27th ETH Nanoparticles Conference (NPC-24)
June 10-14, 2024
ETH Zurich, Switzerland

科研費 KAKENHI

Acknowledgement
This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP 22K03895

Implications of Nanoparticle Emissions from Passenger Car Brakes based on the WLTP Brake Cycle

Hiroyuki Hagino

Japan Automobile Research Institute (JARI)

Data Sources
Hagino, et al., *Wear*, 2015, 334–335, 15, 44-48; https://doi.org/10.1016/j.wear.2015.04.012
Hagino, et al., *Atmos. Environ.,* 2016, 2016, 269-278; https://doi.org/10.1016/j.atmosenv.2016.02.014
Hagino et al., *Atmosphere* 2024, 15(1), 49; https://doi.org/10.3390/atmos15010049
Hagino, *Atmosphere* 2024, 15(1), 75; https://doi.org/10.3390/atmos15010075
Hagino, *Lubricants* 2024, 12(6), 206; https://doi.org/10.3390/lubricants12060206

Contents

- ✓ **Background**
- ✓ **Brakes: General Topics for Brakes and Emissions**
- ✓ **Implication of Nanoparticle Emission**

Background

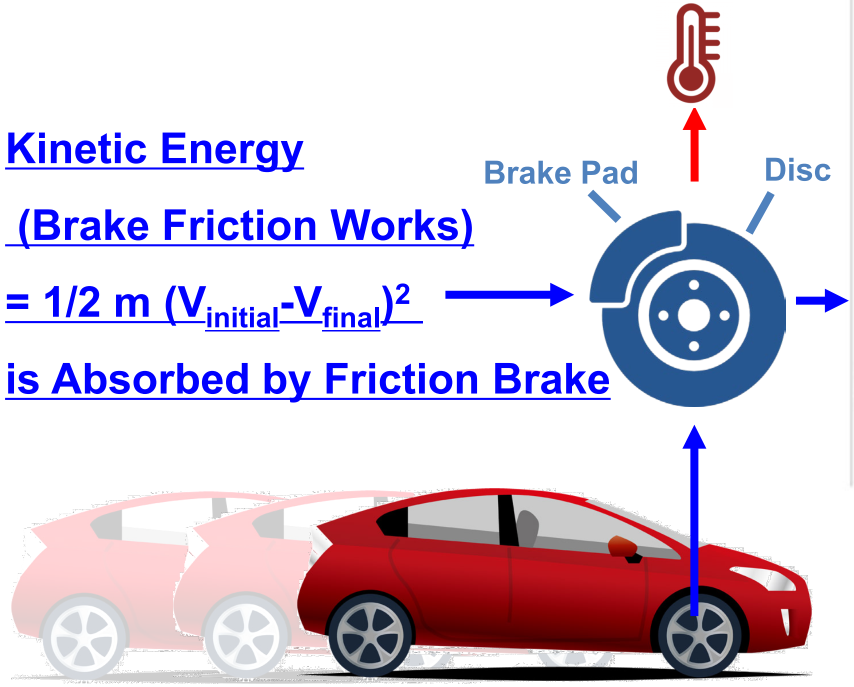
Background

- Automobile brakes are devices to absorb the kinetic energy of driving vehicles for deceleration or stopping.
- Friction between friction material and counterpart material generates brake wear-derived gases and particles.
- In Euro 7, the emission regulation of brake wear particles PM_{10} was established world first, and nanoparticles/particle number is under observation.

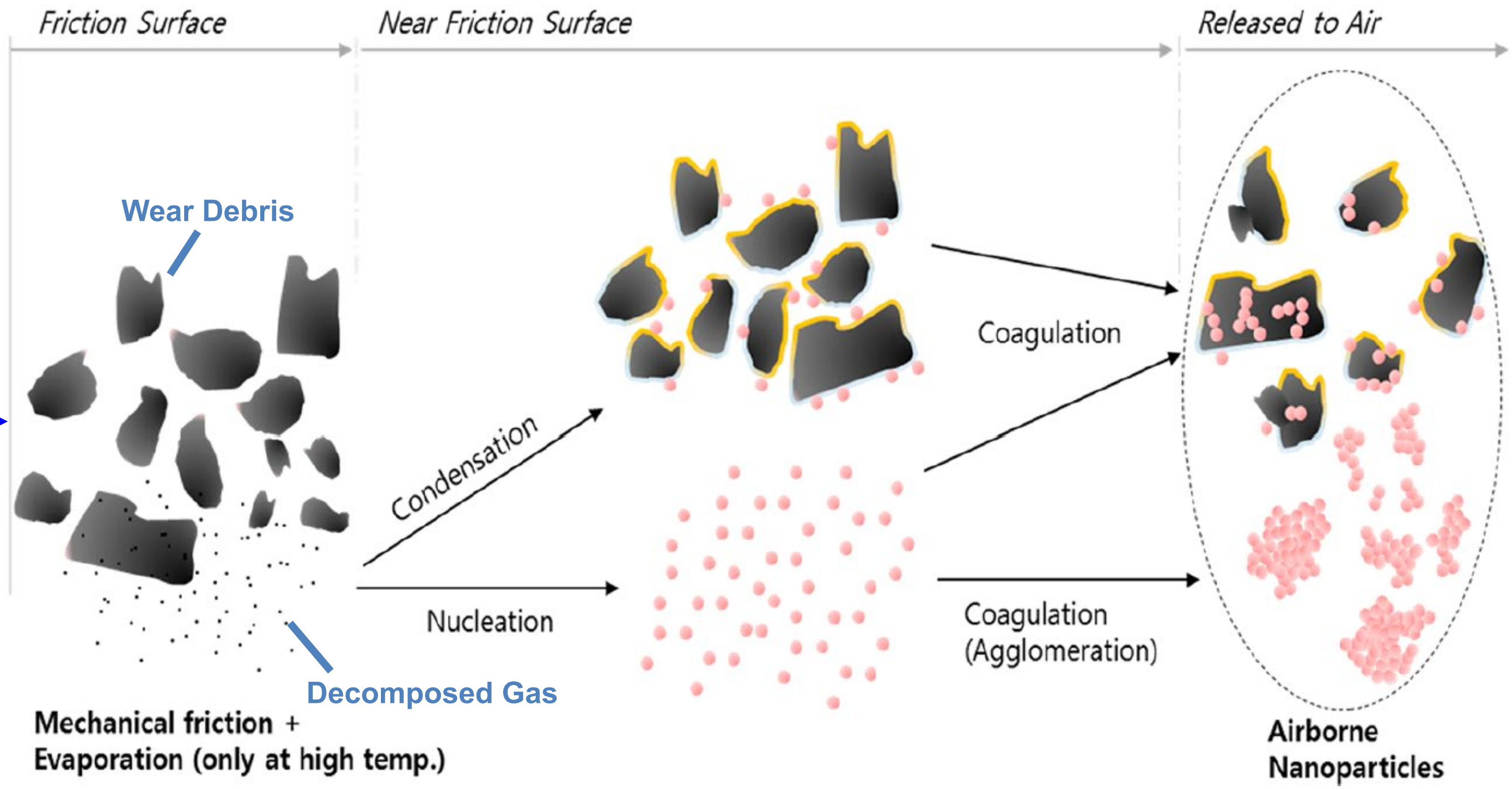
Car Brake Event

Emits Thermal Energy
(Sometimes Noise emitted as Energy)

Kinetic Energy
(Brake Friction Works)
$= 1/2\ m\ (V_{initial}-V_{final})^2$
is Absorbed by Friction Brake



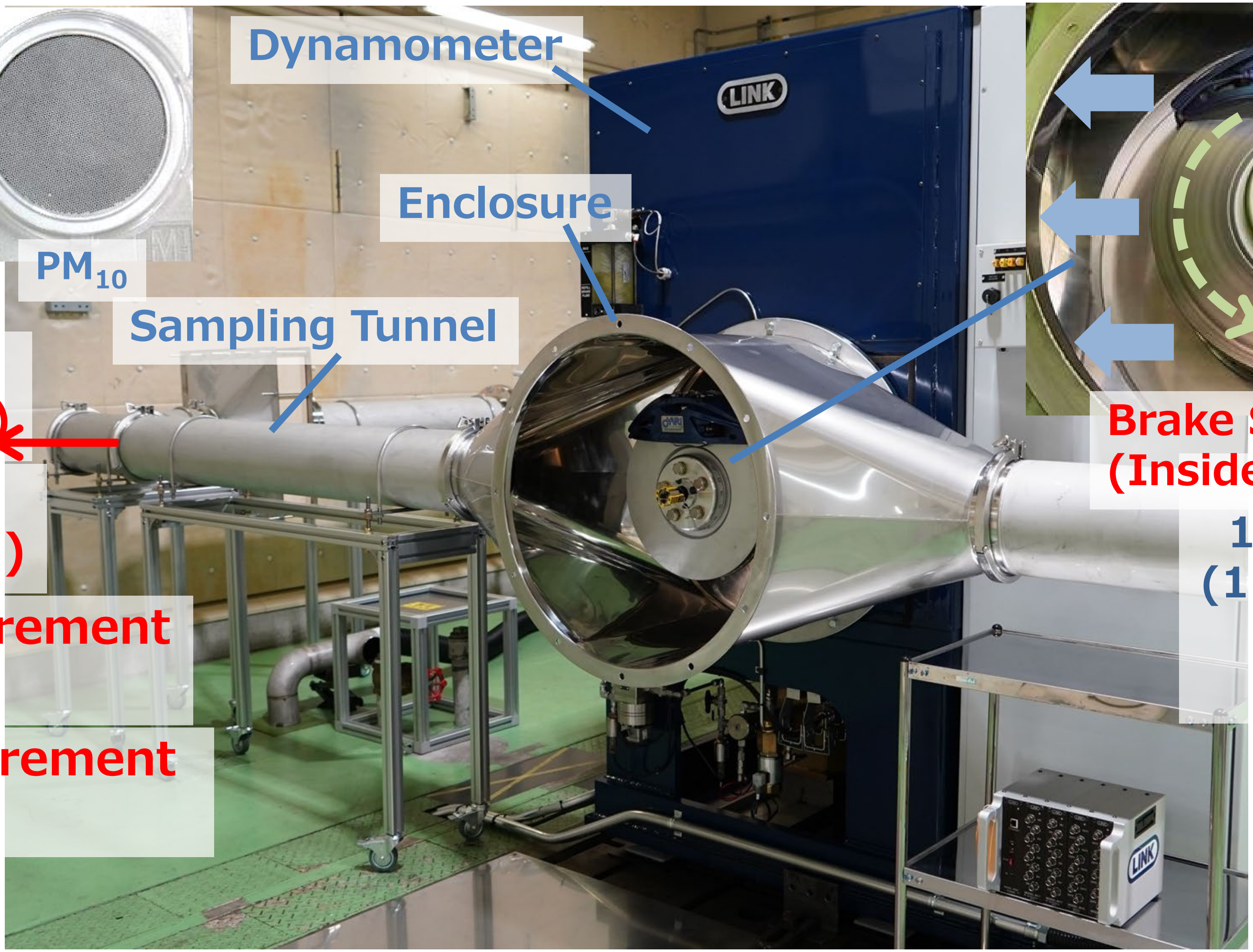
Brake Emission Process



Ref. : Namgung et al., *Environ. Sci. Technol.*, 2016, 50, 3453–3461; https://pubs.acs.org/doi/10.1021/acs.est.5b06252

Brake Wear Particle Measurements

- Common measurement methods for brake emissions have been established by Particle Measuring Program (PMP).
- Recommend dynamometer tests that can provide stable and reproducible data for strict regulations.



PM_{10} cyclone (PM_{10} sampling)

$PM_{2.5}$ cyclone ($PM_{2.5}$ sampling)

Total PN measurement (TPN_{10})

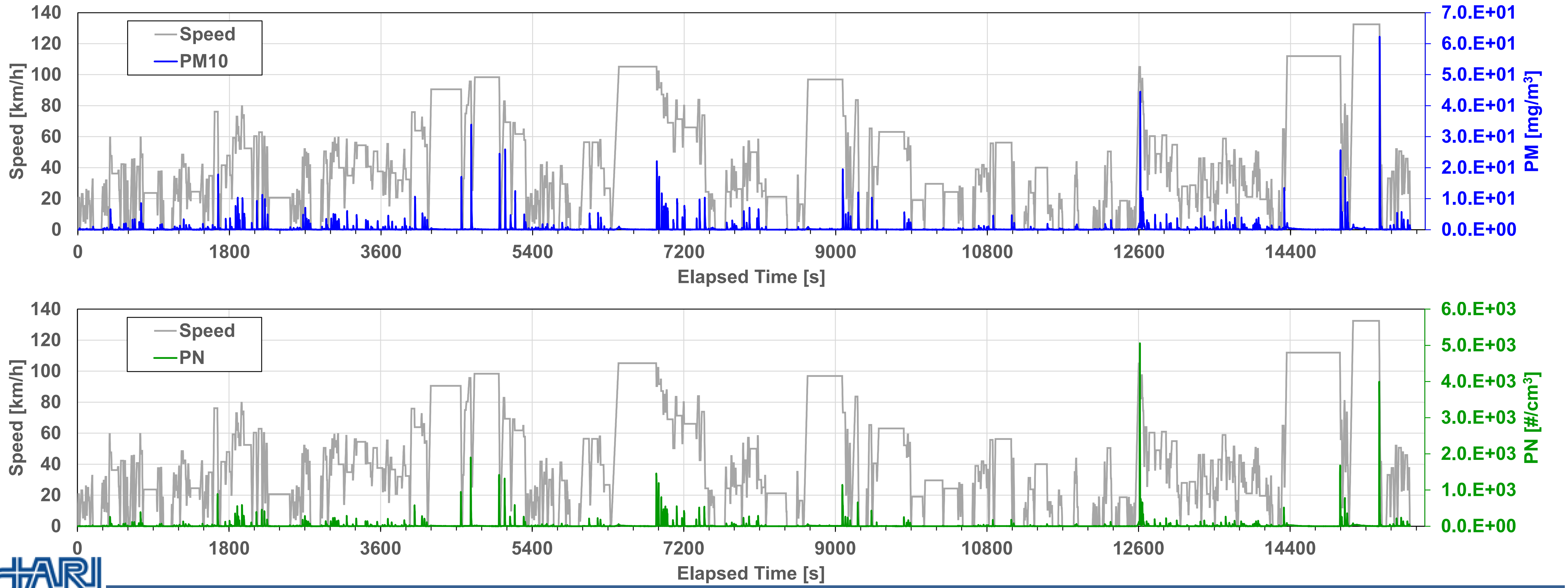
Solid PN measurement (SPN_{10})

Air Flow
100 – 1500 m^3/h
(1.6 – 25 m^3/min)
23 ± 2 °C
50 ± 5 RH%

Photo: JARI Facility

WLTP-Brake Test Cycles

- World Harmonized Test Procedure (WLTP) - Brake Cycle generated from average vehicle speed and braking patterns in the world; Test Time: 15826 s (4.4 h); 192 km of total distance driven; Average speed 43.7 km/h, Maximum speed 132.5 km/h.
- 303 brake deceleration events; 0.97 m/s² average brake deceleration : 2.18 m/s² maximum brake deceleration; 5.7 s average brake deceleration duration; maximum brake deceleration duration of 15 s.
- Typical PM and PN emission behavior is ; further investigation will reveal differences depending on brake assembly.



Brakes

Brakes

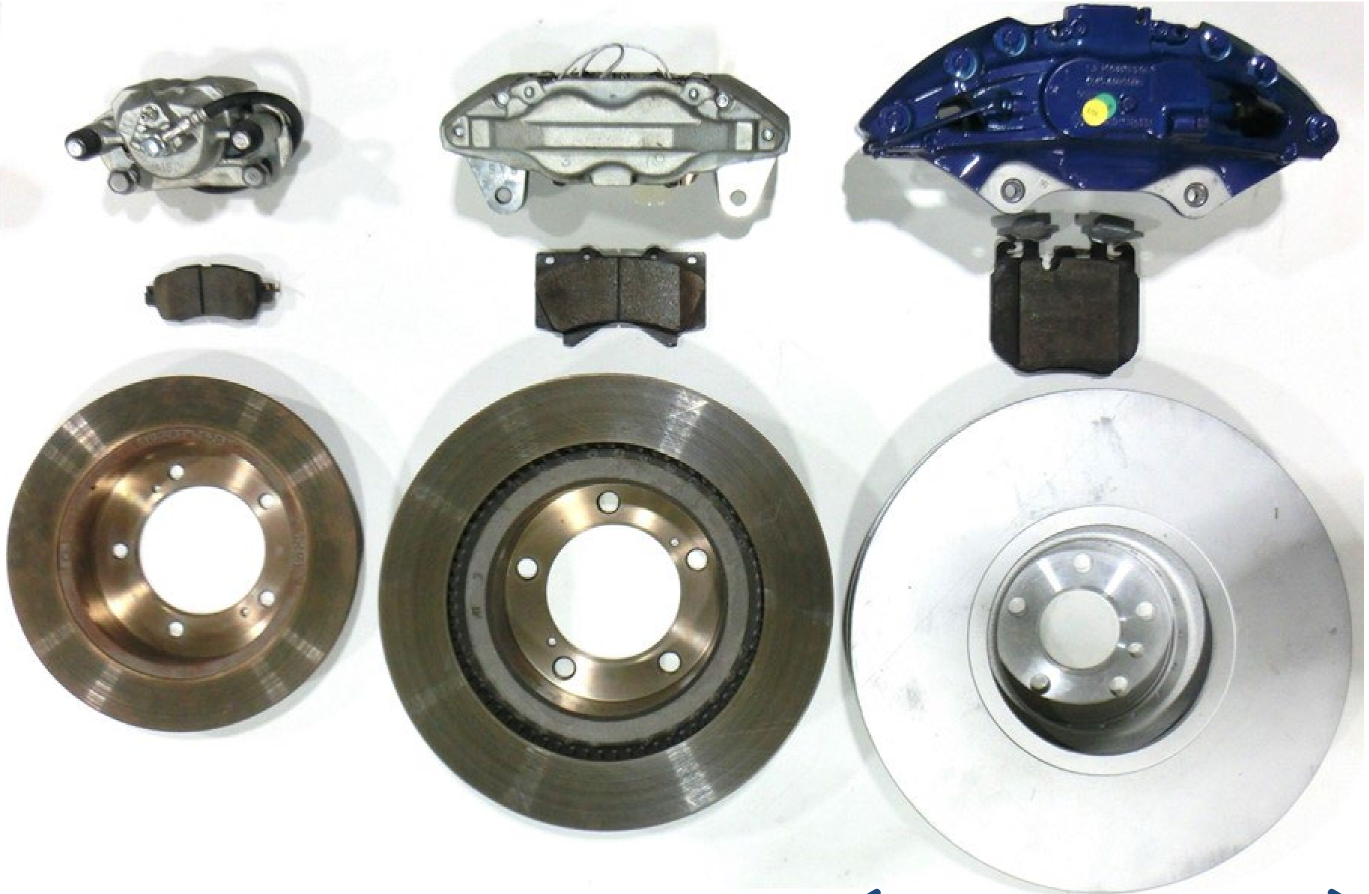
- Wide variety of brakes are available due to design brakes according to vehicles.
- Larger discs increase thermal capacity, reduce heat rise, and stabilize brake friction performance.

	Vehicle 1 (SUV 1, Front)	Vehicle 2 (SUV 2, Front)	Vehicle 3 (SUV 3, Front)
Test mass	1,100kg	2,800kg	2,600kg

Caliper

Pad

Disc



400 mm

Brake Wear Parameters

- Categorized into three parameters
- Mechanical Factor: Depends on vehicle weight, speed pattern
- Environmental Factor: Climatic factor
- Material Factor: Thermal properties (Wear/Gas Emissions), Surface Roughness/Shape/Stiffness (Wear)

Mechanical Factor

- Load (Test Vehicle Mass)
- Speed (Deceleration)
- Contact Pressure (Deceleration/Slippage)

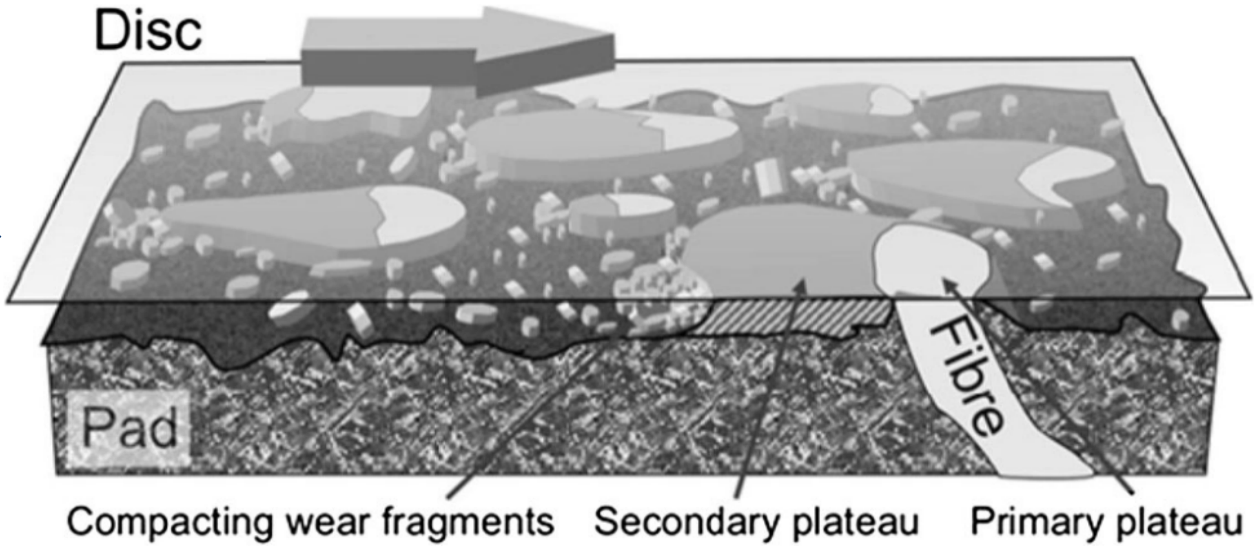
Environmental Factor

- Temperature
- Humidity

Material Factor

- Thermal properties
- Surface Roughness/Shape
- Stiffness

Friction and Wear

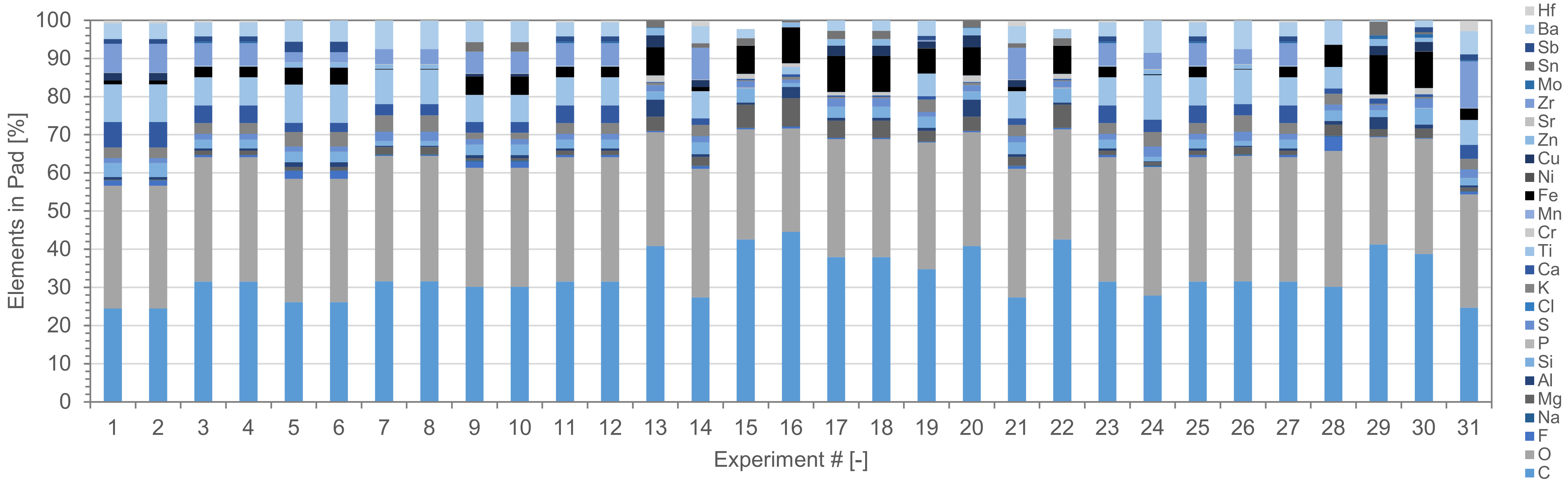


Ref. : Grigoratos and Martini, *Environ Sci Pollut Res.*, 2015, 22, 2491–2504; https://doi.org/10.1007/s11356-014-3696-8

Blue letters: Factors defined in the WLTP-Brake test procedure as common rule.
Red letters: Most important factor under common rule

Brake Pad Composite

- Brake pads are manufactured by compressing and heat molding 20 to 30 different materials and are designed to fit vehicle.
- There is a very wide range of brake pad composites.
- High amounts of carbon (e.g., resin in binders), oxygen (e.g., in compounds) and trace metal elements (e.g., abrasives, solid lubricants, fillers)
- Conventional brake discs are made of cast iron. Tungsten-coated discs are also available to reduce wear.



Data Source : Hagino, Lubricants 2024, 12(6), 206; https://doi.org/10.3390/lubricants12060206

Brake Composite and Their Role

- 20 to 30 materials in a brake pad contribute significantly to braking and wear performance.
- Blending of materials is a matter of know-how.

Typical brake pad formulations and general performance related to brake wear for automotive brake pads

Functions	Materials	Mass %		General Performances		
		Non-Steel NAO	Low Steel ECE	Effectiveness	Abrasion-resistant Pad	Abrasion-resistant Disc
Binder	Phenolic resin	8 – 15	8 – 15	↓	↑	↑
Reinforcement	Heat-resistant organic fibers Aramid fibers	3 – 15	0 – 5	↓	↑	↑
	Inorganic fibers	1 – 15	1 – 10			
	Glass fibers			↑	↑	↓
	Basalt fibers			↑	↓	↑
	Carbon fibers			↓	↑	↑
	Metal fibers					
	Steel fiber	0 – 5	5 – 30	↑	↓	↓
	Copper and brass fibers, etc.	1 – 10	1 – 10	↑	↓	↓
Friction Modifier	Lubricating agents					
	Graphite	5 – 15	5 – 20	↓	↑	↑
	Metal sulfide (MoS_2)			↓	↑	↑
	Metal sulfide (Sb_2S_3)			↑	↑	↓
	Organic fillers					
	Cashew particle	5 – 15	2 – 10	↑	↑	↑
	Rubber (Tyre rubber)	0 – 15	0 – 10	↑	↑	↑
	Inorganic filler					
	$BaSO_4$	5 – 35	5 – 35	—	↑	↑
	Abrasives					
	Hardness : Al_2O_3, SiC etc Soft to medium : ZrO_2 etc	1 – 5	1 – 5	↑	↓	↓
	Metal powder	0 – 5	0 – 5	—	↑	—

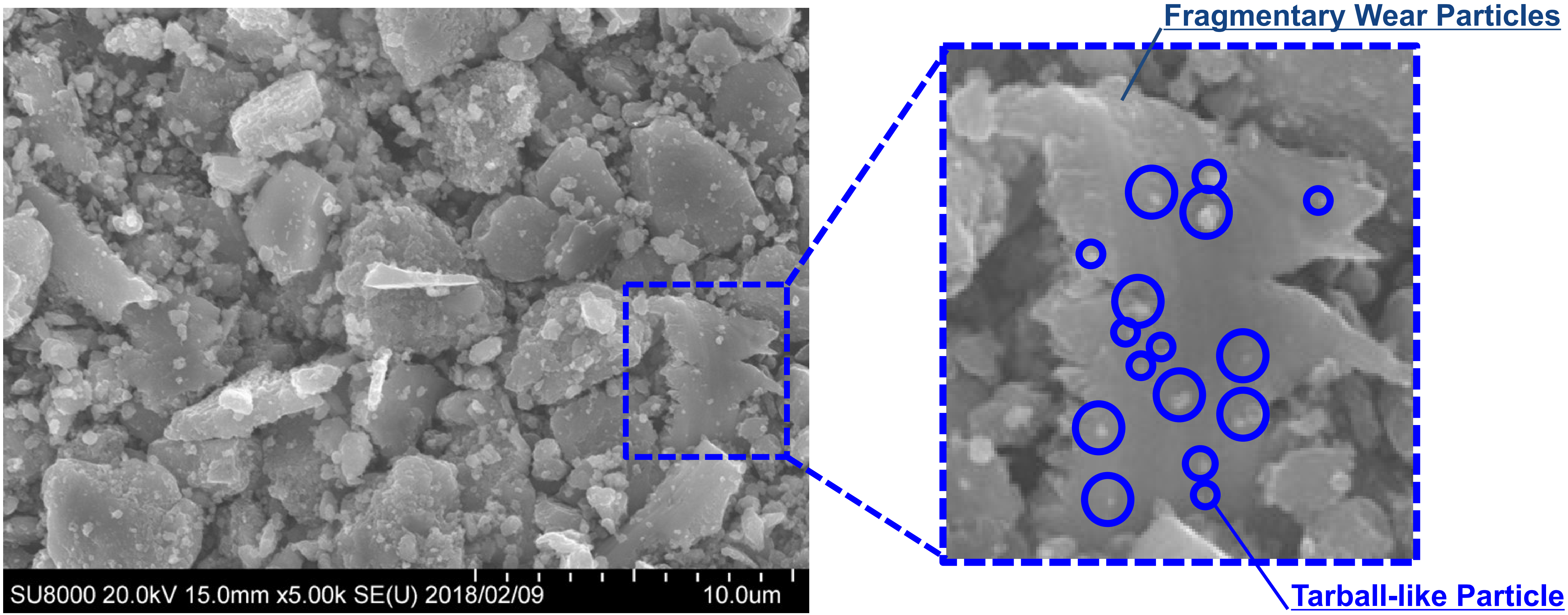
NAO: Non-Asbestos Organics pad for North American and Asian markets
ECE: European performance (ECE) pad for European market.

↑: Improved performance; ↓: Reduced performance.

Ref. :Hagino, *J. Jpn. Soc. Atmos. Environ.*, 2020, 55, A18–A35. (In Japanese); https://doi.org/10.11298/taiki.55.A18

Brake Wear Particle Morphology

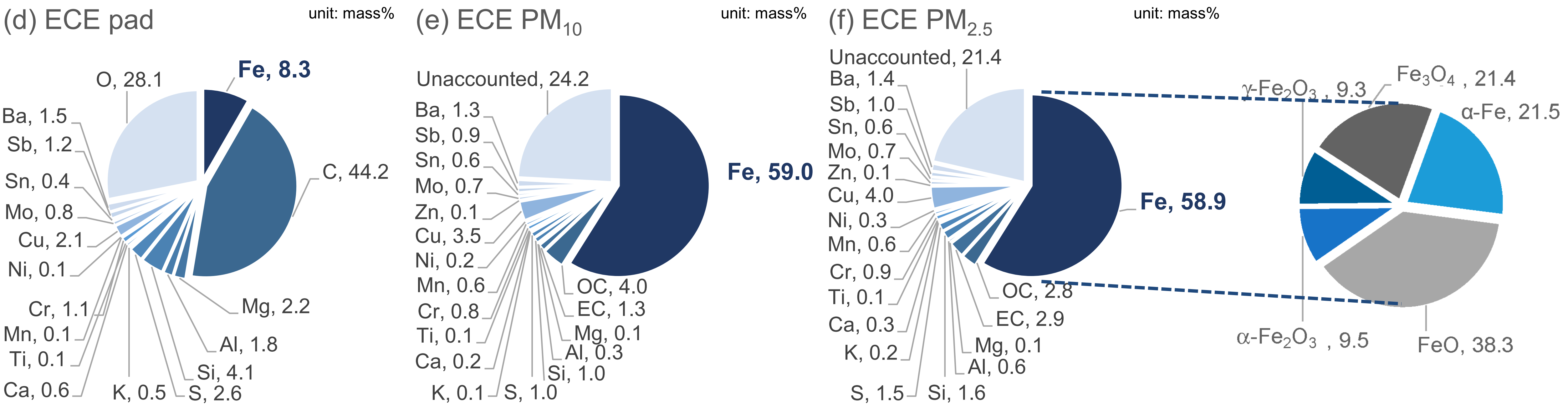
- An example of the morphology of emitted brake wear particles; Cascade impactor (cut-off particle size 5-7um).
- Fragmented (Debris), spherical wear particles are observed.
- Spherical wear particles have nanoparticle size and tarball-like particles are observed.
- This means that nanoparticles may be transported together with larger particles in the atmosphere.



Ref. :Hagino, *J. Jpn. Soc. Atmos. Environ.*, 2020, 55, A18–A35. (In Japanese); https://doi.org/10.11298/taiki.55.A18

Brake Wear Particle Chemicals

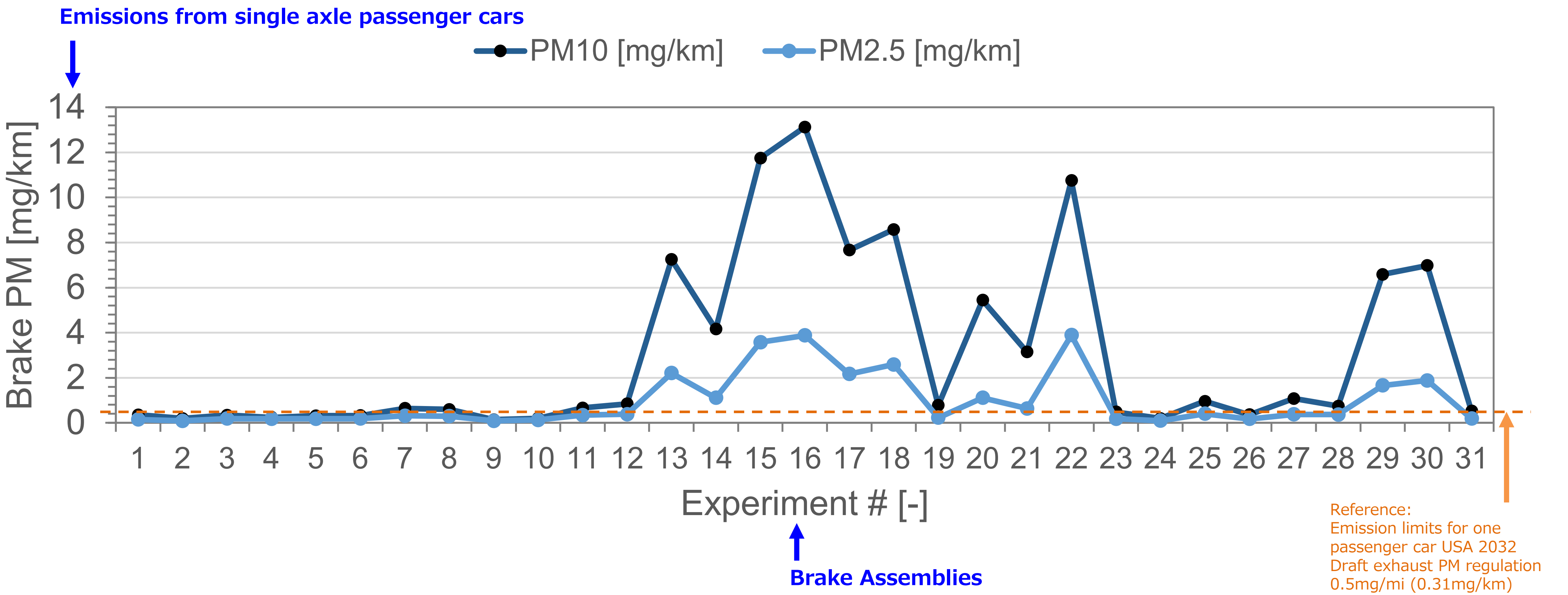
- Comparison of elements in European performance (ECE) brake pad, PM_{10} and $PM_{2.5}$ emission particles.
- Elements in pad and PM emissions are very different, with PM containing more disc-derived iron.
- Carbon and sulfur in pad are related to differences in composition of pad and PM emissions.
- No significant difference in composition between PM_{10} and $PM_{2.5}$, however, iron chemical forms are very different.
- Nanoparticle composition is a subject for future research.



Ref. : Hagino et al., Atmosphere 2024, 15(1), 49; https://doi.org/10.3390/atmos15010049

Brake Wear Particle Mass

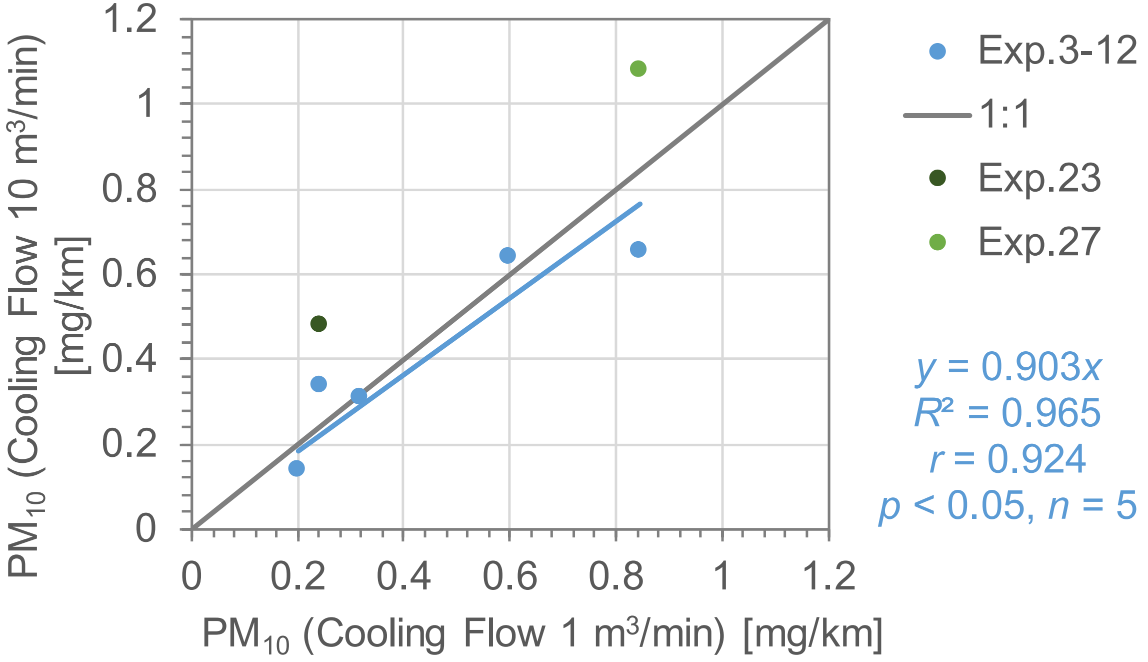
- The Euor7 regulation defines PM_{10} (aerosol particles with an aerodynamic diameter of 10 μm or less, which is the 50% cutoff) as 0.2 to 13 mg/km per wheel (0.6 to 37 mg/km per car).
- Emission levels are very wide, depending on brake components.
- Brake PM exceeds the U.S. vehicle emission limit of 0.31 mg/km (0.5 mg/mi) after 2032.

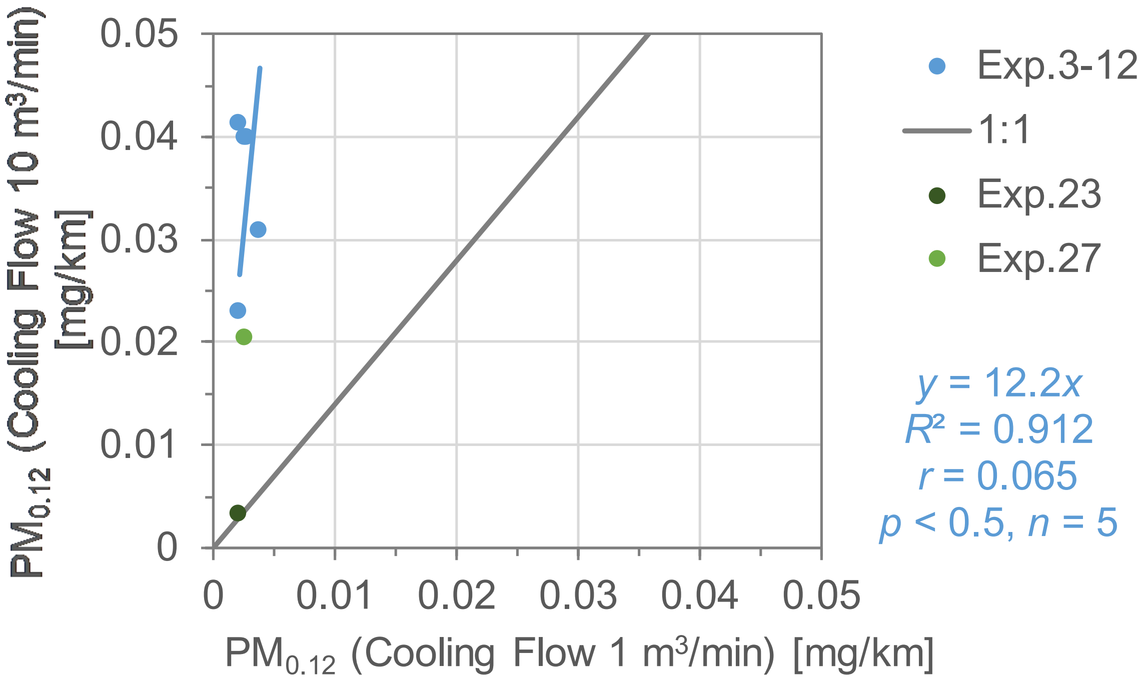


Implication of Nanoparticle Emission

Brake Wear Nano Particle Mass

- Nanoparticle mass varies greatly depending on sampling method.
- PM_{10} does not differ significantly according to sampling method.
- Compared to low sampling flow rates (1 m^3/min) used in vehicle-based measurements or compact lab dyno, high flow rates in dyno experiments lead to be 12 times higher nanoparticle mass emissions.

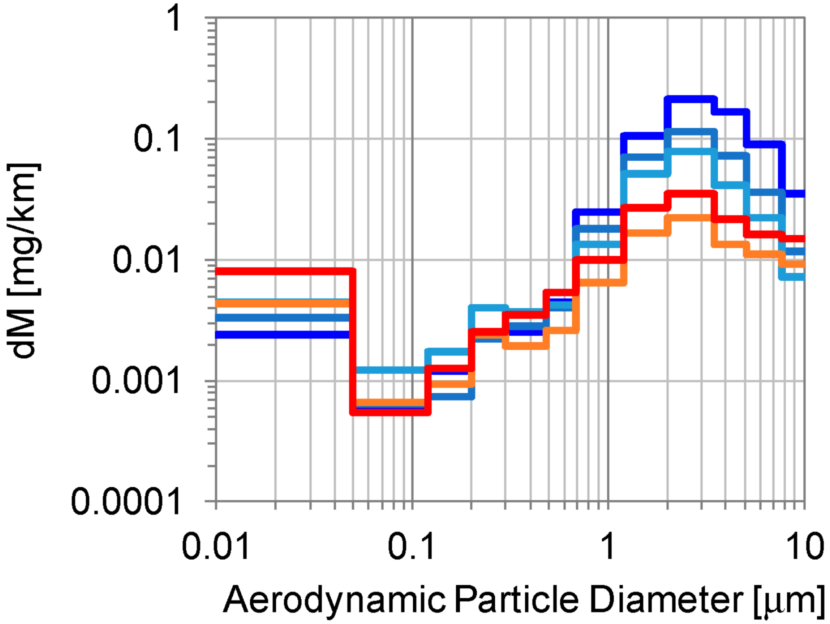




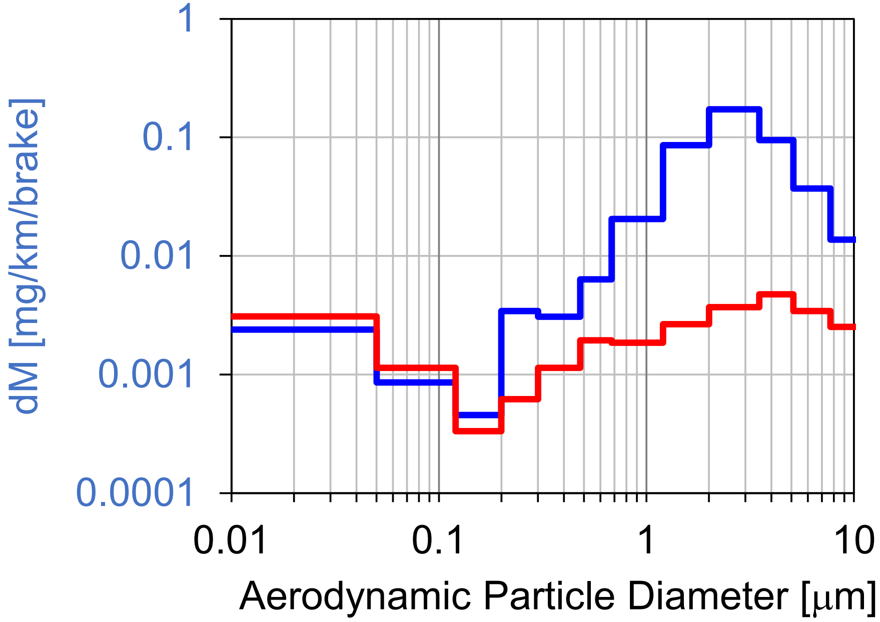
Brake Wear Nano Particle Mass

- **Brake nanoparticle mass is small.**
- **Nanoparticle mass slightly increase with reduction of coarse particles for electrified vehicles (EVs).**
- **Relative increase in peeling of tribo-layers (mainly tarry) on pad surface results in more tarball-like nanoparticles being emitted.**

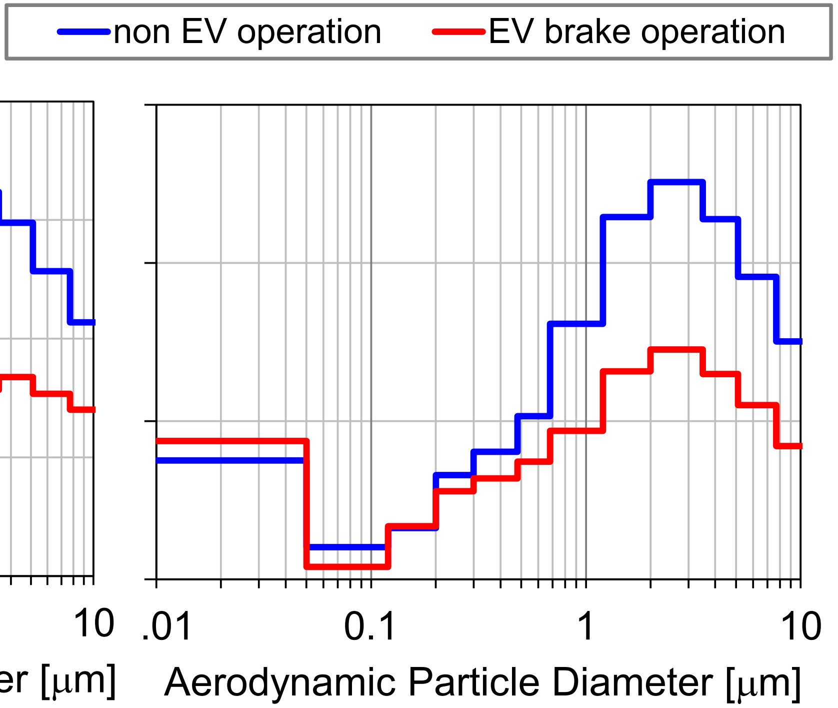
Vehicle A



Vehicle B



Vehicle C

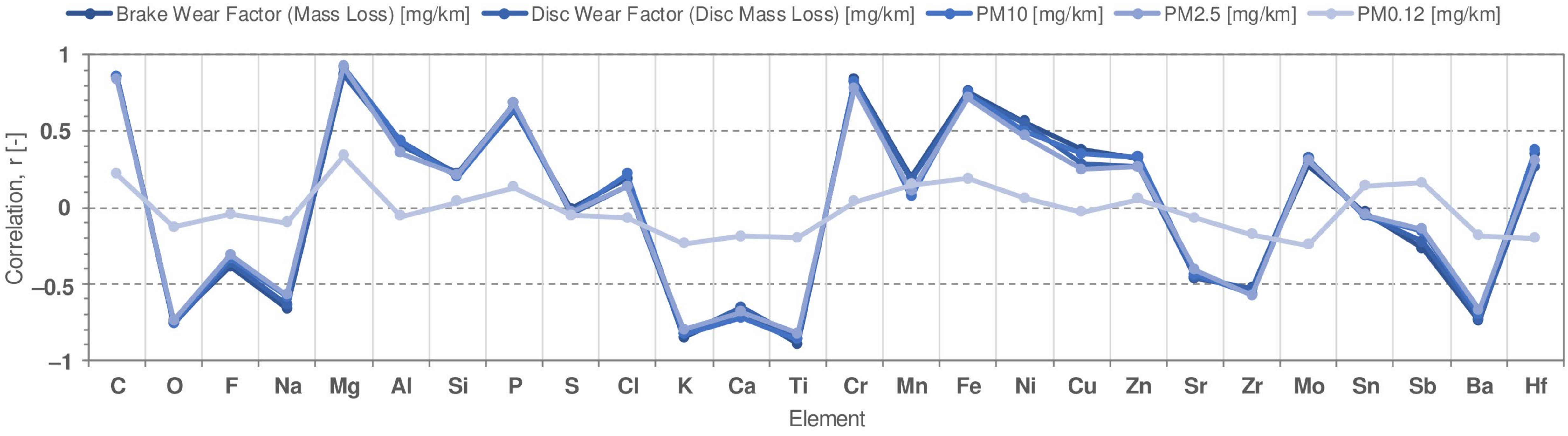


Ref. : Hagino, Atmosphere 2024, 15(1), 75; https://doi.org/10.3390/atmos15010075

Data Source : Hagino, in preperation

Brake Wear Nano Particle Mass and Friction Materials

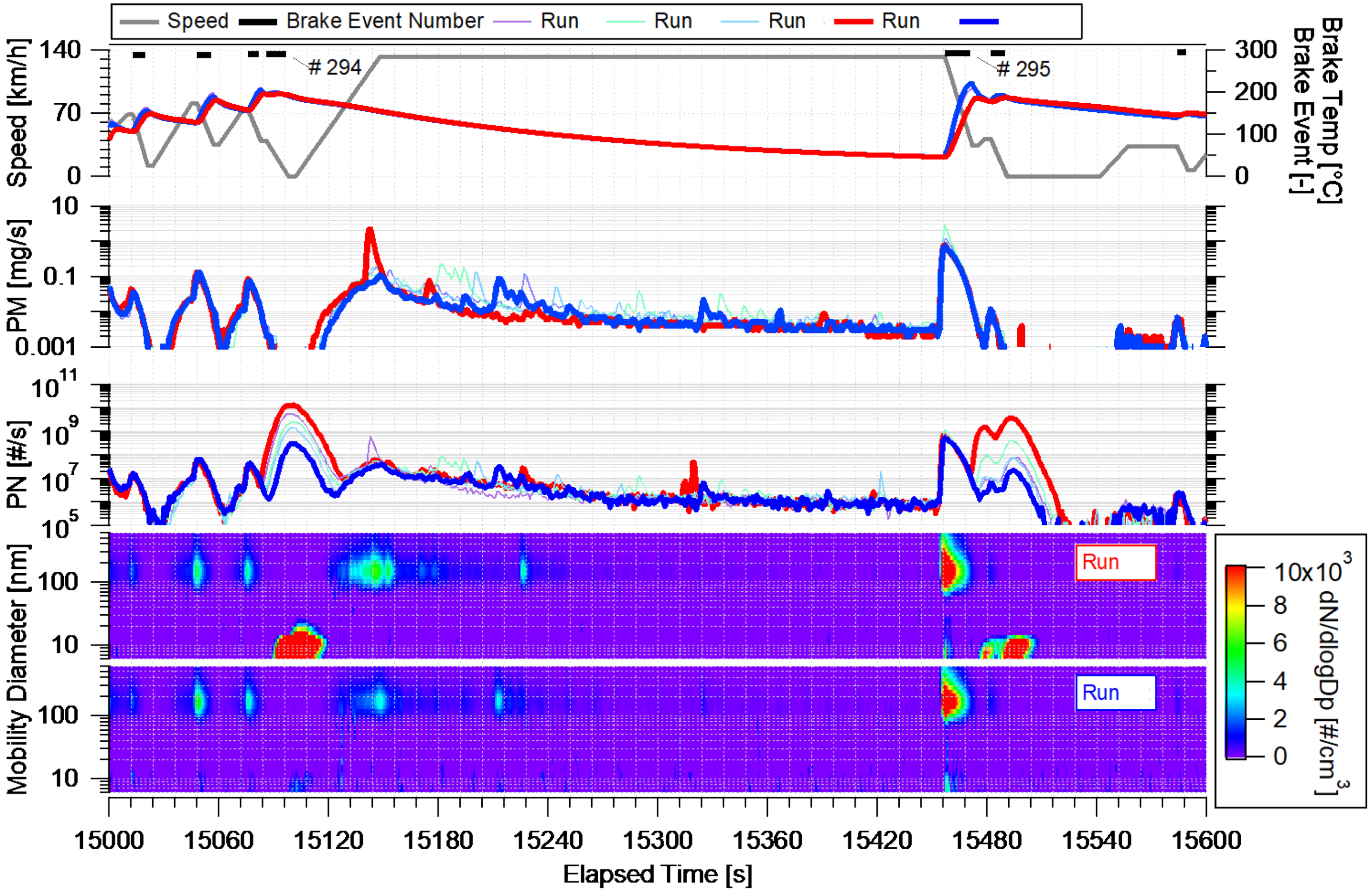
- Based on an investigation of 31 brake assemblies.
- Wear factors, PM_{10}, and $PM_{2.5}$ emissions show a positive correlation with C (derived from resin: filler), Mg (filler and abrasive), Cr and Fe (steel fiber) in the pad, and a negative correlation with O (resin and metal oxide), K and Ti (fade resistant), Ba (barium sulfate) in the pad.
- Nanoparticle mass ($PM_{0.12}$) emissions cannot be found to correlate with composition of pad.



Ref. : Hagino, Lubricants 2024, 12(6), 206; https://doi.org/10.3390/lubricants12060206

Brake Wear Particle Nucleation

- Particle number and mass emission behavior are very different.
- Many literature report that nanoparticles increase at higher braking temperatures.
- In our opinion, even if the brake temperature is kept reproducibly low, the formation of nuclei particles (emission of particles smaller than 20 nm in size) occurs and is not reproducible.
- Nucleation (Dp < 20 nm particles) occurs due to burning (evaporating) of friction material.

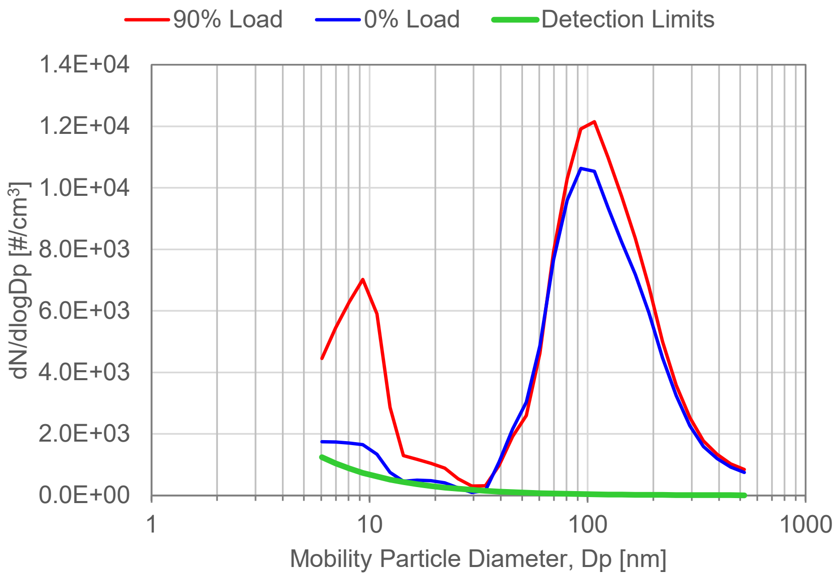


Particle Size Distributions:
TSI FMPS3091
Particle Number (PN):
TSI CPC3750
Particle Mass:
TSI DustTrak II 8530

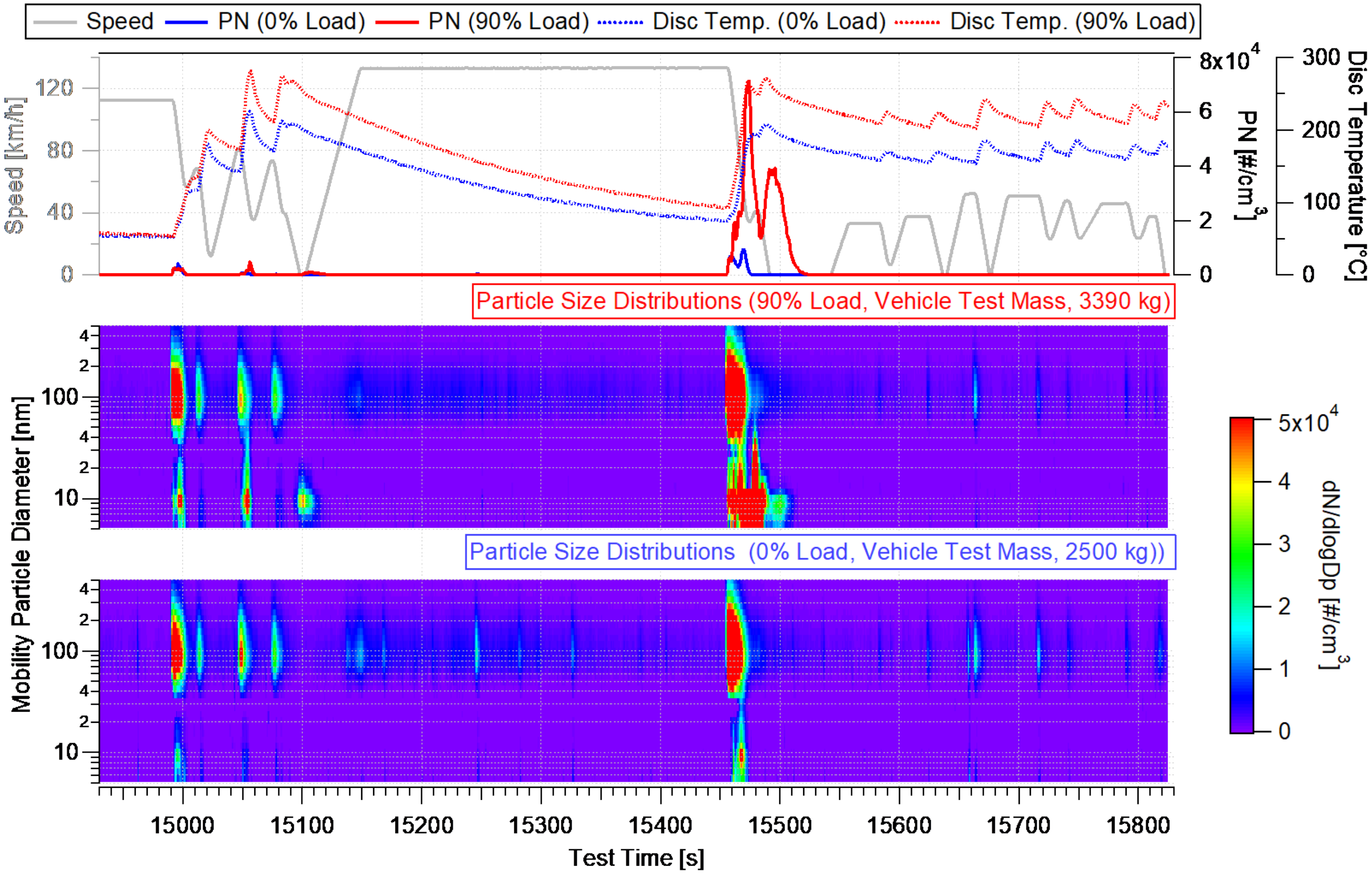
PM data added to Ref. : Hagino, *Atmosphere* 2024, 15(1), 75; https://doi.org/10.3390/atmos15010075

Brake Wear Particle Nucleation with High Loading

- Sub-20 nm particles increase with increasing test vehicle mass
- Brake energy for Light Commercial Vehicles (LCVs) greatly depends on loading of cargo.
- Example of particle number size distribution for nominal (0%) and 90% loading, high loading leads to increase in particle number and sub-20 nm particles emissions.



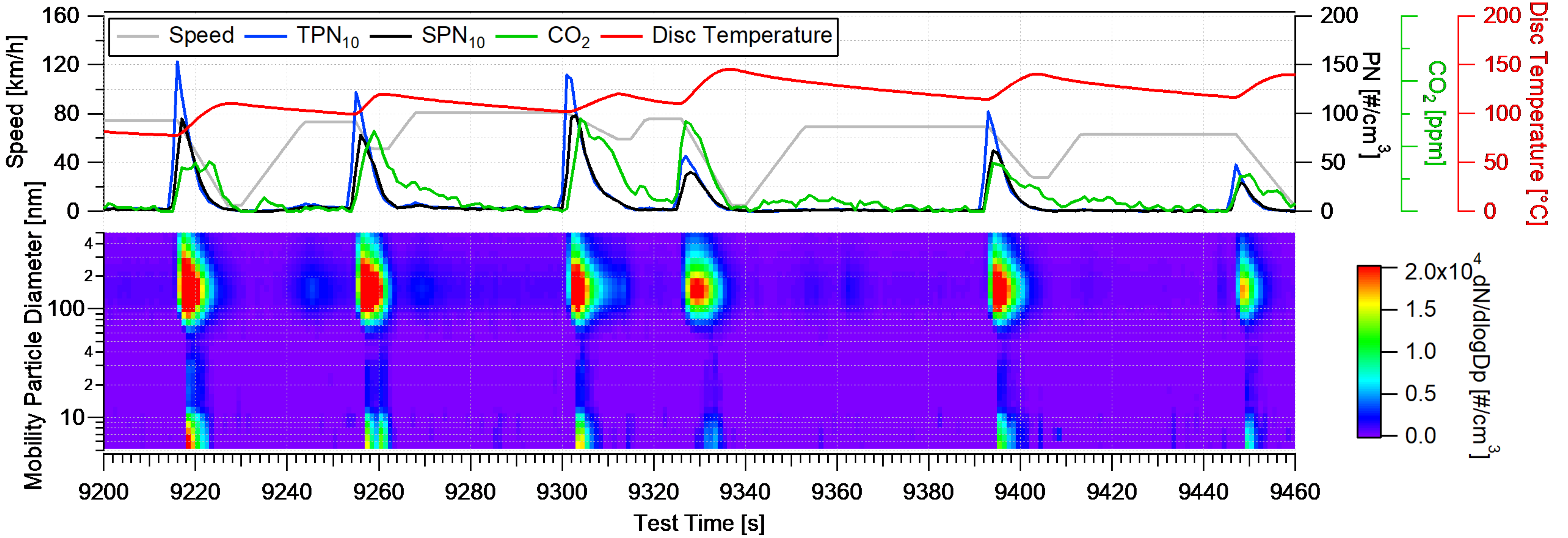
Particle Size Distributions: TSI FMPS3091
Particle Number (PN):TSI CPC3750



Data Source : Hagino, In preparation for submission to peer-reviewed journals

Brake Wear Particle Nucleation with High Deacceleration

- Example measured with Los Angeles City Traffic (LACT) Cycle.
- Sub-20 nm particles have been observed in higher braking energy (deceleration) cycle than WLTP-Brake Cycle.
- CO_2 emissions have been observed from brake as well as particles, supporting that brake friction material is burning (including decompositions) at low brake temperatures (<150°C).



Particle Size Distributions: TSI FMPS3091, Total Particle Number (TPN_{10}):TSI CPC3750. Solid Particle Number (SPN_{10}): Catalytic Instrument CS015 + TSI CPC3750, CO_2: LI-COR LI-820

Data Source : Hagino, In preparation for submission to peer-reviewed journals

Take-Home Message

[Brakes]

- Brake types are very wide due to their design in accordance with vehicles.
- Brake pads are composed of various chemical compositions that affect brake performance.

[Wear and PM emissions]

- Brake wear increases with mechanical, environmental and material factors, respectively.
- Vehicle mass and brake material factors are the most important for PM and PN emissions, as the test methods are defined as common factors by the WLTP-Brake Cycle.

[Nano Particle Emissions]

- Brake wear certainly emits nanoparticles.
- Sampling methods lead to very different measurement values.
- Particle number size distributions are generally shown with a mode diameter of 160 nm with out nucleation events.
- Nucleation (Dp < 20 nm particles) may occur due to burning (decomposition) of friction material.

[Compositions]

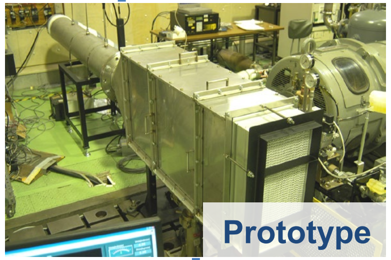
- Chemical composition measurement of nanoparticles is a future challenge.

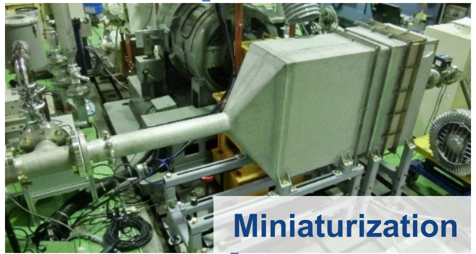
Appendix

Background of Brake Emissions Research in Japan

- Start of research to create chemical composition profiles of brake wear particles.
- Highly reproducible experiments using dynamometer, and reproduce realistic driving conditions for automobiles.
- Japan's Ministry of the Environment has stated that it will actively contribute emission assessment data on brake wear particles to the World Forum for Harmonization of Vehicle Regulations (WP.29).[*1]
- Update over time and brake emission studies for a wide range of vehicle types from LDV to HDV.

1981 — Asbestos PM
2010 — $PM_{2.5}$, Urban Cycles, PN
2017 — Regen Brake, JASO
2021 — ILS-2
2022 — Brake Family
2024 — Pre-ILS-3, ILS-3, HDV


Prototype

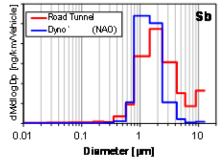

Miniaturization


High Efficient Cooling

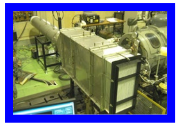

GTR24 Compliant Tunnel

GTR24 Compliant

Environmental Impacts



Dyno



Traffic Road Tunnel

Ref: Hagino, Atmos. Environ., 2016

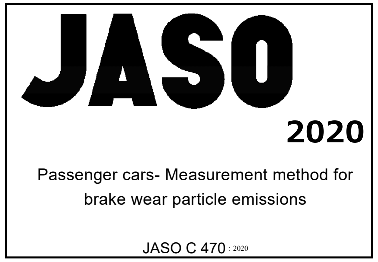
Hands-On
World's First Brake Emission Seminar

Hands-On Brake Emission with JSAE
Ref: Hagino, EuroBrake 2018, EB2018-VDT-018

Homage Works
World's First Inter Lab Study

Ref: Hayakawa, EuroBrake 2022, EB2022-MFM-001

World's First Industrial Standard


JASO
2020
Passenger cars- Measurement method for brake wear particle emissions
JASO C 470 : 2020

*1 Ref. :Kasai, *J. Jpn. Soc. Atmos. Environ.*, 2017, 52, A91–A96. (In Japanese); https://doi.org/10.11298/taiki.52.A91