PARTICULATE EMISSIONS FROM LDVs USED FOR SHORT TRIPS – THE IMPACT OF THE COLD START EFFECT

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There are now more light-duty vehicles on the roads than there were people on Earth two hundred years ago. All internal combustion engines emit solid pollutants in their exhaust gas (i.e. particulate matter), to varying degrees. Even if each individual light-duty vehicle is a relatively modest source of particulates, the sheer number of vehicles (and the impact of some high emitters) multiply up the emissions massively to very high levels. In fact, for 2004, almost a million tonnes of particulate matter were estimated to have been emitted from the exhausts of the global light duty vehicle fleet [1], very roughly equivalent to emissions of 1 kg/vehicle/year.

Concern over particulate matter emissions remains high, and the introduction of strict particle number and mass emissions limits and the roll-out of DPFs has not been enough to close the topic. There is also considerable technical and political concern over real-world emissions and their relation to the values obtained during legislative testing in the laboratory.

Legislative cycles used for measuring emissions from light-duty vehicles cover distances on the order of 10^1 km, but the emissions impact of performing a much shorter journey (sometimes on the order of 10^0 km, and possibly even as low as 10^{-1} km) is greater than would be suggested by the distance travelled. This is due to the cold start effect, where low temperatures, high friction, and fuel injection phenomena can conspire to increase particulate matter emissions (among others). The particulate matter emissions associated with just starting the engine can be equivalent to many kilometres of fully warmed-up driving (see e.g. [2]). A reasonable proportion of particulate matter is emitted when the vehicle is almost stationary (or moving very slowly) – the appropriateness of units of [mass (or number) / kilometre] is somewhat debatable, as journeys covering very different distances could have quite similar total emissions of particulate matter. If a vehicle is never used, its in-use particulate emissions are zero. From a non-technical viewpoint, it's reasonable to assume that since no distance=no emissions, very short trips=very low emissions. However, this is generally not the case, due to the cold start effect. In contrast to some other vehicle types, passenger cars are often used for a relatively high number of short journeys, magnifying the impact of the cold start effect.

A series of experiments were performed on various vehicles on a chassis dynamometer in a climate-controlled test facility [3,4] to measure particulate mass (PM) and particle number (PN). The results of these experiments were made the subject of various analyses to determine the fraction of the total emissions resulting from early stages of the driving cycle. The impact of 'abandoning' the test cycle part way through and the influence that not completing the rest of the cycle would have had was investigated to simulate short trips (albeit under laboratory conditions). A simple 'distance value' was used for analysis , defined as the proportion of the total emissions that would be expected based on the proportion of the cycle covered (e.g. if half the total distance of the cycle is performed, the distance value is the total emissions divided by two, and so on.) Simple linearity analyses were also performed by comparing cumulative PN emissions with cumulative distance covered.

Cold start emissions, quantified by both particle mass and number, were found to be significant (see Figures 1-3). Performing a short urban journey will, in some cases, emit almost as much particulate matter as performing a short urban journey plus a longer extra-urban journey, although the effect is highly variable. With a few exceptions, the test vehicles were found to emit more PM and PN over short urban journeys (~1 to ~4 km) than would be predicted from the distance covered. The strength of this effect was found to increase somewhat with decreasing ambient temperature (Figure 2). The repeatability of the effect was variable (high for some vehicles; low for others) and the correlation between relative PM and relative PN emissions was rather variable in many cases. The presence of absence of a DPF changed behaviour for Diesel vehicles, as did ambient temperature (Figures 4 & 5).

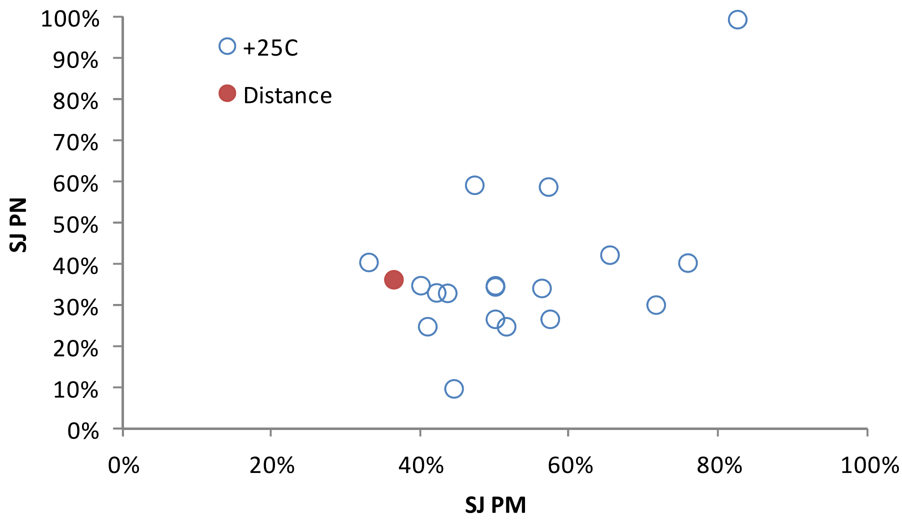

Figure 1. A distance-based short journey analysis performed on PM and PN emissions from 18 Euro 5 Diesel vehicles for the first phase of the NEDC

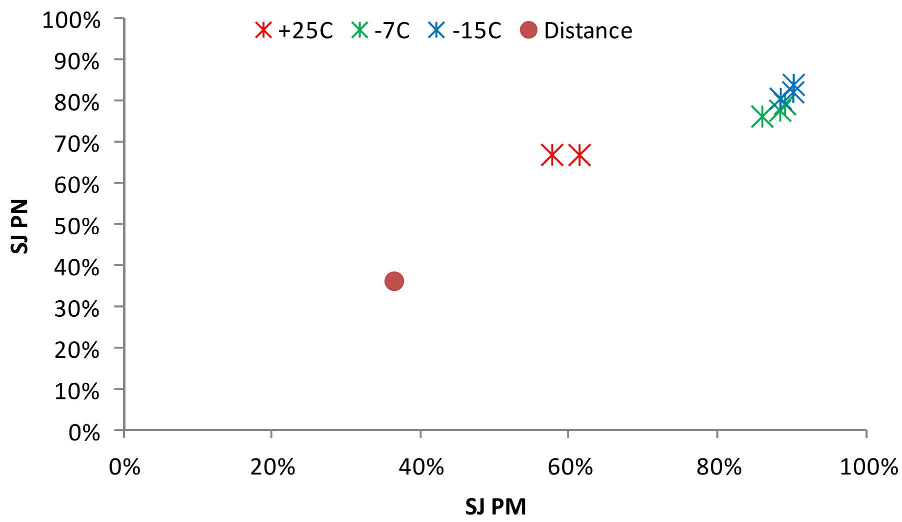

Figure 2. A distance-based short journey analysis performed on PM and PN emissions from a direct injection petrol vehicle tested at three ambient temperatures for the first phase of the NEDC

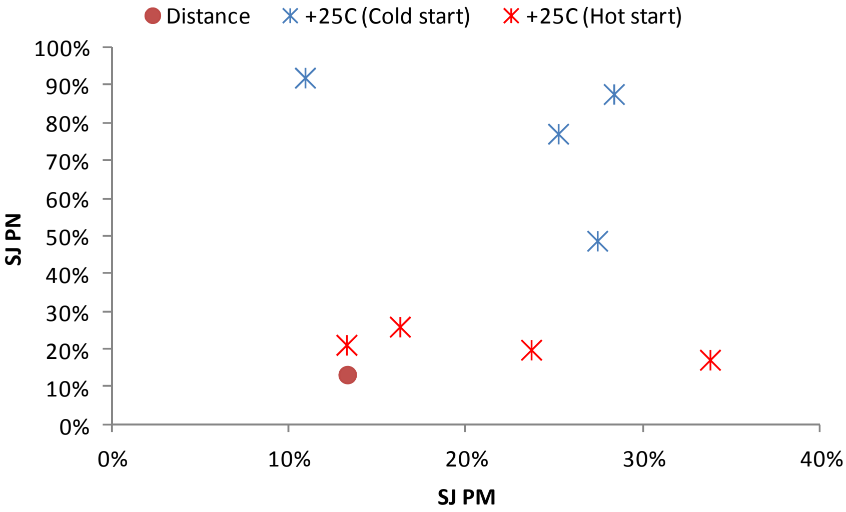

Figure 3. A distance-based short journey analysis performed on PM and PN emissions from a direct injection petrol vehicle tested at two thermal startup conditions for the first phase of the WLTC (note the maximum values of the scales)

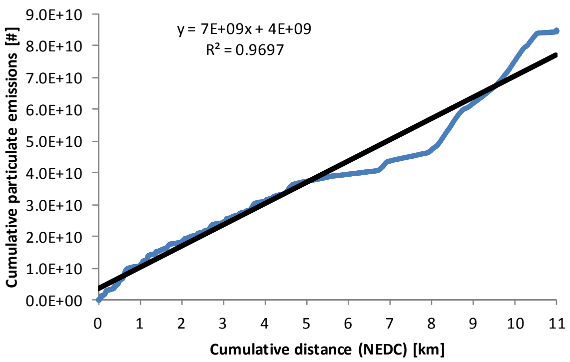

Figure 4. Cumulative PN emissions as a function of cumulative distance covered during the NEDC for a Diesel vehicle with DPF, tested at 25°C

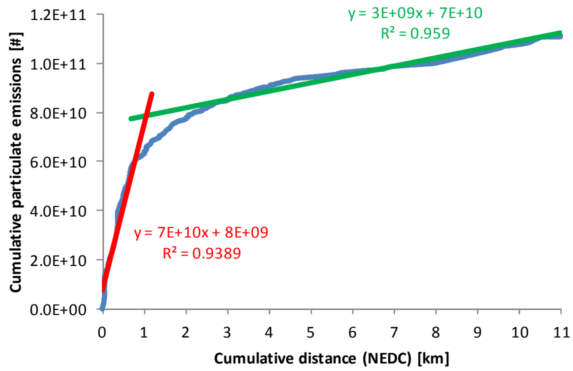

Figure 5. Cumulative PN emissions as a function of cumulative distance covered during the NEDC for a Diesel vehicle with DPF, tested at -7°C

Potentially interesting and important topics for future research include further investigations into the following areas: the impact of ambient temperature; DPF/GPF accumulation studies; rigorous characterisation of various engine/fuel types; further testing over the WLTC, American test cycles and real-world cycle; on-board measuring approaches; and the impact of vehicle mileage on emissions behaviour in this area. The possibility that radical alternatives to distance-based emissions limits could be appropriate should be considered from theoretical, legal and practical points of view.

References:

[1] Wallington, T.J, et al., Emissions of CO_2, CO, NO_x, HC, PM, HFC-134a, N_2O and CH_4 from the global light duty vehicle fleet, Meteorologische Zeitschrift, Vol.17, No. 2, 109-116 (April 2008), 2008, DOI: 10.1127/0941-2948/2008/0275.

[2] Weilennmann, M., et al., Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories, Atmospheric Environment, 43, 2419-2429, 2009, DOI: 10.1016/j.atmosenv.2009.02.005.

[3] Bielaczyc, P., Szczotka, A. and Woodburn, J., Development of vehicle exhaust emission testing methods – BOSMAL's new emission testing laboratory, Combustion Engines, ISSN: 0138-0346, 1/2011 (144), 3-12, 2011, bit.ly/19kvVl3.

[4] Bielaczyc, P., Pajdowski, P., Szczotka, A. and Woodburn, J., Development of automotive emissions testing equipment and test methods in response to legislative, technical and commercial requirements, Combustion Engines, ISSN: 0138-0346, 1/2013 (152), 28-41, 2013, bit.ly/11EcDCd.

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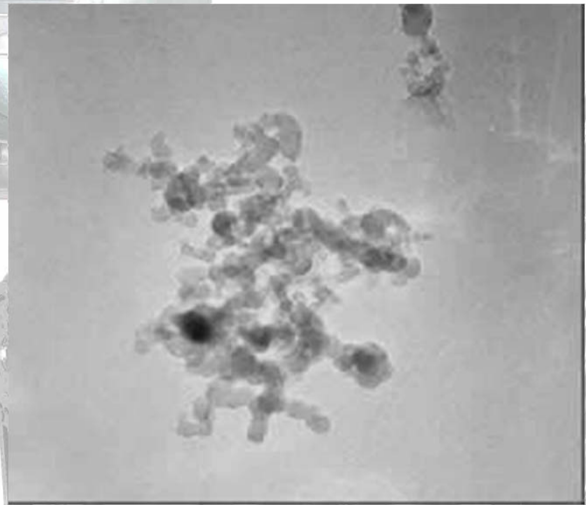
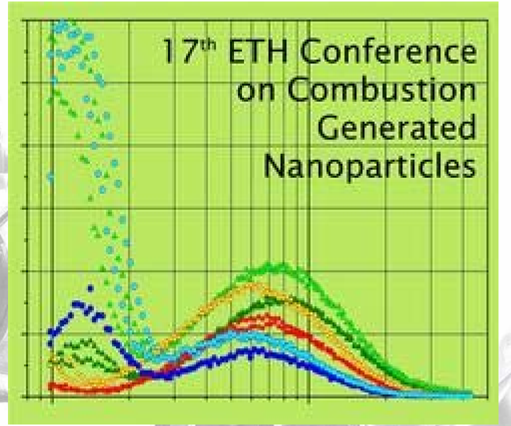
23rd – 26th June 2013, Zurich, Switzerland





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Particulate Emissions from LDVs used for Short Trips – the Impact of the Cold Start Effect

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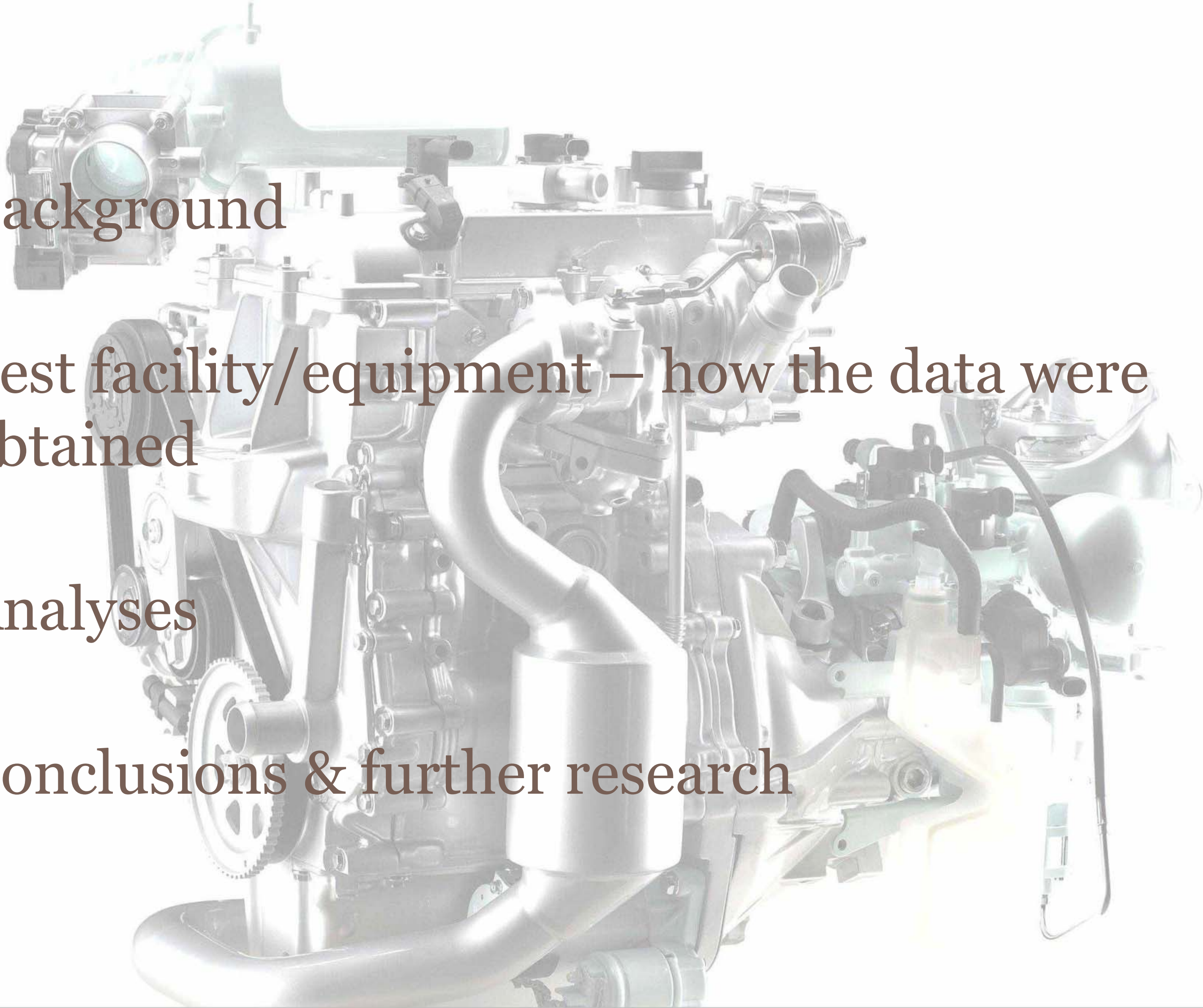
Presentation contents



- Background
- Test facility/equipment – how the data were obtained
- Analyses
- Conclusions & further research

Cars and global particulate matter emissions

There are now more light-duty vehicles on the roads than there were people on Earth two hundred years ago

Even if each individual vehicle is a relatively modest source of particulates, the sheer number of vehicles (and the impact of some very high emitters) multiply up the emissions massively

If each light-duty vehicle in the world is used on average twice a day, six days a week, that's over 600 billion trips a year in total

In 2004, almost a million tonnes of particulate matter were estimated to have been emitted from the exhausts of the global light duty vehicle fleet (Wallington et al., 2008, DOI: 10.1127/0941-2948/2008/0275)

≈ 1 kg/vehicle/year (*very roughly*)

Why emission limits in [quantity/distance]?

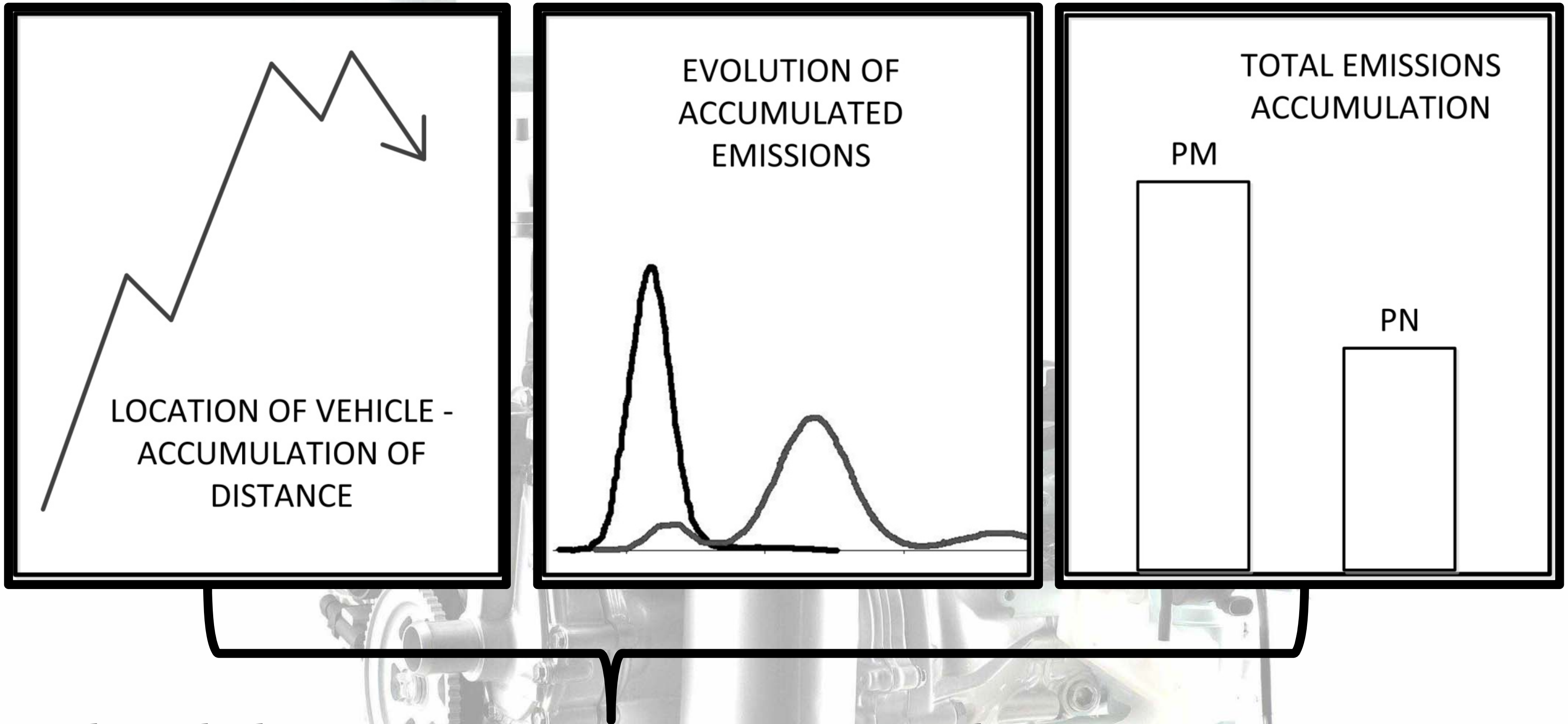
From <u>the driver's/passenger's</u> point of view, the main useful thing a car does is cover distance

From <u>a legislator's</u> point of view, the benefit of a car is that it enables people (voters!) to cover distance; the cost is that it emits. An attempt is made to balance these two aspects by setting limits in units of [mass/distance] (and now [number/distance])

From <u>the environment's</u> point of view, the only thing a car does is emit. It is of no real direct consequence to the environment how far the vehicle travels; the impact is determined by the total emissions (per day…per year…per life-cycle).

If a vehicle is never used, its in use emissions are zero. From a non-technical viewpoint, it's reasonable to assume that since no distance≈no emissions, very short trips≈very low emissions. However, this is generally not the case for multiple pollutant types (both gaseous and solid). Low ambient temperature generally magnifies these effects considerably.

‘Legislative emissions’ & ‘total emissions’



Legislators look at: **total emissions/total distance**, but…
…the environment suffers: **total emissions** (• particle characteristics)
…human health suffers: **total emissions** • particle characteristics *(size, mobility, toxicity)*

The impact of test cycle distance (1)

There are practical limits to defining 'emissions' as mass (& number) / distance

• if an engine is started, but no distance is covered, then the 'emissions' are ∞

• if an engine is used to drive a very long distance, 'emissions' can begin to approach zero, due to much lower hot running emissions

Between zero and infinity, the distance covered can strongly affect emissions per distance. Short trips and long trips are very different, and test cycles lie imbetween.

10^{-1} km 10^{0} km 10^{1}km 10^{2} km … 10^{3} km

(very) short trip test cycle long trip… …range on full tank

The impact of test cycle distance (2)

"…emissions appear to almost independent of drive cycle: per km emissions are only elevated from drive cycles that divide by small distances."
-- Particle Measurement Programme (PMP) Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report (bit.ly/1bQGxoG)

If emissions are strongly related to the start-up event, then total emissions are in fact divided by an arbitrary amount (around 11 for the NEDC; around 23 for the WLTC cl. 3)

Obviously, identical emissions per distance can be obtained from very different total emissions divided by different distances

$$\frac{10}{1} = \frac{100}{10}$$

Furthermore, under real-world driving conditions, a reasonable proportion of solid pollutant emissions are emitted when the vehicle is stationary or barely moving – are 'per distance' units appropriate at all?

Particulate emissions per start: literature

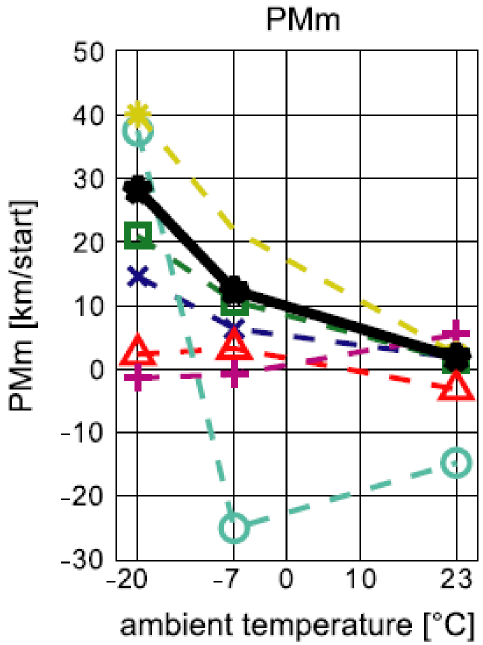
Vehicle	Temperature (°C)	Particle mass ($g\,start^{-1}$)	Particle number ($cm^{-3}\,start^{-1}$)
		Filter (CVS)	CPC without TD
PISI 1	23	0.02	3.8×10^{13}
	−7	0.24	1.5×10^{14}
	−20	0.61	3.1×10^{14}
PISI 2	23	0.01	8.4×10^{13}
	−7	0.07	2.0×10^{14}
	−20	0.06	5.2×10^{14}
CI	23	*−0.01*	1.3×10^{14}
	−7	0.27	6.7×10^{14}
	−20	1.02	6.2×10^{14}
CI-DPF	23	—	4.4×10^{12}
	−7	—	3.2×10^{12}
	−20	0.01	3.7×10^{12}
DISI	23	0.07	1.4×10^{14}
	−7	0.39	3.7×10^{14}
	−20	1.00	6.1×10^{14}

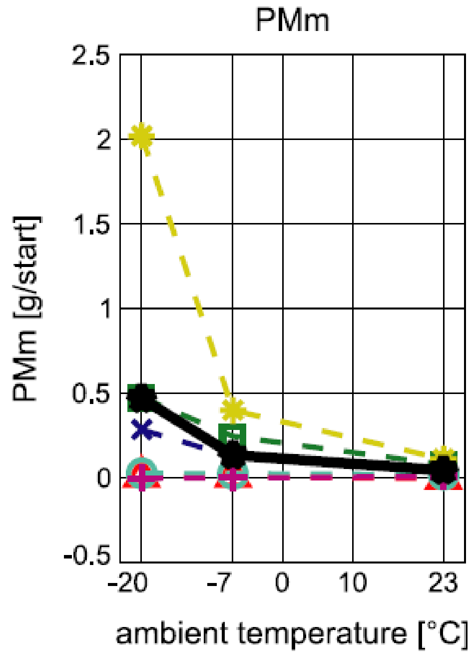
↑ Emissions of up to 1 g/start calculated, with a clear temperature dependency. PN results are high (no thermodenuder); with the temperature trend less clear/evident

Taken from Mathis, Mohr & Forss (2005), DOI: 10.1016/j.atmosenv.2004.09.029 (edited)

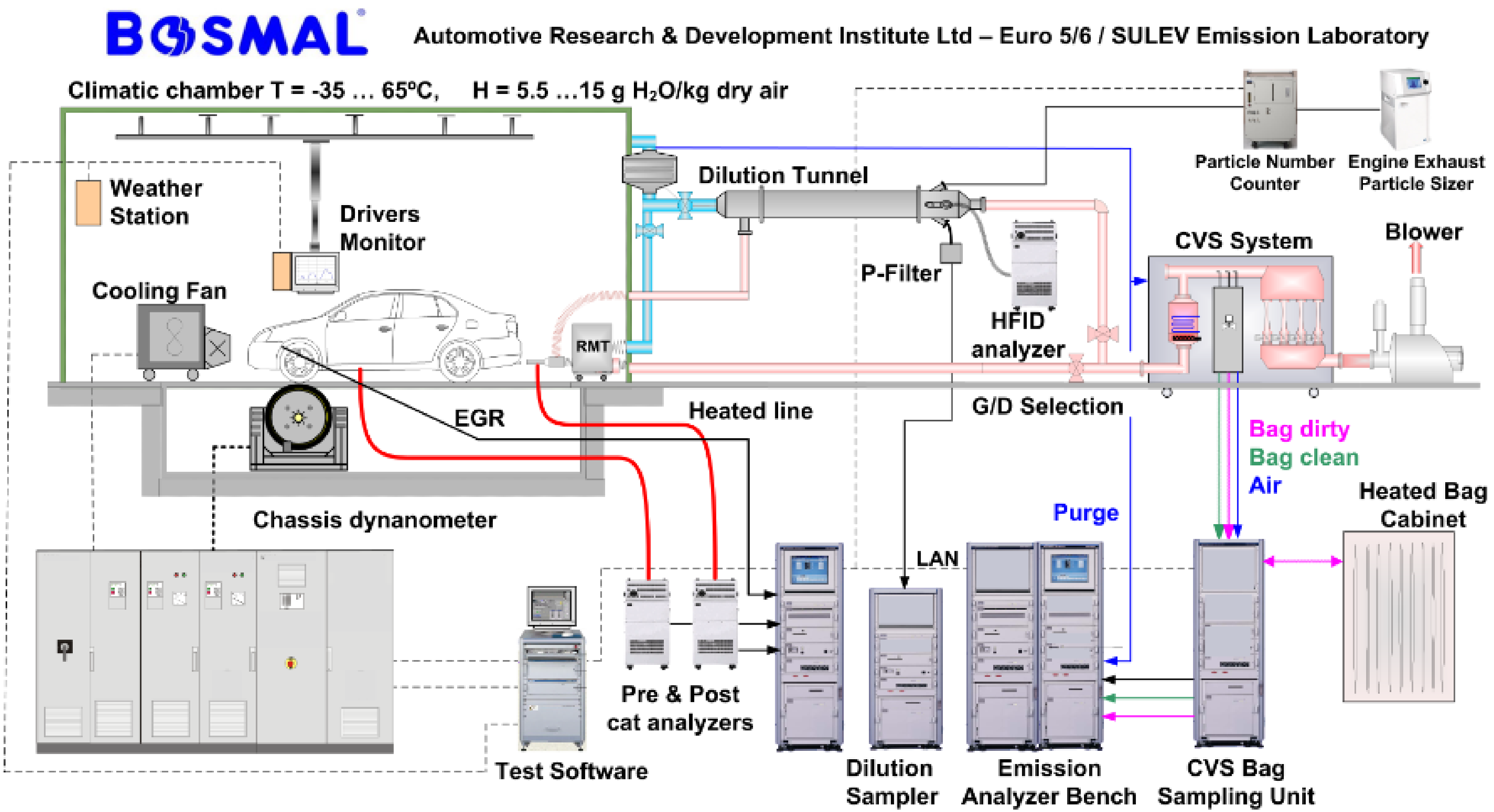
↓ Similar approach with a range of test vehicles, measuring PM. Massive increase in emissions per start as ambient temperature decreases; considerable variation between vehicles. Heavy black line is the average of all test vehicles.

Taken from Weilennman, Favez & Alvarez (2009), DOI: 10.1016/j.atmosenv.2009.02.005





Test facility/equipment (1)



Test facility/equipment (2)

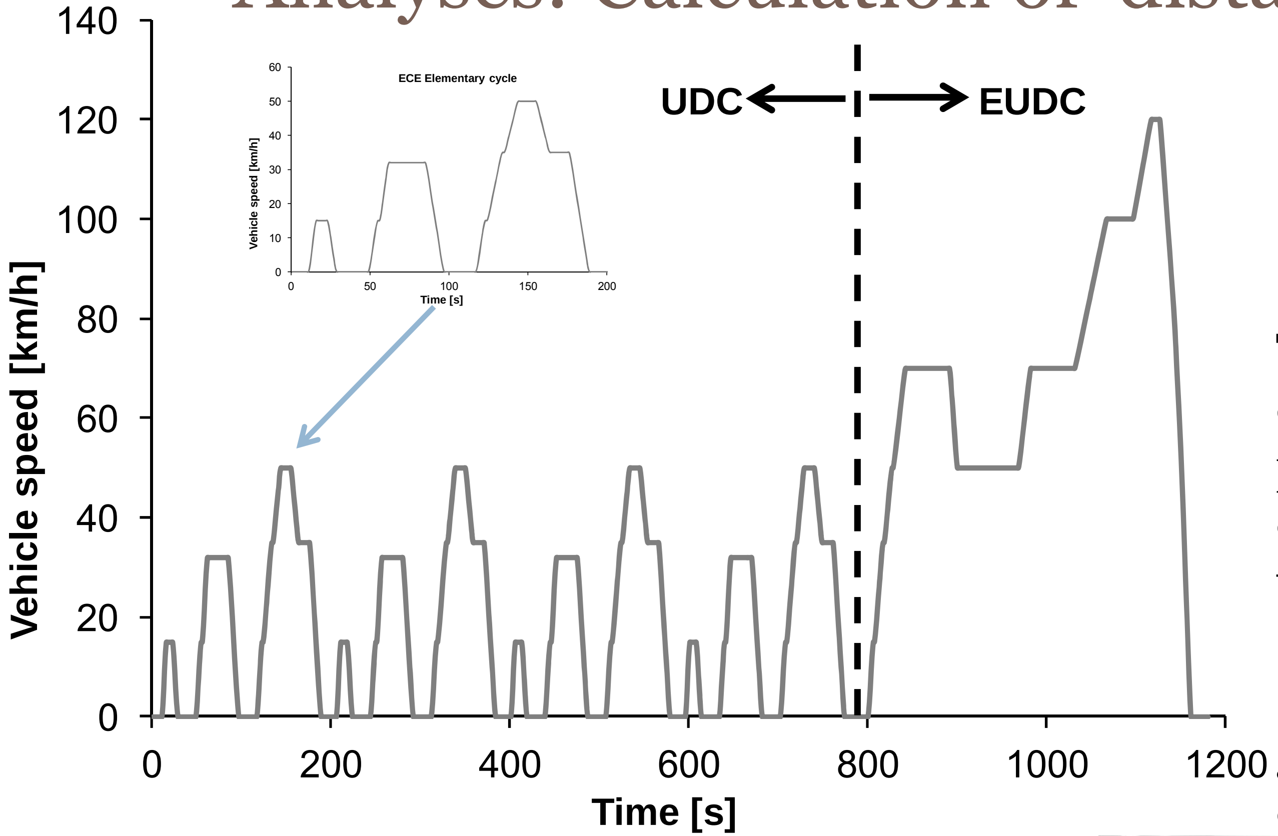
- Euro 6/SULEV emissions laboratory in a climatic chamber
- Equipment in line with UNECE Reg. No. 83

Further details:

Bielaczyc, P., Szczotka, A. and Woodburn, J., Development of vehicle exhaust emission testing methods – BOSMAL's new emission testing laboratory, Combustion Engines, ISSN: 0138-0346, 1/2011 (144), 3-12, 2011, bit.ly/19kvVl3.

Bielaczyc, P., Pajdowski, P., Szczotka, A. and Woodburn, J., Development of automotive emissions testing equipment and test methods in response to legislative, technical and commercial requirements, Combustion Engines, ISSN: 0138-0346, 1/2013 (152), 28-41, 2013, bit.ly/11EcDCd.

Analyses: Calculation of 'distance values'



"What proportion was emitted during the UDC / the first ECE sub-cycle?"

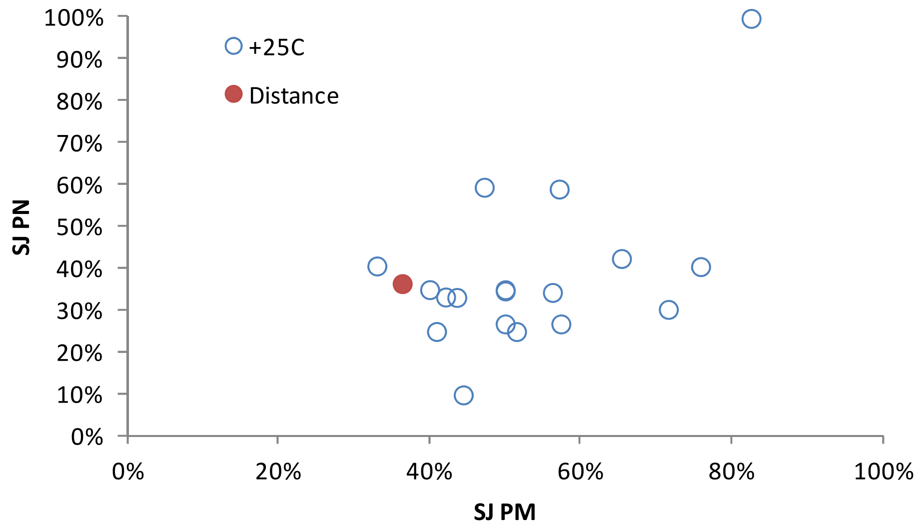
This proportion can be compared with the proportion of the total distance covered; we can call this the 'distance value'

Real emissions can be greater than, smaller than or equal to this 'distance value'

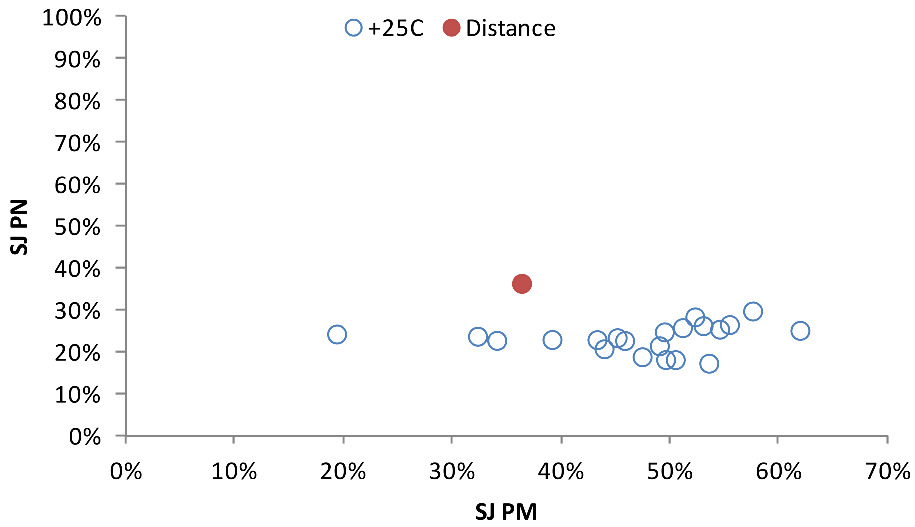
Cycle (phase)	Approx. distance [km]	% of total cycle
NEDC	11	100
UDC	4	36
ECE	1	9

The same approach can be used for analyses of data obtained over other driving cycles

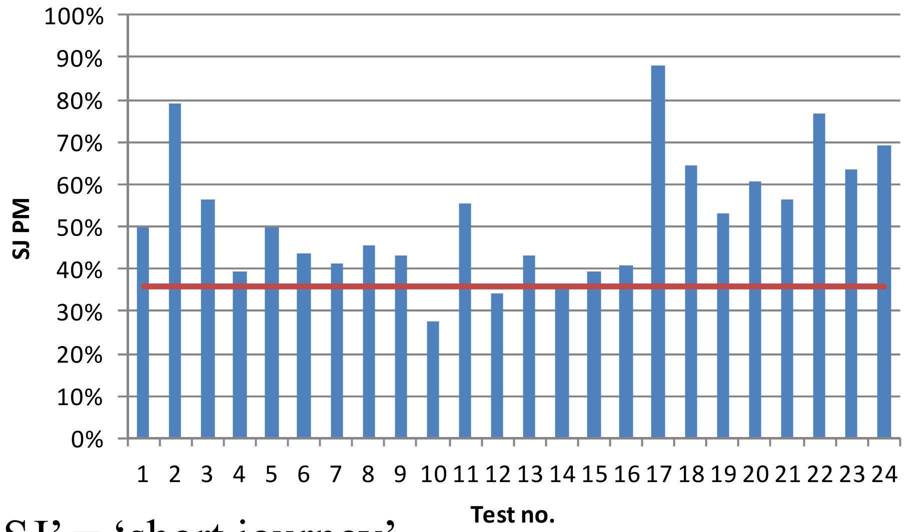
Analyses: Diesel (UDC/NEDC)



↑18 Euro 5 Diesel vehicles with DPF



↑ A single Euro 5 Diesel vehicle with DPF

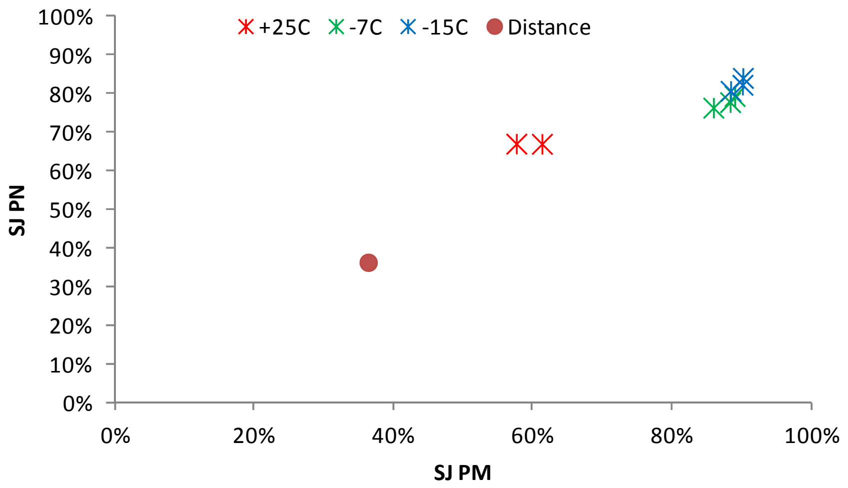


←A single Euro 5 Diesel vehicle with a range of aftertreatment systems installed

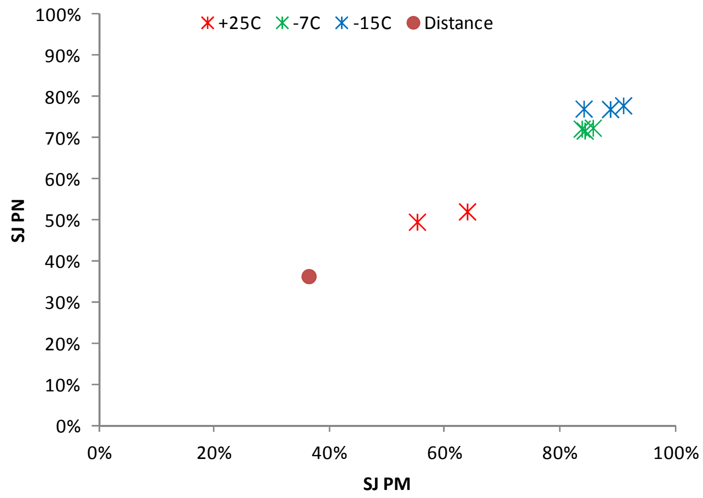
'SJ' = 'short journey'

- Trends a bit variable (DPF type/age?)
- PM and PN often greater than the distance value, repeatability variable
- In certain cases values approach 100%, but can also lie *below* the distance value

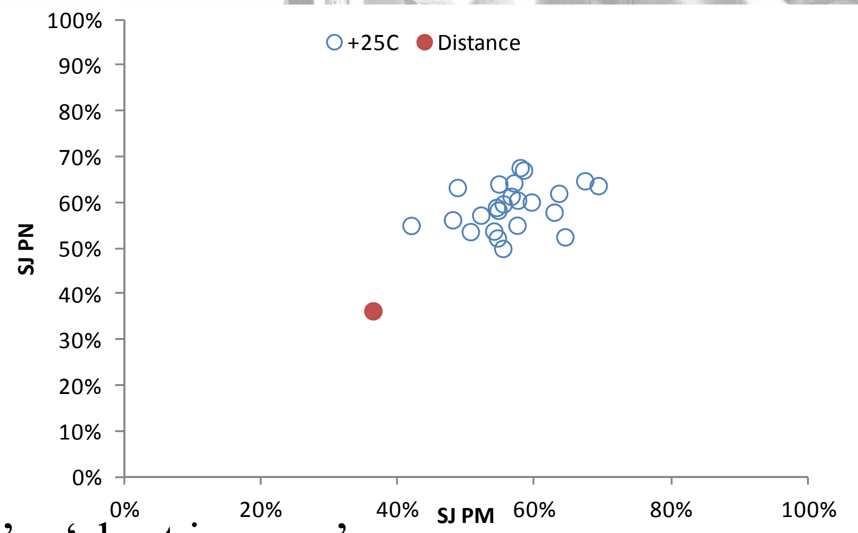
Analyses: Direct injection petrol(UDC/NEDC)



↑A direct injection vehicle (inertia=1360 kg)



↑ A direct injection vehicle (inertia=1700 kg)

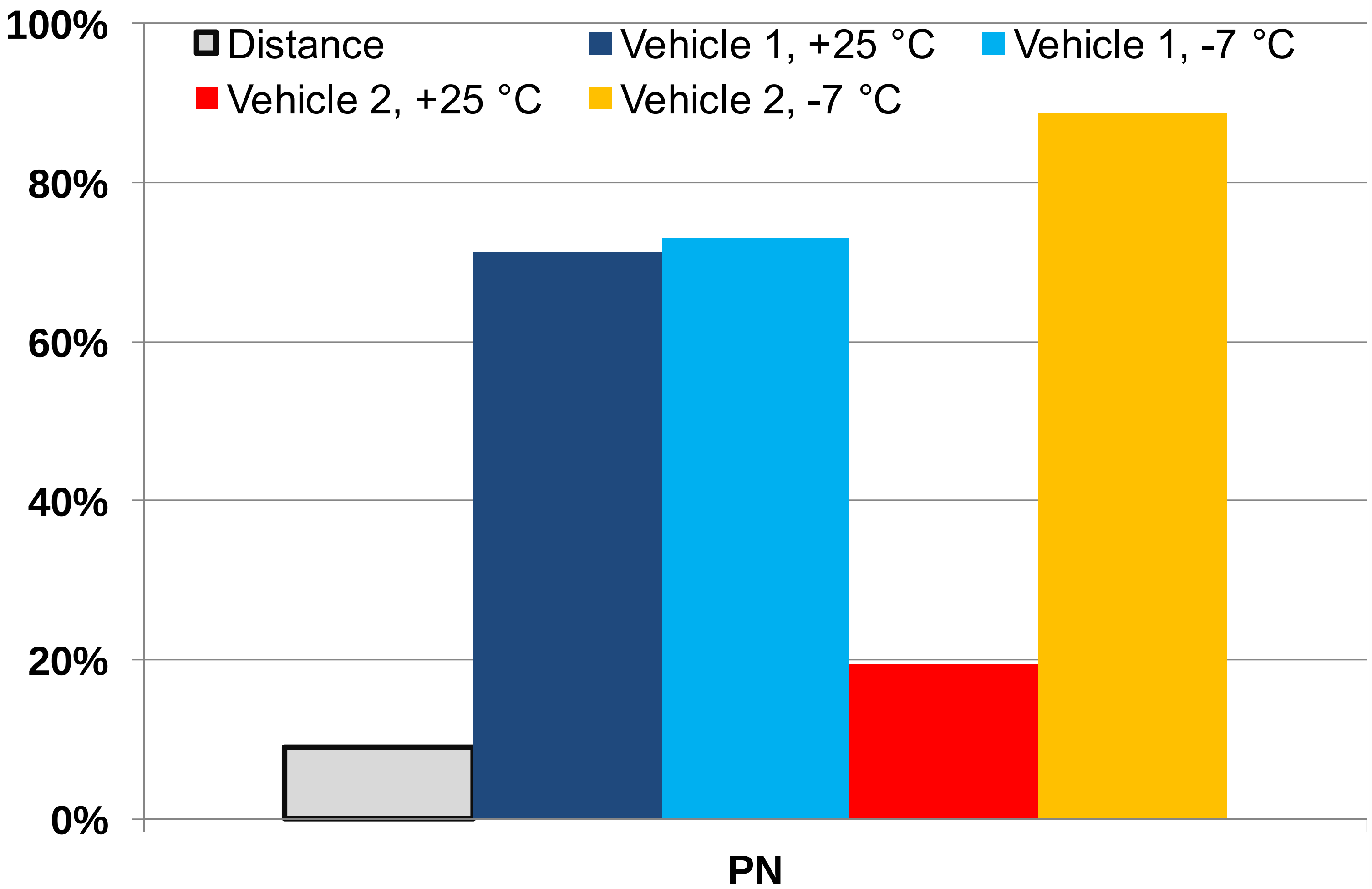


- Much clearer trends than the Diesel vehicles (lack of filter?)
- PM and PN always greater than the distance value, highly repeatable
- Temperature dependent, but -7°C≈-15°C

←24 repeat tests on the same vehicle

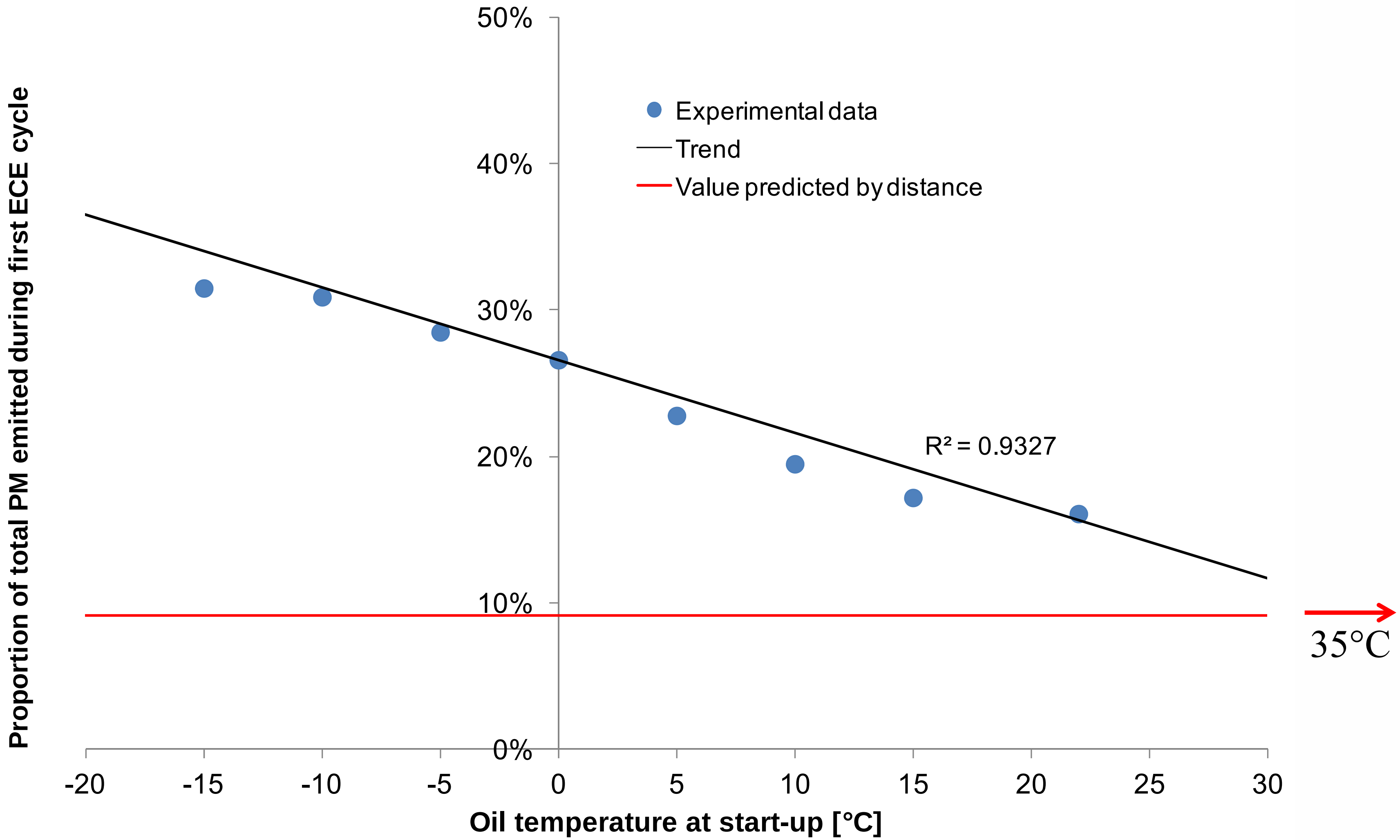
'SJ' = 'short journey'

Analyses: First ECE/NEDC (1)



Two Diesel vehicles, multiple differences (inertia, displacement, aftertreatment) tested at two test temperatures

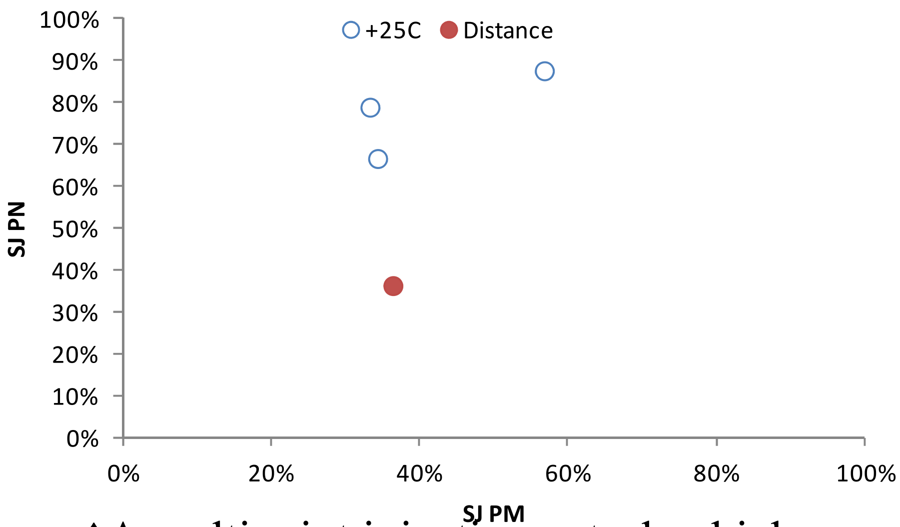
Analyses: First ECE/NEDC (2)



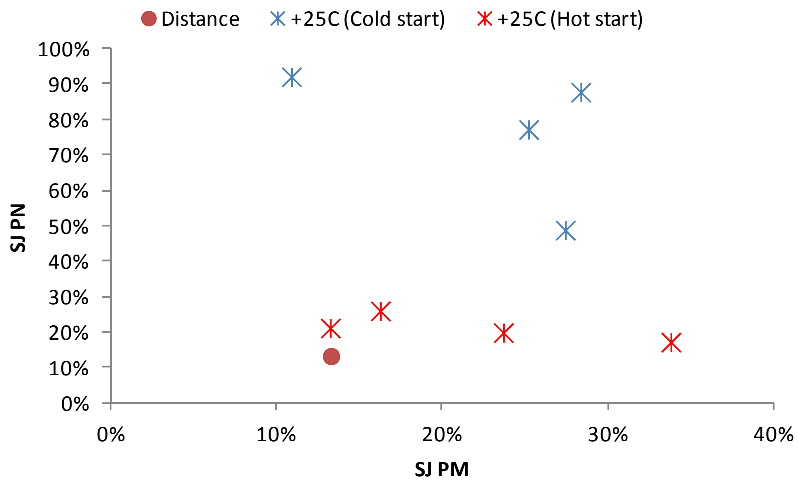
Euro 4 Diesel vehicle (no DPF) started in a range of thermal states

(Data from: Pajdowski, P., PhD thesis, Poznan Technical University, Poznan, Poland, 2006.)

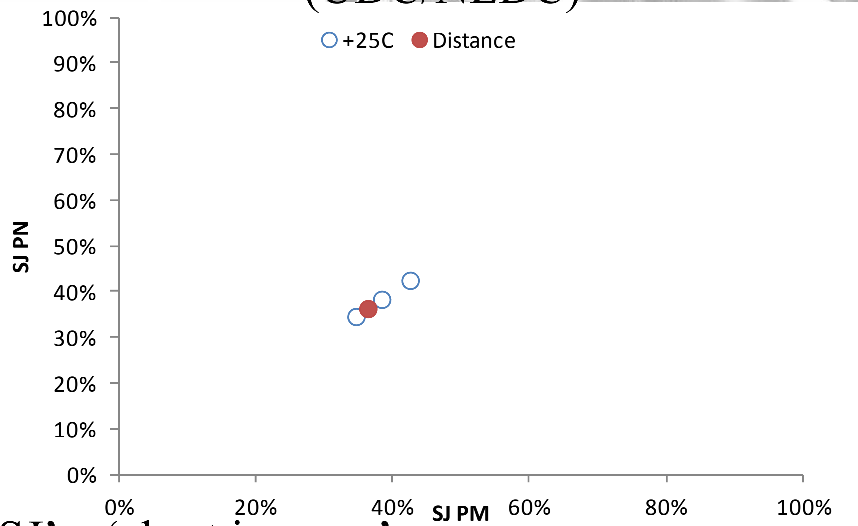
Analyses: Additional tests (NEDC/WLTC)



↑A multipoint injection petrol vehicle (UDC/NEDC)



↑ A Diesel vehicle with DPF running over the WLTC (first phase/entire cycle)

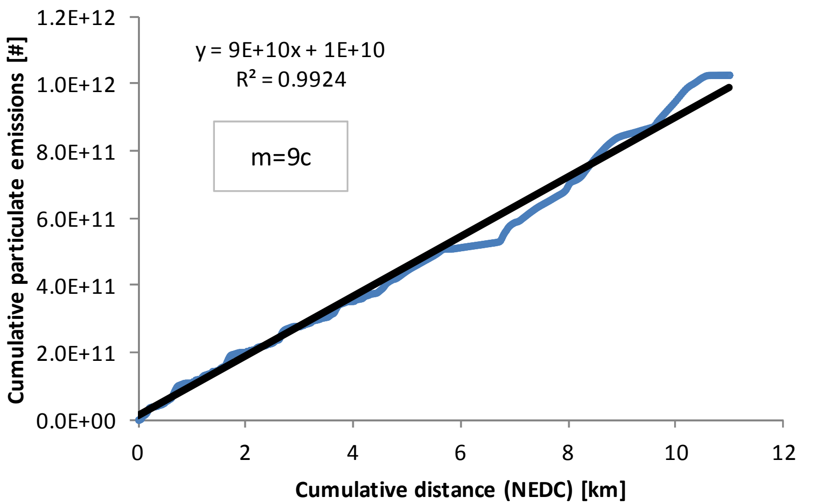


‘SJ’ = ‘short journey’

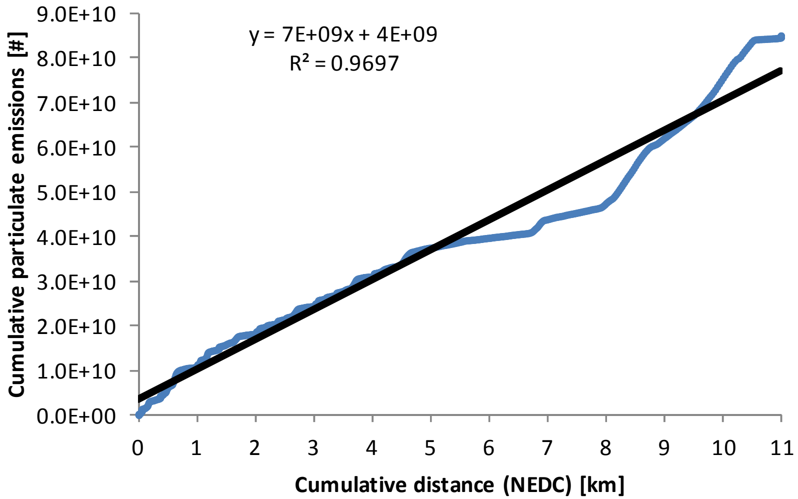
- Broadly similar trend for the petrol vehicle – well above PN distance value
- PM and PN greater than the distance value for the WLTC, more so for cold start
- A commercial vehicle with a much larger engine emitted very close to the distance value

← A light commerical vehicle with DPF (UDC/NEDC)

Analyses: (Non-)Linearity in PN over the NEDC (1)



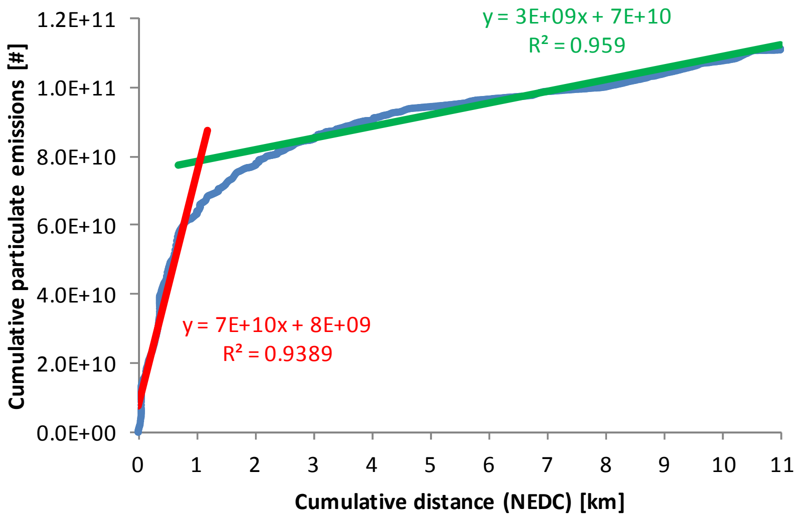
↑ Downsized Diesel with DPF tested at 25°C



↑ A Diesel vehicle with DPF tested at 25°C

- Different mathamatical relationships and magntitudes of intercept (c) and gradient (m)
- Reasonable repeatability, but results from other vehicles (not shown) showed quite different trends
- Testing over a longer driving cycle could be informative (e.g. d=10² km…)

The same Diesel vehicle tested at -7°C →



Analyses: (Non-)Linearity in PN over the NEDC (2)

Test condition → / **Metric** ↓	CI (with DPF), NEDC at +25°C	CI (with DPF), NEDC at -7°C	CI (no DPF), NEDC at 25°C	CI (no DPF), NEDC at -7°C
Distance covered at 1% of total PN emissions	51 metres =1.67E10/km	13 metres =9.33E10/km	52 metres =1.11E14/km	20 metres =2.17E14/km
Distance covered at 10% of total PN emissions	617 metres =1.38E10/km	52 metres =2.14E11/km	1.16 km =4.91E13/km	438 metres =1.01E14/km
Proportion of PN emissions after 1 km	12.9% =1.09E10/km	56.8% =6.32E10/km	8.2% =4.67E13/km	14.6% =6.43E13/km
Proportion of PN emissions after 2 km	21.5% =9.13E09/km	69.6% =3.87E10/km	14.9% =4.24E13/km	25.6% =5.66E13/km

Conclusions

- Overall, short trips cause disproportionate emissions of particulate matter, as quantified by mass and number
- The presence/absence of a particulate filter can have a large impact
- Ambient temperature has an impact – lower temperatures cause greater proportional emissions from short trips
- Even multipoint injection petrol vehicles suffer this effect
- This should be taken into account in emissions inventories and air quality projections
- Reducing the number of cold starts (particularly those at low ambient temperature) *could* have a bigger impact on air quality than reducing the total distance travelled
- The shorter the trip distance, the more critical the startup behaviour is for emissions of particulate matter

Further research

- Topics for further research might include:
  - Characterisation of different engine/fuel types: Diesel with/without DPF, SCR), direct injection petrol with/without GPF, multipoint injection petrol/CNG/LPG/ethanol blends
  - DPF/GPF accumulation studies – what is created, but not emitted?
  - Driving cycle investigations: further WLTC testing, use of Amercian cycles and non-legislative cycles
  - Real driving emissions: portable emissions monitoring systems – do we really see this effect in the real world? To what extent?
  - Consideration of the possibility of radical alternatives to traditional ‘emissions’ – mg/start? number/start? cold idle test? emissions tests of two different lengths?
  - Further investigations into the impact of ambient temperature, including emissions from warm/cool starts, as well as cold starts
  - Deterioration – does the proportion change significantly with vehicle mileage?
  - Further development of models to predict emissions from trips of highly variable lengths

Thank you for your attention

- Any questions?

“Any emissions can be made low if the test cycle is long enough!”

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