



Particle Emissions From Brake and Tyre Wear – Results from the Phase 1 study for the UK DfT

Jon Andersson, Louisa Kramer, Michael Campbell, Ian Marshall, John Norris, Simon de Vries, Gary Waite and Jason Southgate (Ricardo), Arup AECOM consortium, UK Department for Transport (DfT)

AGENDA

Introduction to non-exhaust emissions

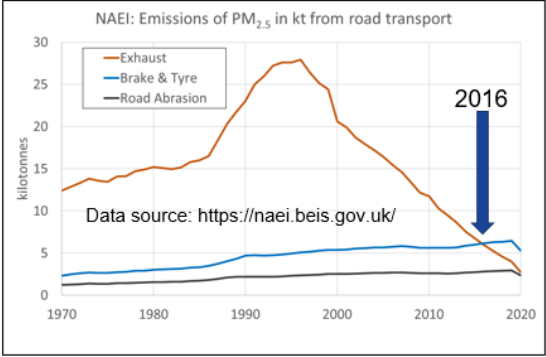
Measurement of Brake and Tyre Wear

System design and testing

Results

Conclusions

Non Exhaust Emissions (NEE)



Brake Wear
Friction between the brake disc and brake pads occur when the brake pedal is pressed – releasing particles.

~~Tailpipe emissions, gases / particulates~~

Road surface wear
Friction between the tyre tread and road surface

Re-suspension of road dust

Tyre Wear
Friction between the tyre tread and road surface releases particles from the tyres.

International work on regulation

- UNECE is developing internationally recognised test procedures to measure brake and tyre particles
- Measuring specific properties of **tyre and road** wear particles is technically very complex
 - UNECE has adopted two methods for measuring *tyre abrasion* in early 2024, including an 8000 km convoy method
- Work on measuring **brake** wear is more advanced
 - UN regulation on test procedure, GTR 24, (co-sponsored by UK DfT) introduced
 - Limits on car (M1/N1) brake emissions within Euro 7, from brake dynamometer testing, at 7 mg/km
 - Proposal for this limit to drop to 3 mg/km in 2035



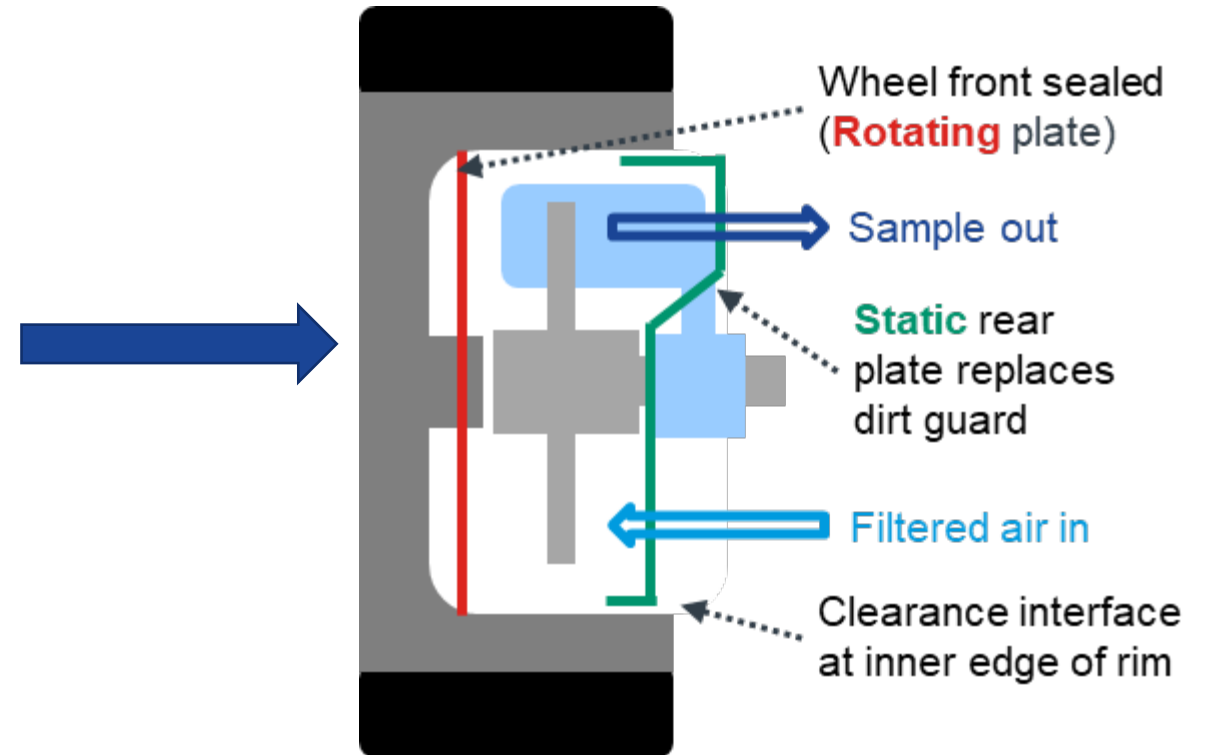
Measurement of Brake and Tyre Wear

- Ricardo has supported the Department for Transport in the UK to develop an effective system and methodology for measuring and characterising particles emitted from brake and tyre wear under **real driving** conditions **(Phase 1)**
- **Primary aim was to develop emissions factors**
- In developing the system there was a need to consider:
 - A common sampling system and measurement equipment which can be used for both brake and tyre wear
 - Representative sample collection of particles from brake or tyre wear
 - Repeatable and reproducible measurements
 - Careful consideration of background particles (i.e., re-suspension of road dust, tailpipe emissions)
 - Power and spatial demands of the system



System Design Example – Brake Wear Sampling

Front face of the
brake enclosure



3 enclosure approaches used – to explore application to different braking system types



System Design – Tyre Wear Sampling



Tyre sample duct fitted behind wheel



Sample duct with support bracket and safety wire



Sample duct at max left steering lock



Wheel removed showing mounting of tyre sample duct, and rear of brake enclosure

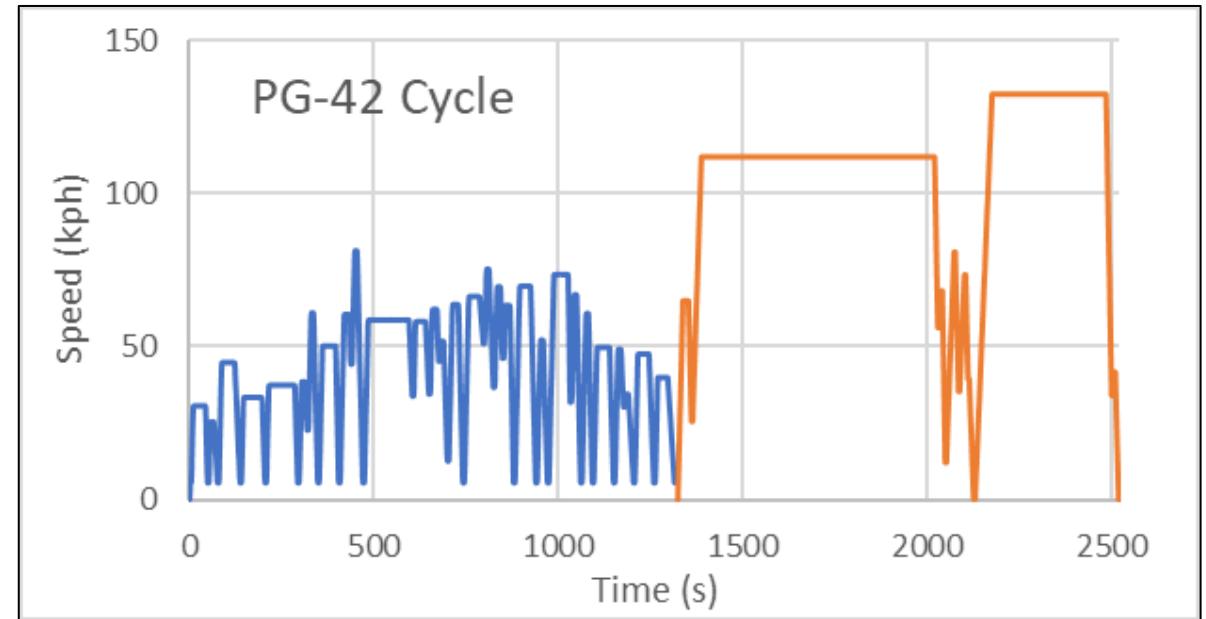
- Open duct to draw sample from behind the tyre-road contact patch into the measurement system
- Inlet fabricated to be slightly wider than the tyre, just above the road and angled to keep sufficient entry velocity for the sample flow and allow large material to drop out
- Duct inlet area and flow designed for isokinetic PM10 sampling
- The duct was mounted to a bracket which in turn was fixed to the rear of the wheel hub carrier, so that the duct position is fixed relative to the wheel and swings with the wheel as it steers
- Sample probes for monitoring background ambient particulates were fitted to the front of the vehicle



Test Plan and Drive Cycles

Tests	Details
Background sampling	Sampling background emissions from different inlets
Chassis Dyno	PG-42 cycles - sampling from brake and tyres
On-road/Track	Urban driving; track braking events of different magnitudes

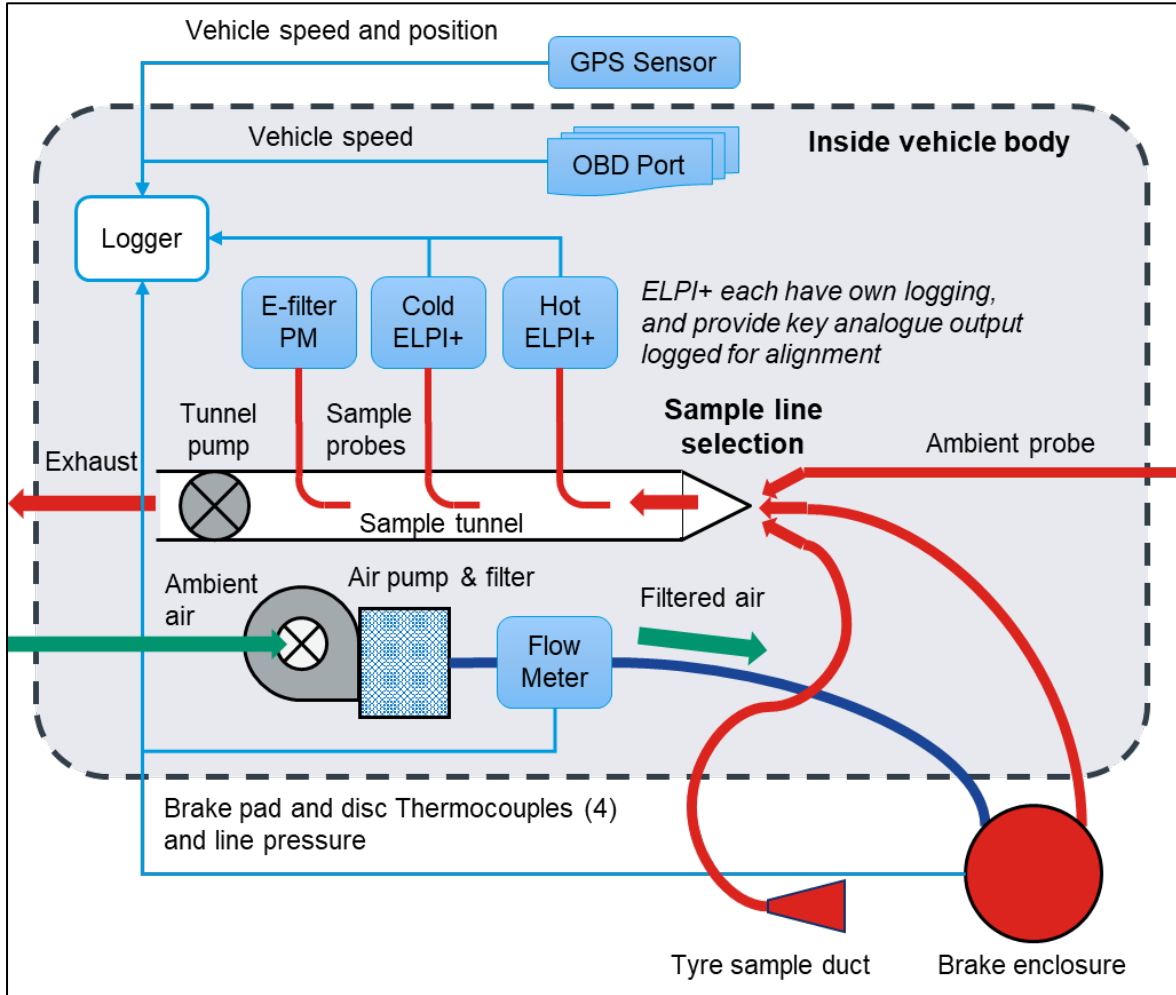
- Repeated measurements were undertaken for all tests
- Results shown from instrumented **front** brake and front tyre from the same wheel



PG-42: 42 minutes cycle based on high particle emitting sections of two well-known braking cycles: Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and Los Angeles City Traffic (LACT) cycle



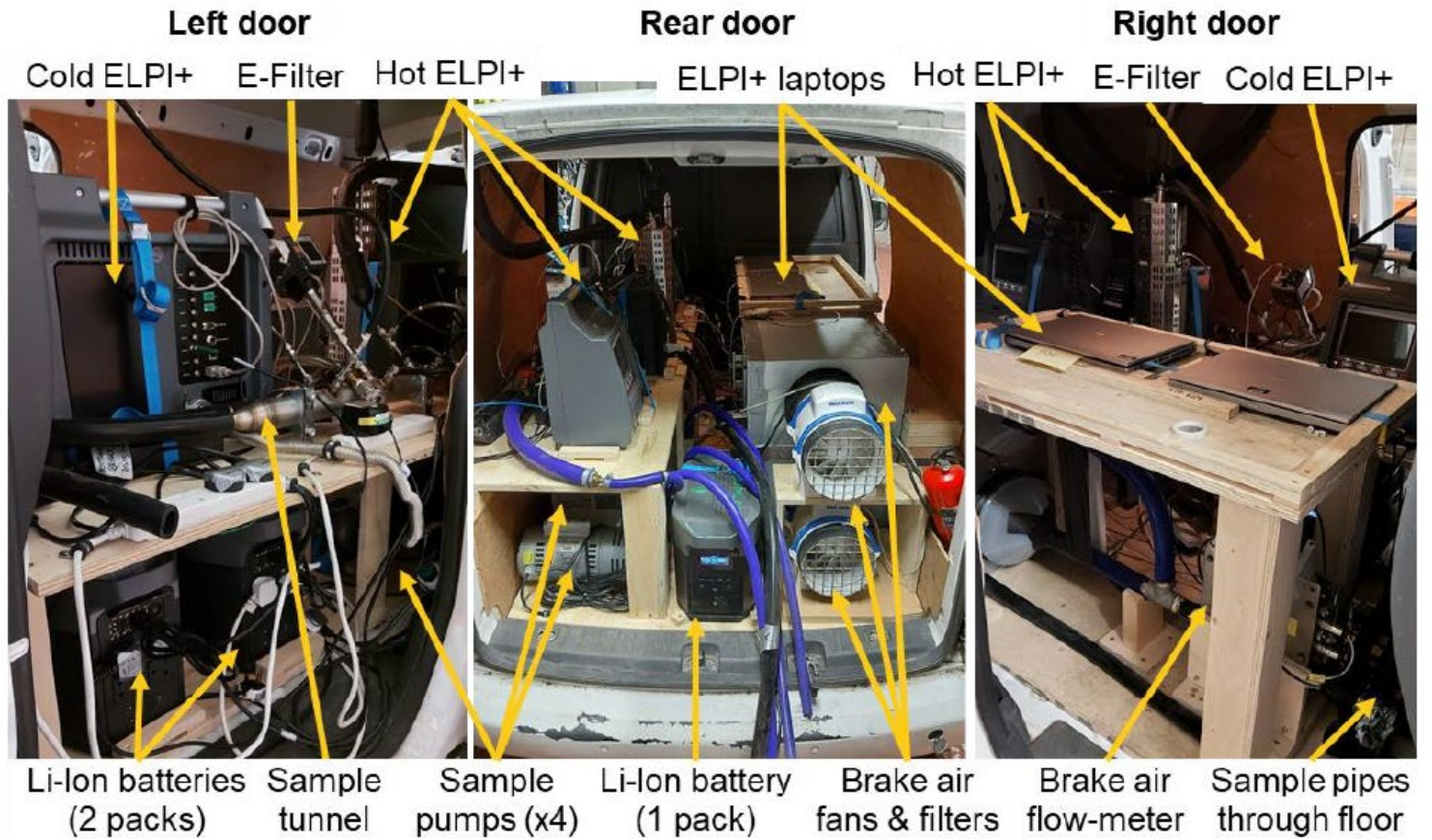
System Design – Instrumentation



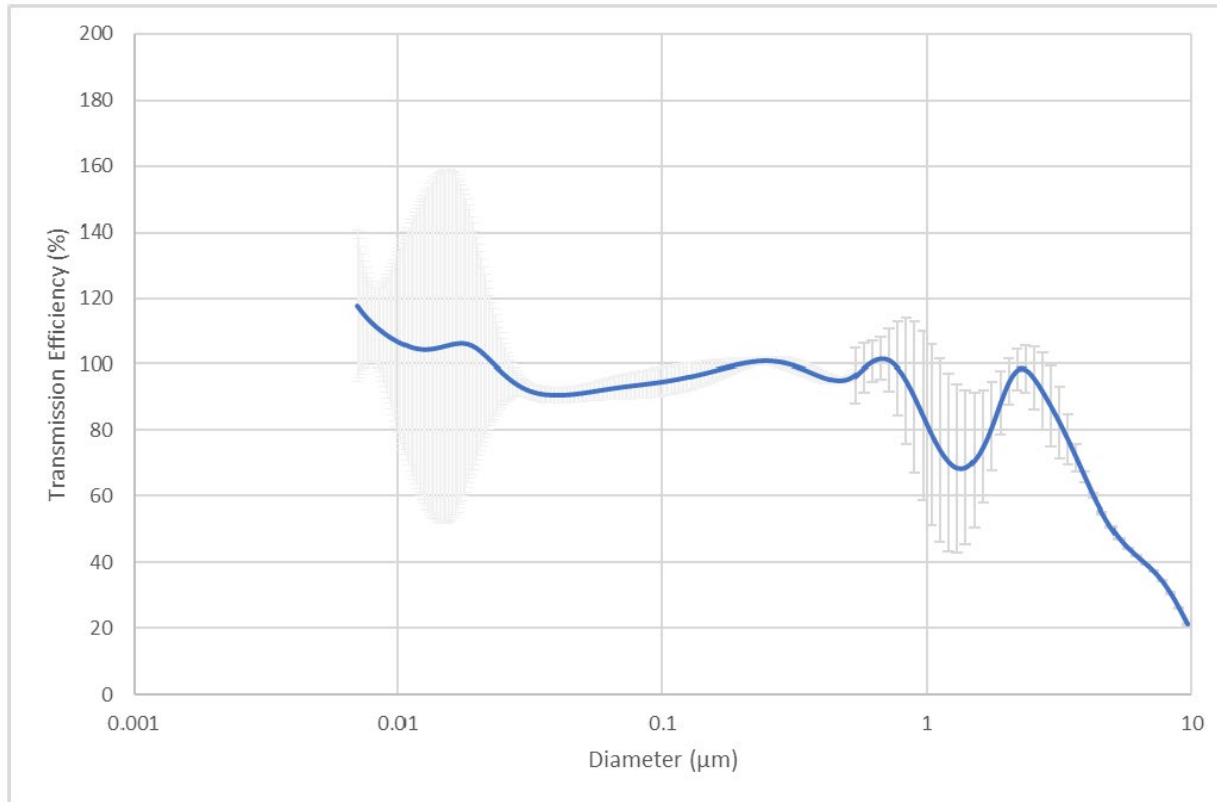
Sample analysis included:

- Combination of two Dekati® Electrical Low Pressure Impactors (ELPI+) for real-time particle size distribution and concentration (size range 6 nm – 10 µm)
 - “Cold” ELPI+ measures solid and volatile particles
 - “Hot” ELPI+ includes a 180°C heated inlet to remove the volatile component of the PM
- Dekati® eFilter for real-time PM mass concentration measurements – also includes a filter for reference gravimetric determination and analysis
- Horiba SPCS PN23 system (raw) used in parallel from tunnel for lab tests (non-volatile PN23)
- Entire system was installed to a small light duty van
- Measurements from driver’s side front wheel

VW Caddy vehicle



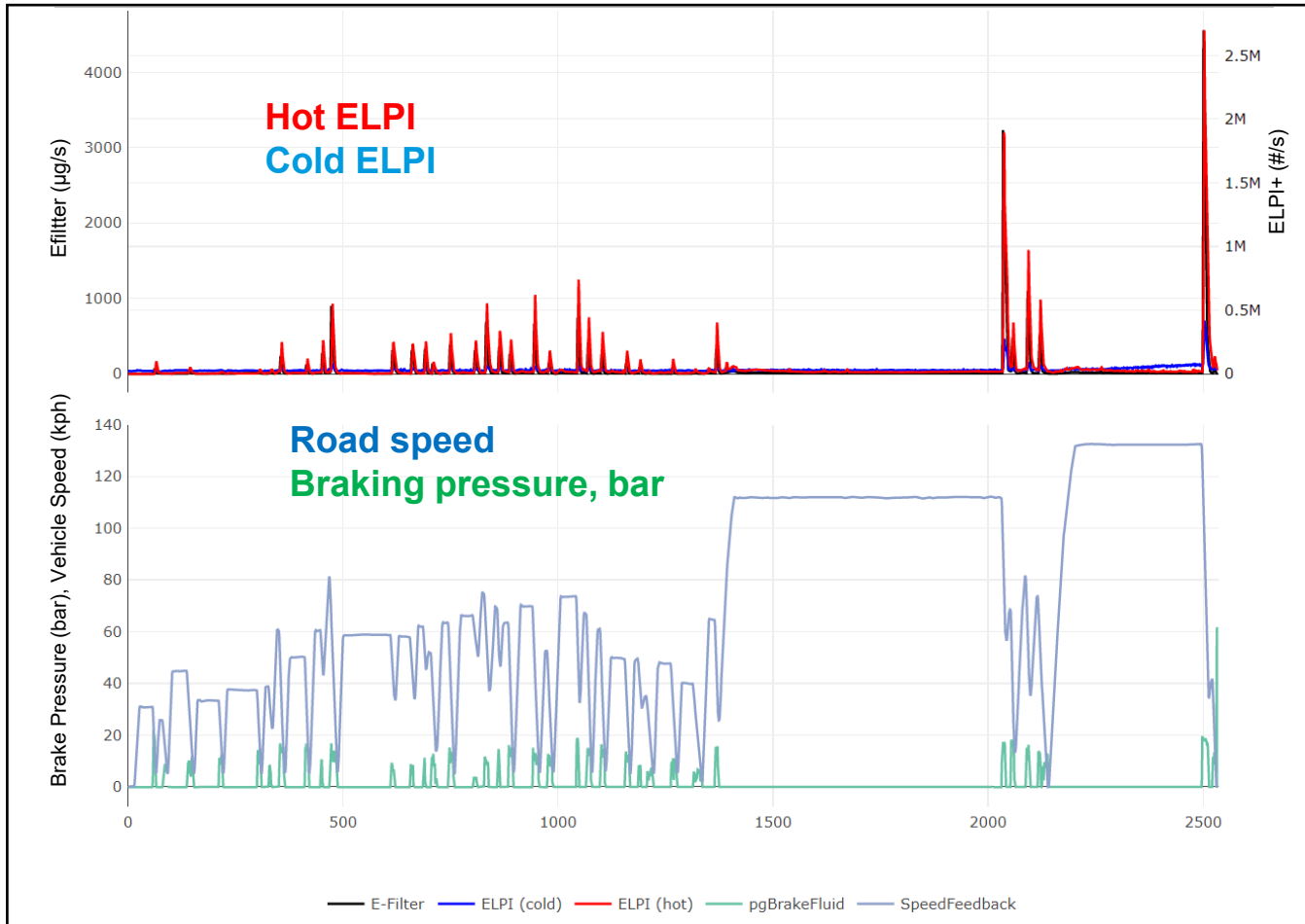
Particle penetration through sampling system



- Penetration close to 100% for particles up to $\sim 3\mu\text{m}$
 - Hence under-sampling of larger particles, which will have impacted PM_{10} determination by eFilter and gravimetry
- $\text{PM}_{2.5}$ quantification likely to be more representative, and a more realistic objective for on-board sampling

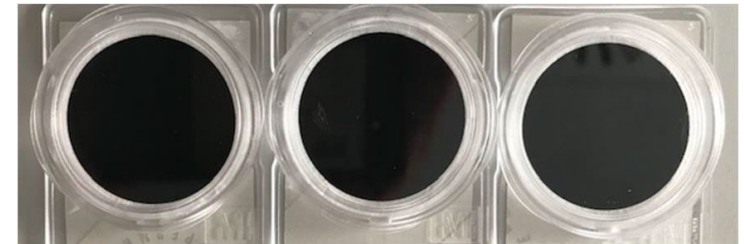


Real time brake emissions – Chassis Dynamometer



- Particle number and particle mass emissions from the hot ELPI and eFilter coincided with increased braking pressure events on the chassis dynamometer
- Emissions from the cold ELPI were coincident, but more challenging to resolve
- Hot ELPI/SPCS emissions $\sim 5 \times 10^9$ #/km/brake, PG-42 CoV - 4% SPCS and 40% hot ELPI
- PM filter emissions ~ 1.6 mg/km/brake

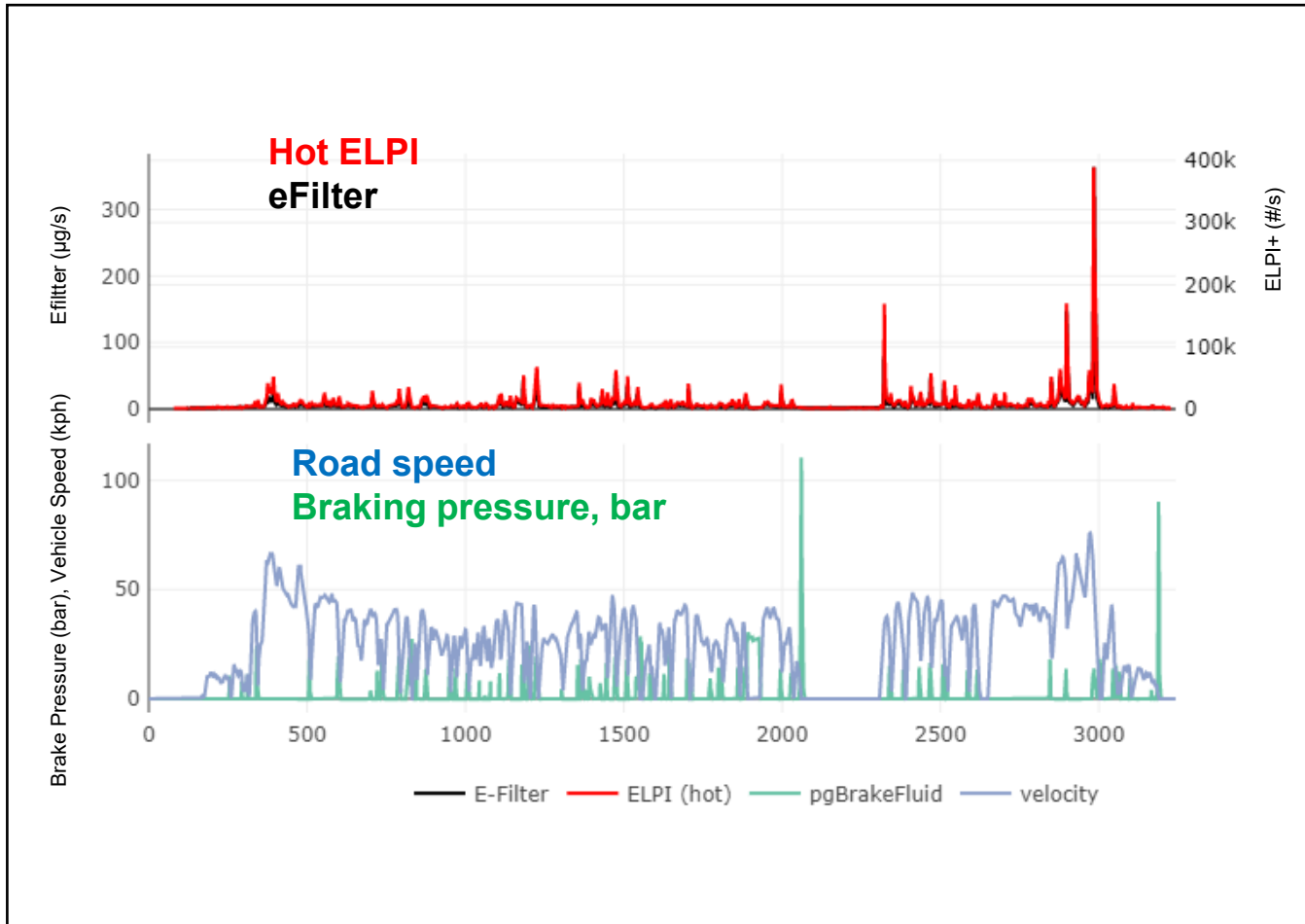
3 repeat PM filters from PG-42 brake testing



Thermogravimetric analysis of filters indicated $\sim 95\%$ non-volatile and non-oxidizable material



Real time brake emissions – Urban Road

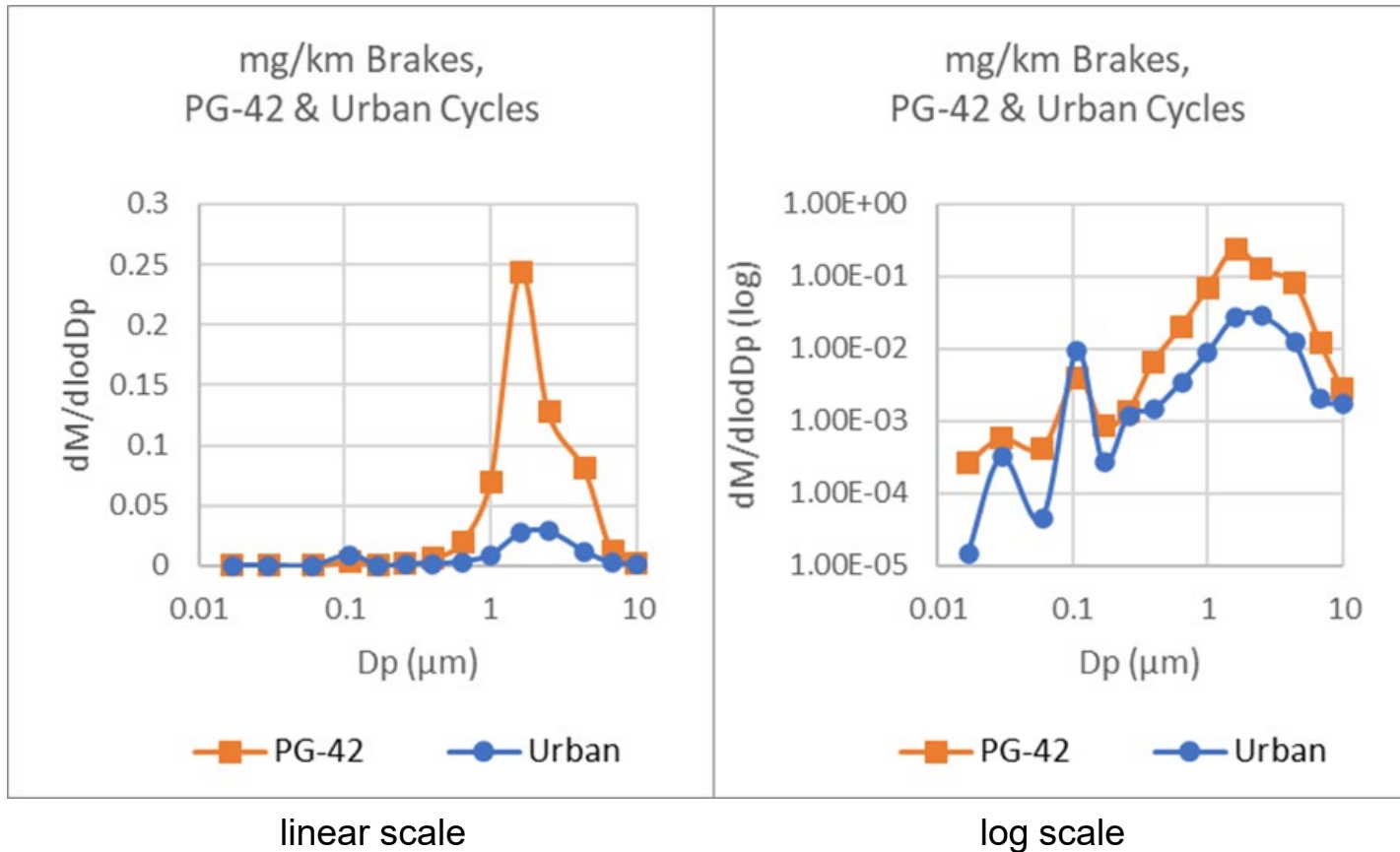


- Braking events on the urban road are representative of real-world driving
- Particle number and particle mass emissions events reported from braking overlay from the hot ELPI and eFilter
- Similar to the chassis dyno tests - emissions from the cold ELPI were more challenging to attribute to specific braking events
- Hot ELPI emissions $2 \text{ to } 5 \times 10^9 \text{ \#/km/brake}$
- PM filter emissions $\sim 0.9 \text{ mg/km/brake}$



Real time brake emissions – particle mass size distributions

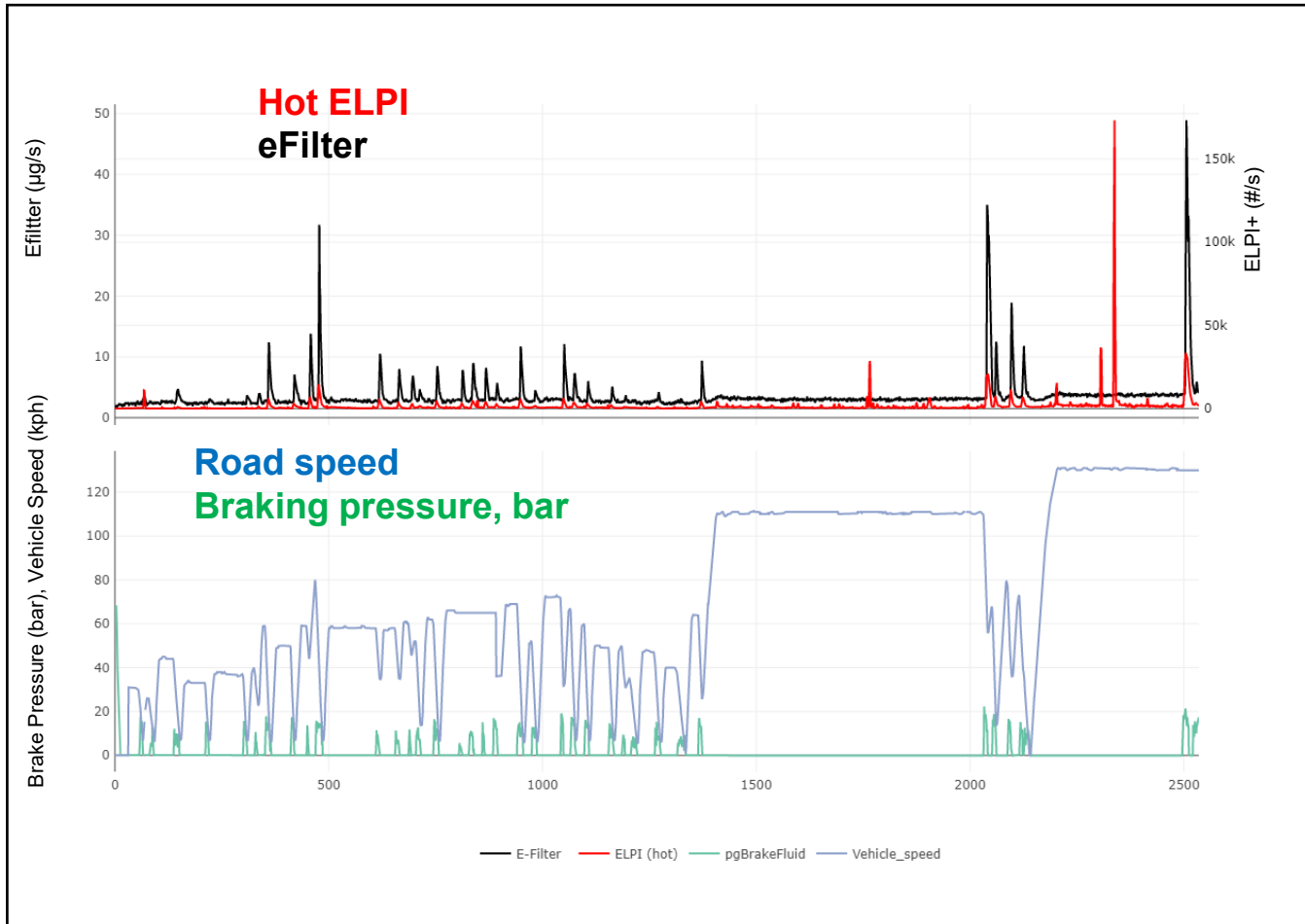
Mass Weighted Particle Size Distributions, Cold ELPI



- Mass weighted particle size distributions from the PG-42 and urban drives are generally similar
 - mass greater from more aggressive PG-42
- Two modes observed: a minor mode at $\sim 100nm$ ($0.1\mu m$) and a dominant mode at $\sim 1.6\mu m$
- The $>1\mu m$ mode is likely to be mechanically generated wear materials primarily released from the brake pad



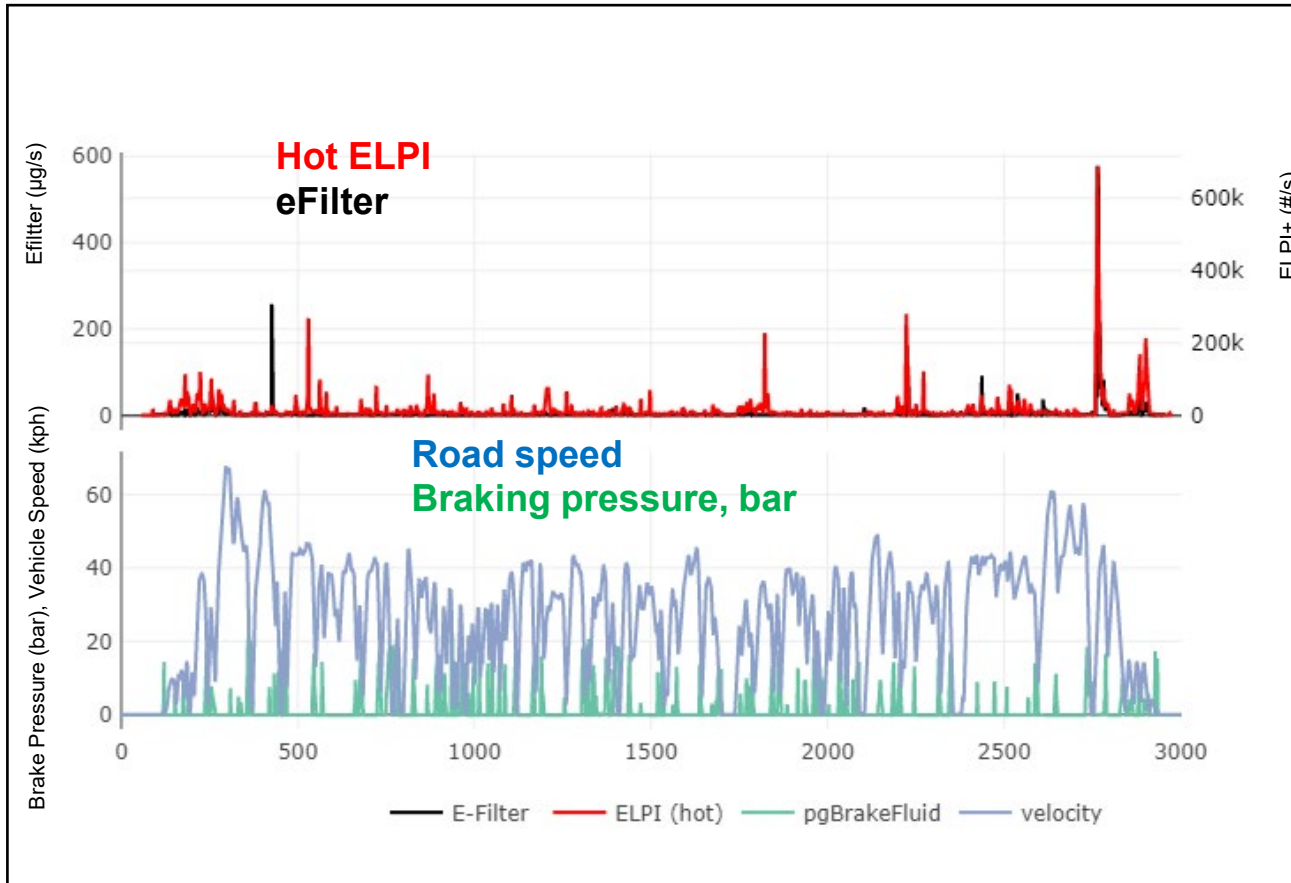
Real time tyre emissions – Chassis Dynamometer



- Spikes of particle number emissions were observed from the ELPIs, both during braking events but also during accelerations and cruises
 - Indicating particles maybe be lost following, as well as during, braking events
- eFilter mass emissions appear to be closely related to the braking events
 - Most mass is lost immediately on braking
- Masses measured were more than an order of magnitude lower for tyre emissions than for the brake emissions
 - The efficiency of the tyre scoop is uncertain, and is to be explored in further work



Real time tyre emissions – Urban Road

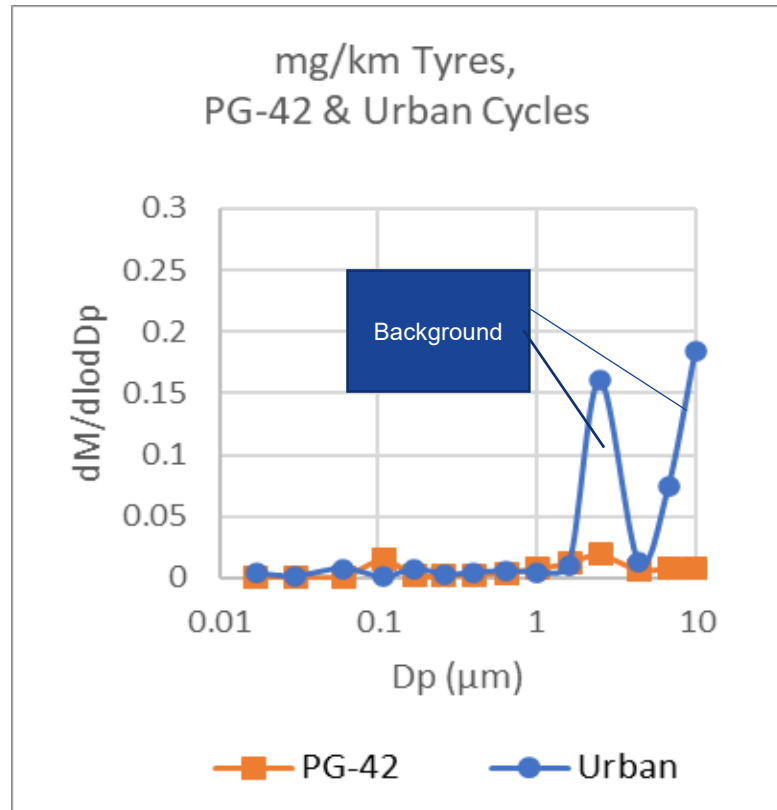


- Some urban braking events coincide with an emissions peak, however, not all do
- Peaks of both mass and number can also be observed that are not related to instantaneous braking events
- Emissions of both mass and number were higher on the urban road, compared to the chassis dyno, despite less severe braking events
 - Substantial contribution from source(s) other than tyre emissions during braking

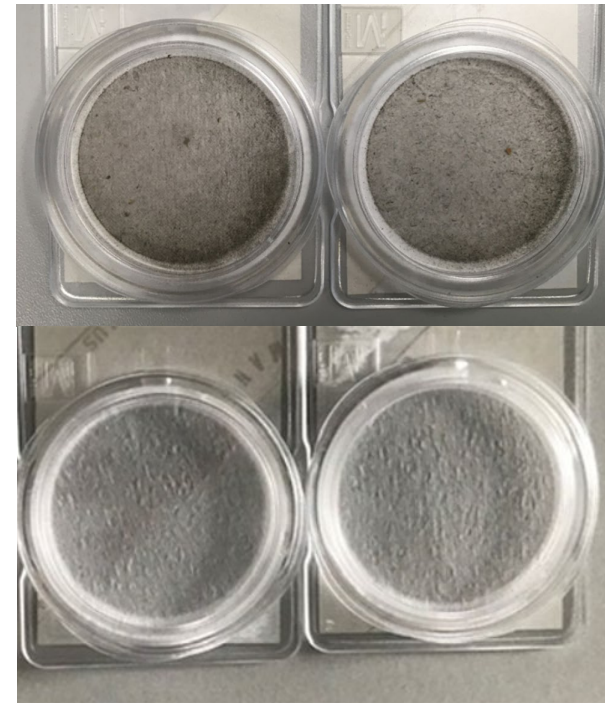


Real time tyre emissions – particle mass size distributions

Mass Weighted Particle Size Distributions, Cold ELPI



- Chassis dyno PG-42 emissions show much lower masses than from urban, despite the increased braking severity
 - Urban background contribution very high from $>1\mu\text{m}$ materials



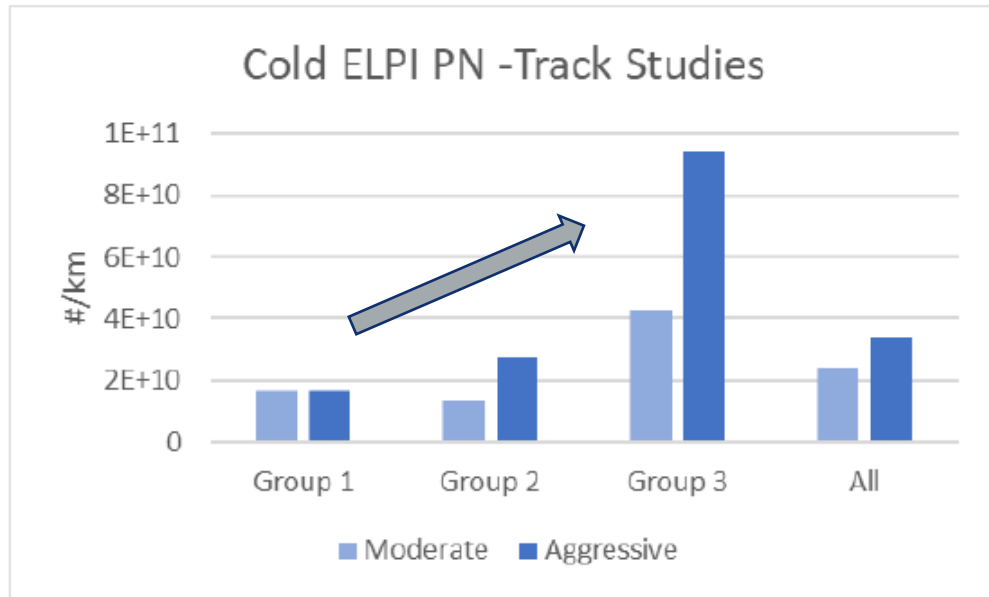
Urban testing PM filters are dirty & contaminated with discrete large particulates

Chassis Dyno filters show uniform PM material



Real time tyre emissions – Test Track

Data from three consecutive repeat sets of braking from 80kph down to 16kph, grouped and the integrated particle number for the cold ELPI calculated for each group



Integrated particle numbers from moderate and aggressive tyre emissions tests

- Higher PN is measured by the cold ELPI as the aggressive braking tests proceed, than from the moderate braking tests
 - As the tyres heated up from repeated braking, an 'out-gassing' of volatile particles was observed
 - (The effect is also present with the hot ELPI, though less apparent, which suggests that many of these particles are volatile below ~200°C)
- Background contributions could be very significant to both mass and number
 - and were highly variable day to day



Summary

- An on-road system for measuring brake and tyre wear was developed and installed to a small light duty van
- Testing was successfully undertaken in a chassis dynamometer facility; on a nearby test-track; and on-road in an urban environment
- Brakes: Real-time non/low volatility particle number emissions corresponded to real-time braking events, with emissions around $2 - 5 \times 10^9 \#/\text{km}/\text{brake}$, lowest emissions were seen at lowest speeds
- Brakes: Real-time particle mass emissions responses also aligned with braking events, and mass emissions ($\sim \text{PM}_{2.5}$) were around $1 \text{ mg}/\text{brake}/\text{km}$
- Tyres: Non-volatile PN, and PM, emissions can be related to individual braking events on the chassis dynamometer, but not easily on the track or road
- Tyres: Exact quantification of $\text{PM}_{2.5}$ and PN emissions is dependent on the sampling duct efficiency, which is currently unknown. This is to be investigated. Without correction, measured levels were lower than brakes on a per km basis
- Tyres: Repeated aggressive braking events appear to lead to outgassing of volatile particles from tyres, many of these particles are eliminated by the hot ELPI, heated to 200°C

Phase 2 work – just completed

- Focused on PN10 (using PN-PEMS type devices), both total and non-volatile particles and PM2.5
- Continued with real-time mass and a filter-based approach to enable chemical analysis and visualisation of the PM materials collected
- Optimised sampling system, e.g., for power consumption, size, flow rate ...
- New sample duct for sampling measurements for tyre wear – chassis dyno measurements only
- Comparative emissions measurements of tyre types, brake types etc
 - Specific influences on brake particle emissions on chassis dyno, test track and road
 - E.g., disc and pad compositions, driving dynamics ...
 - Specific influences on tyre particle emissions on chassis dyno
 - E.g., tyre compositions, tyre sizes ...
 - Evaluated impacts of regenerative braking, test mass and emission-reducing technologies

Report of Phase 1 available here: <https://www.gov.uk/government/publications/measurement-of-emissions-from-brake-and-tyre-wear>
Open access paper: [A Practical Approach for On-Road Measurements of Brake Wear Particles from a Light-Duty Vehicle](#)
Phase 2 reporting in process