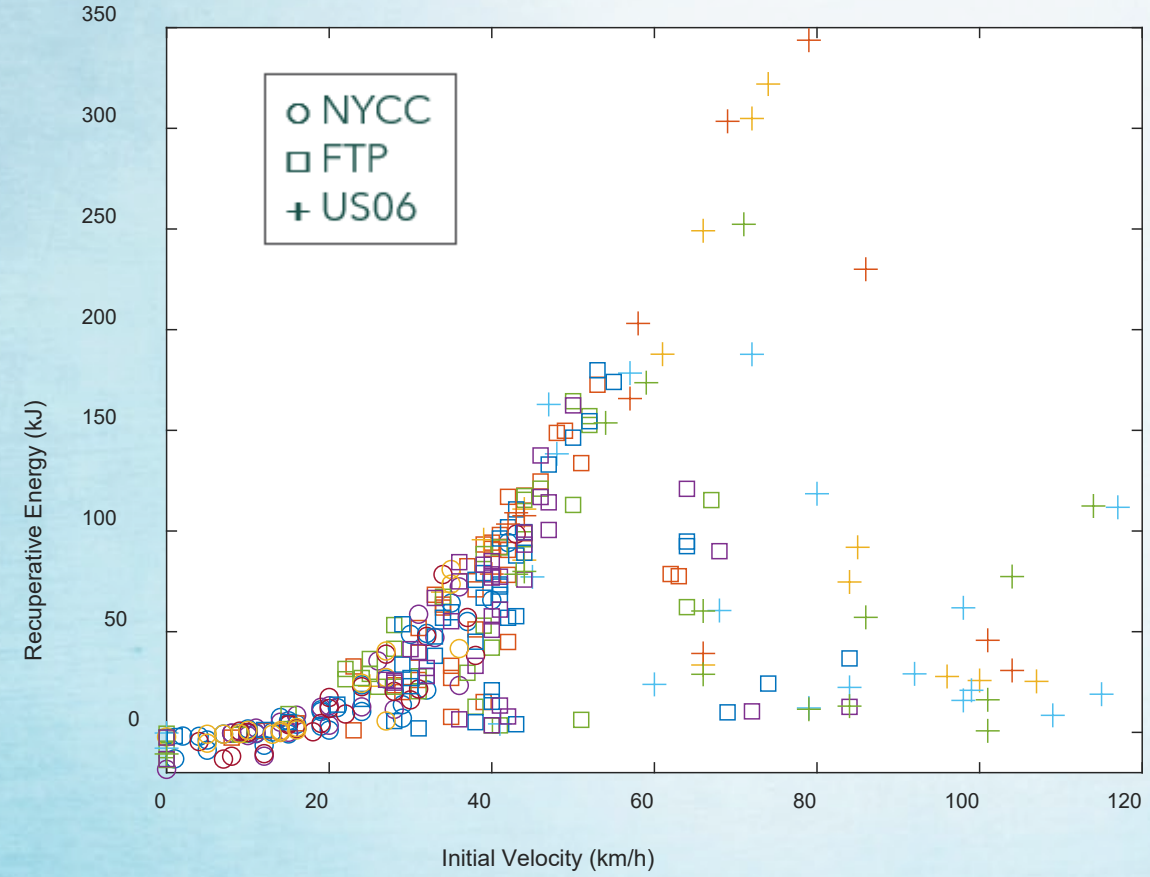
- Conditional Expectation of Regen Energy Given Braking Force

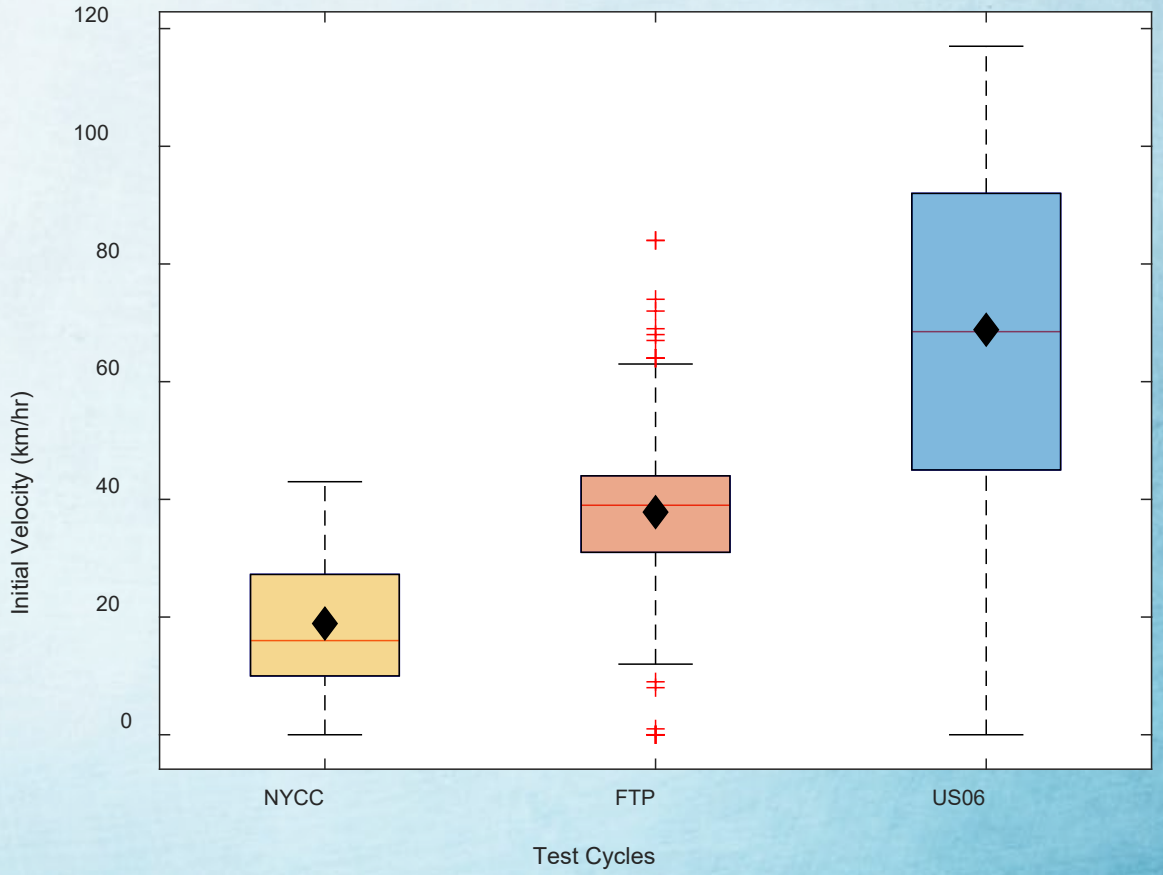


CARB

Recuperated Energy vs. Braking Events

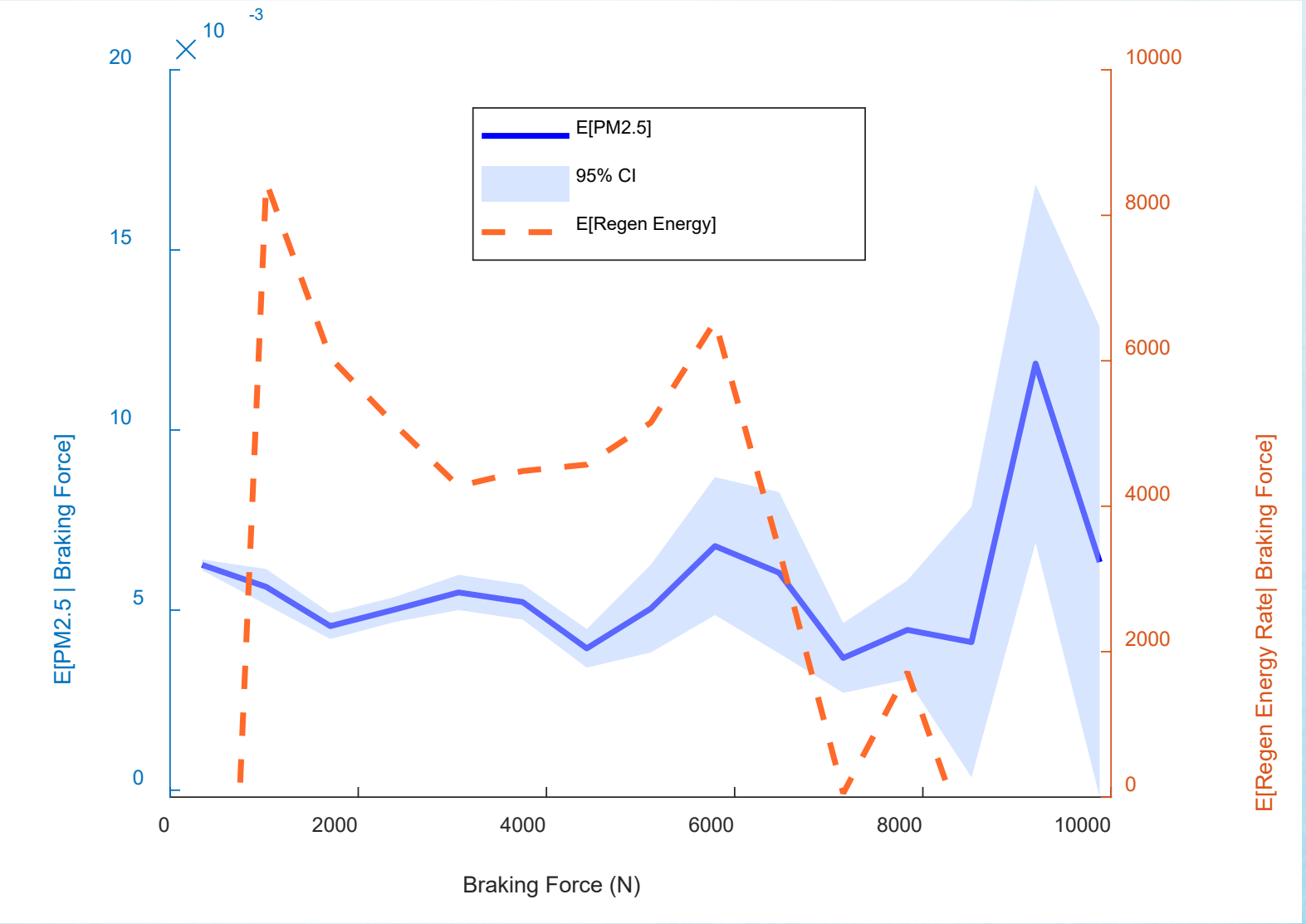
- Major braking events @ initial velocity 30 – 60 km/hr.
- At high initial velocity (> 80 km/h), regen was less effective





CARB

Braking vs. PM Emissions



Summary and Next Steps

- A battery electric vehicle (BEV) was tested over three driving cycles on a chassis dynamometer to quantify energy recovered through regenerative braking and assess its relationship to brake-wear emissions.
- Battery current and voltage were measured in real-time using the vehicle's ECU diagnostic tool and Hioki power meter.
- Regenerative braking was applied during most braking events across the test cycles, with the highest effectiveness observed between 20 and 60 km/h initial braking velocity.
- Less effective at higher initial velocity.
- Higher PM emissions were observed at low regenerative braking power.
- Additional vehicle testing will be conducted including HEVs and BEVs.