18th ETH Conference on Combustion Generated Nanoparticles, 2014

Particulate Emissions from Passenger Cars with DISI[1] Engines Tested at Sub-Zero Temperatures

Dr. Piotr Bielaczyc* Joseph Woodburn Dr. Andrzej Szczotka

BOSMAL Automotive Research & Development Institute Ltd (Bielsko-Biala, Poland)

The particulates present in vehicular exhaust are coming under ever closer scrutiny and are subject to legislative limits in many cases (in the European Union, the only exception being port fuel injected petrol fuelled vehicles, for the time being). It is widely acknowledged that current legislative laboratory test procedures in many ways represent a best case scenario – more aggressive driving cycles and less favourable ambient conditions can increase particulate emissions massively.

Ambient temperature is generally the *environmental* parameter of most importance regarding particulate emissions from an engine, particularly for the relatively brief, periods of operation typical for passenger cars operating from a cold start.

In general, cold start is challenging for an internal combustion engine for many reasons, with multiple emissions impacts for all types of automotive engines [1,2]. Sub-zero ambient temperatures exacerbate these problems, leading to significant difficulties in forming combustible mixtures and maintaining acceptable drivability. Furthermore, increased fuel flow rates [1] and the potential for reduced particle elimination via oxidation in-cylinder (and also in the cold three-way catalyst) conspire to increase cold start emissions further still. While DISI engines typically require less excess fuel to achieve start-up than their indirectly injected counterparts, any excess fuelling can potentially cause excess particle emissions. It is estimated that for passenger cars, around 7 out of every 10 journeys commence from a cold start [1]. In regions where ambient temperatures frequently fall below zero (even if only overnight), a reasonable proportion of the cold starts experienced by a vehicle will be at these temperatures – and if decent drivability is to be maintained, this represents a real challenge in terms of excess emissions and fuel consumption. The current EU type-approval process does in fact require that all SI vehicles (including DISI) be tested at -7°C, but there is currently no limit for particulate emissions at this lower test temperature. It is worth noting that one in four new vehicles sold in the EU in 2012 running on petrol featured a DISI engine [3] and that the majority of EU member states experience temperatures down as low as -7°C in certain areas during the European winter.

However, various studies available in the literature have examined particulate matter emissions at the “legislative” test temperature of -7°C. In the latest experimental work performed at BOSMAL, two Euro 5 vehicles with DISI engines were tested at low ambient temperatures (-7°C/-15°C) on three fuels, with particulate emissions results compared to results from the same fuels when the vehicles were tested at 25°C. Testing was performed on a chassis dynamometer in an advanced climatic chamber, with the standard European test procedure used (NEDC, dilution tunnel, TX40 filters, condensation particle counter). The impact of the fuel type of particulate emissions was found to be over an order of magnitude smaller than the impact of ambient temperature on those emissions. Over the whole test cycle, the results implied a power-type relationship between ambient

[1] Direct injection spark ignitron; *piotr.bielaczyc@bosmal.com.pl

temperature and both particle mass and particle number (although this is only a preliminary finding from three datapoints). If this relationship holds true over a wider range of temperatures, then ambient temperatures lower than -15°C would cause even greater deteriorations in particulate emissions.

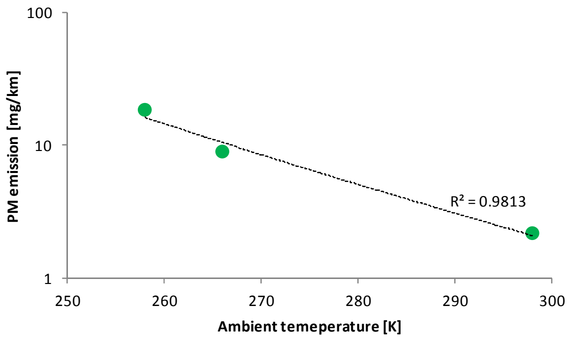


Figure 1. PM emissions from vehicle 1 at three ambient temperatures (two of which were sub-zero). Note the $\log_{10}$ scale on the y-axis

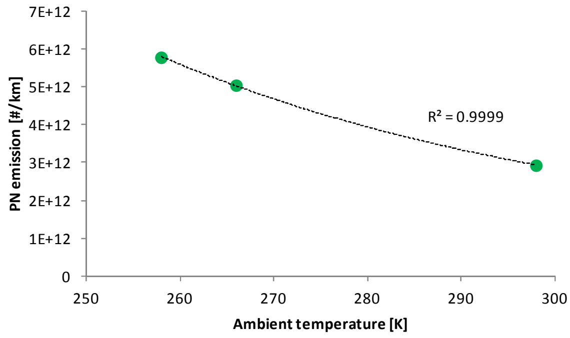


Figure 2. PN emissions from vehicle 1 at three ambient temperatures (two of which were sub-zero)

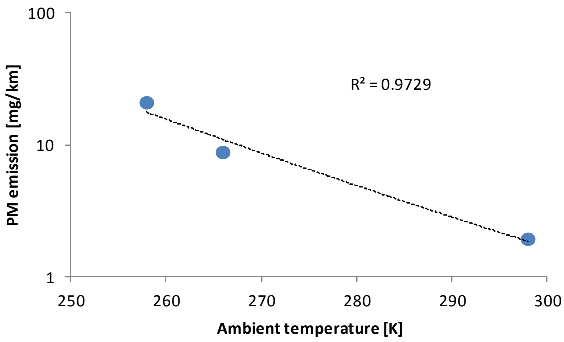


Figure 3. PM emissions from vehicle 2 at three ambient temperatures (two of which were sub-zero). Note the $\log_{10}$ scale on the y-axis

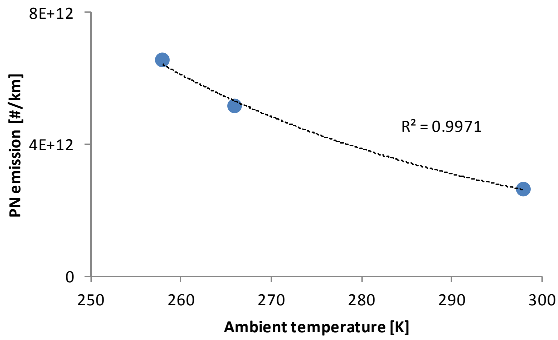


Figure 4. PN emissions from vehicle 2 at three ambient temperatures (two of which were sub-zero)

When comparing the results to those obtained at 25°C, an emissions deterioration result can be calculated by dividing the result at the sub-zero test temperature by the result at 25°C. Deterioration factors for both PM and PN (over the entire NEDC) are shown in Table 1. (Self-evidently, the value at 25°C is 1, by definition.)

Test temperature	PM deterioration [-]		PN deterioration [-]	
	Vehicle 1	Vehicle 2	Vehicle 1	Vehicle 2
25°C (298K)	1	1	1	1
-7°C (266K)	4.01	4.53	1.72	1.96
-15°C (258K)	8.44	10.77	1.97	2.49

Table 1. Deterioration factors (dimensionless) obtained over the entire NEDC

Two main trends are immediately apparent from the results shown in Table 1: that the deterioration factors for PM are very high – *a value of 10 represents an order of magnitude increase in emissions* – and that disparity in the values of the PM and PN deteriorations implies changes in the properties of the particles emitted.

Analysing results from the two phases (UDC/EUDC) showed that even when the engine is fully warmed up, ambient temperature continues to have an impact on particulate emissions from this engine type, although the impact is much smaller than during the cold start phase. The impact of ambient temperature diminishes as the engine reaches thermal equilibrium, but of course many journeys are not long enough to allow this to happen. (This concurs with a recent study using hot and cold start driving cycles at various ambient temperatures [5].)

Simple corrections were applied to the results to better understand the impact of ambient temperature on the emissions. Two types of correction were applied: thermal and fuel consumption. Thermal correction compares the result to the result obtained at 25°C, correcting for the absolute (Kelvin) difference in ambient temperature. For example, at -7°C, the absolute temperature is 266 K, so the thermal correction coefficient is 266 K / 298 K = 0.893. The fuel consumption correction coefficient was calculated in the same way, by dividing the fuel consumption at the lower test temperatures by the fuel consumption value obtained at 25°C. For the cold start UDC phase, neither the thermal nor the fuel consumption correction had much of an influence on the results – the particle emissions excess was much larger than the absolute difference in ambient temperature or the excess fuel consumption. However, for PN over EUDC, applying both the thermal and the fuel consumption correction caused the results to normalise (vehicle 1; Figure 5) and to begin approach normalcy (vehicle 2; not shown here). This implies that PN emissions at other low ambient temperatures could be predicted with reasonable accuracy using these simple metrics, albeit only over the EUDC phase. More complex corrections and modelling would likely be required to predict emissions of PM and over the UDC. Other parameters which vary with ambient temperature and which could be examined are the viscosity and density of the intake air, fuel effects, etc. The formation of particulates in DISI engines differs from formation in CI engines [6]; the question of the impact of ambient temperature on particulate emissions from a fully warmed up engine is intriguing, given the complexities of the formation processes and the suspected role of pool fires [6].

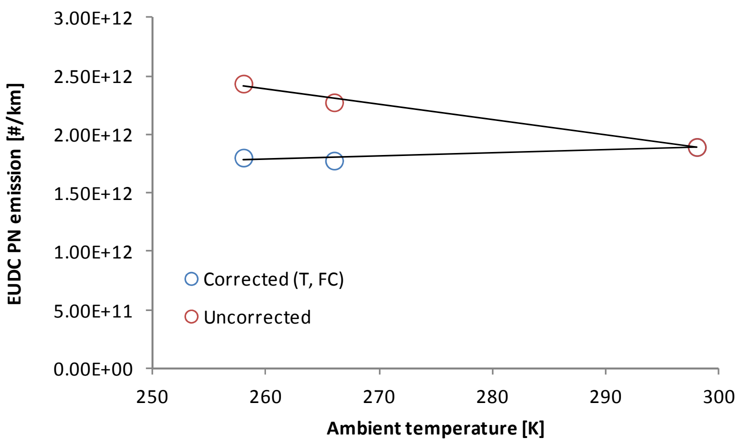


Figure 5. Uncorrected and corrected PN results for vehicle 1 over the EUDC. When corrected using the thermal and fuel consumption coefficients, the results normalised to an almost flat line, in contrast to the uncorrected results

A brief evaluation of the sub-cycles of the NEDC driving cycle also elucidated further trends regarding the impact of ambient temperature on particulate matter emissions from shorter 'trips' [4]. This analysis confirmed the massive degree of excess emissions immediately following cold start and the large impact this has for short trips. For example, the UDC covers around 4 km (36% of the distance of the entire NEDC), yet the proportion of total emissions during this phase is considerably higher, and this proportion rises further still as ambient temperature falls. At -15°C, some 88% of PM and

77% of PN were emitted over the first four km of the cycle. This is not unexcepted, given the impact of the cold start, but it also has air quality implications – excess emissions from short journeys appear to be *even worse* at sub-zero temperatures. In general, the shorter the journey and the lower the temperature, the worse the emissions excess, to the point where the appropriateness of units of [(mg and #)/km] are somewhat debatable (see [4]). In light of the 2017 Euro 6 PN limit and the introduction of GPFs in response, the real world loading profile of DISI vehicles used in cool/cold climates should be carefully studied.

This experimental work has confirmed the large increased in particle emissions that occur at sub-zero ambient temperatures (compared to the standard temperature range for laboratory testing). Thermal and fuel consumption corrections, when applied simultaneously, accounted for much of the excess PN emissions over the EUDC. Further work at even lower temperatures, as well as temperatures in the range of 0°C, would be advantageous to further explore these results and findings. While particulate emissions from Euro 5 DISI vehicles are quite modest at 25°C (perhaps a similar order of magnitude to the mass-based particulate emissions from the brakes and clutch of a passenger car [6]), real usage of such vehicles in many regions will entail emissions up to over an order of magnitude greater, because of the impact of ambient temperature alone.

References:

1. Bielaczyc, P., Szczotka, A., Woodburn, J., The Effect of a Low Ambient Temperature on the Cold-Start Emissions and Fuel Consumption of Passenger Cars. Proc Inst Mech E Part D: Journal of Automobile Engineering, 225, 9, 1253-1264, 2011, doi:10.1177/0954407011406613

2. Weilenmann, 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

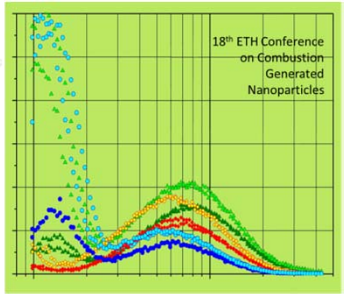
3. European Vehicle Market Statistics – Pocketbook 2013, The International Council on Clean Transportation, 2013. Available online: http://eupocketbook.theicct.org/

4. Woodburn, J., Particulate Emissions from LDVs Used for Short Trips – The Impact of the Cold Start Effect. Proceedings of the 17th ETH Conference on Combustion Generated Nanoparticles, 23-26 June 2013, Zurich, Switzerland (CDROM), ISBN: 978-3-033-04114-1.

5. Chan, T., et al., Impact of Ambient Temperature on Gaseous and Particle Emissions from a Direct Injection Gasoline Vehicle and its Implications on Particle Filtration, *SAE Int. J. Fuels Lubr.* 6(2):350-371, 2013, doi:10.4271/2013-01-0527.

6. Eastwood, P., Particulate Emissions from Vehicles, John Wiley & Sons Ltd (Chichester, England), 2008, ISBN: 978-0-470-72455-2.

18th ETH Conference on Combustion Generated Nanoparticles
22-25 June 2014 / ETH Zürich, Switzerland



Particulate Emissions from Passenger Cars with DISI[1] Engines Tested at Sub-Zero Temperatures

Dr. Piotr Bielaczyc, Joseph Woodburn, Dr. Andrzej Szczotka
BOSMAL Automotive Research & Development Institute Ltd
(Bielsko-Biala, Poland)

[1] Direct injection spark ignition

18th ETH Conference on Combustion Generated Nanoparticles
22-25 June 2014 / ETH Zürich, Switzerland

Contents:

1. Background info on cold start
2. Background info on DISI engines and their particulate emissions
3. Test facility / equipment / vehicles / procedures
4. Results and analysis
5. Conclusions

Background info on cold start (1)

• Cold start of an engine is a **challenging transient event**

• Particularly relevant for passenger cars

• Low temp: **increased friction**, ineffective lubrication, cold metal surfaces, **sluggish kinetics**, etc

•Substantial **increases in emissions** (gaseous and **solid**) and fuel consumption result

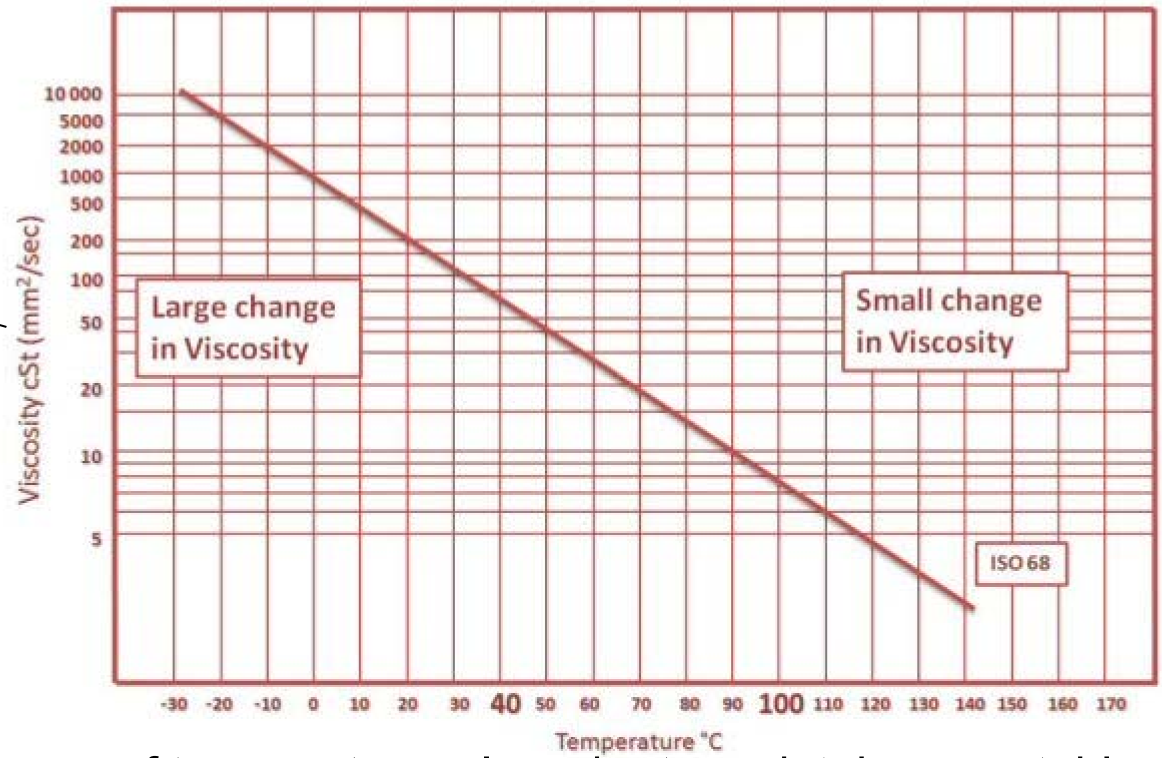
• For engines running on petrol, **fuel enrichment** is required to achieve acceptable drivability. This can continue for **hundreds of seconds**, but the journey may be terminated much earlier

• Cold start is performed at a **wide range of ambient temperatures** (depending on the climate of the area of operation of the vehicle), **often twice (or more) a day.** Many areas in Europe, Asia and the Americas frequently experience **sub-zero temperatures**. A vehicle does not have to be parked (switched off) for long to achieve **thermal equilibrium with its surroundings**

Further info: Bielaczyc, P., et al., 2011, doi:10.1177/0954407011406613; Weilenmann, M., et al., 2009, doi:10.1016/j.atmosenv.2009.02.005; Andre & Jourmard, 2005, bit.ly/Tdi7TO

Background info on cold start (2)

Log$_{10}$ scale!



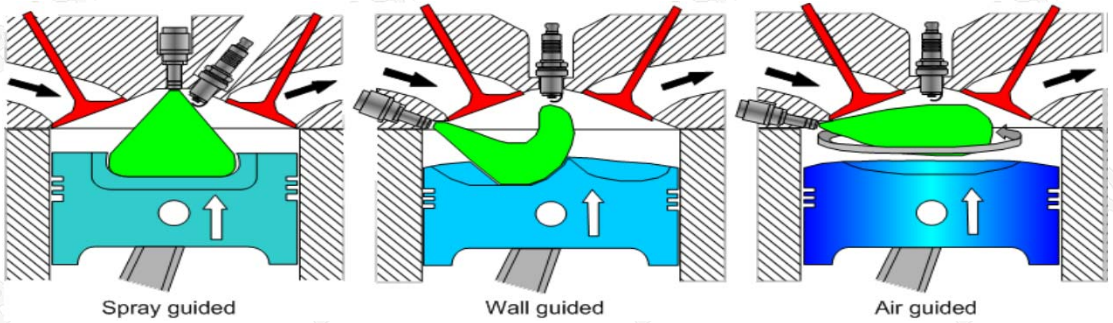
Engine oils experience a wide range of temperatures. In order to maintain acceptable lubricity at higher temperatures, viscosity is sub-optimal at lower temperatures. As the cold start temperature falls below zero, even oils designed for use in colder climates suffer massive increases in viscosity, as shown above.

↓ Ambient temperature =

↑ Viscosity ,↑ Friction ,↑ Fuel dosing, ↓ Combustion efficiency =

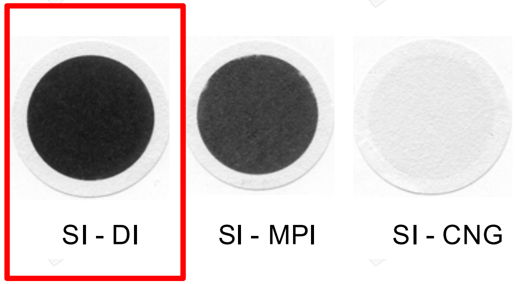
↑ Particulate Emissions

Background info on DISI engines and their particulate emissions



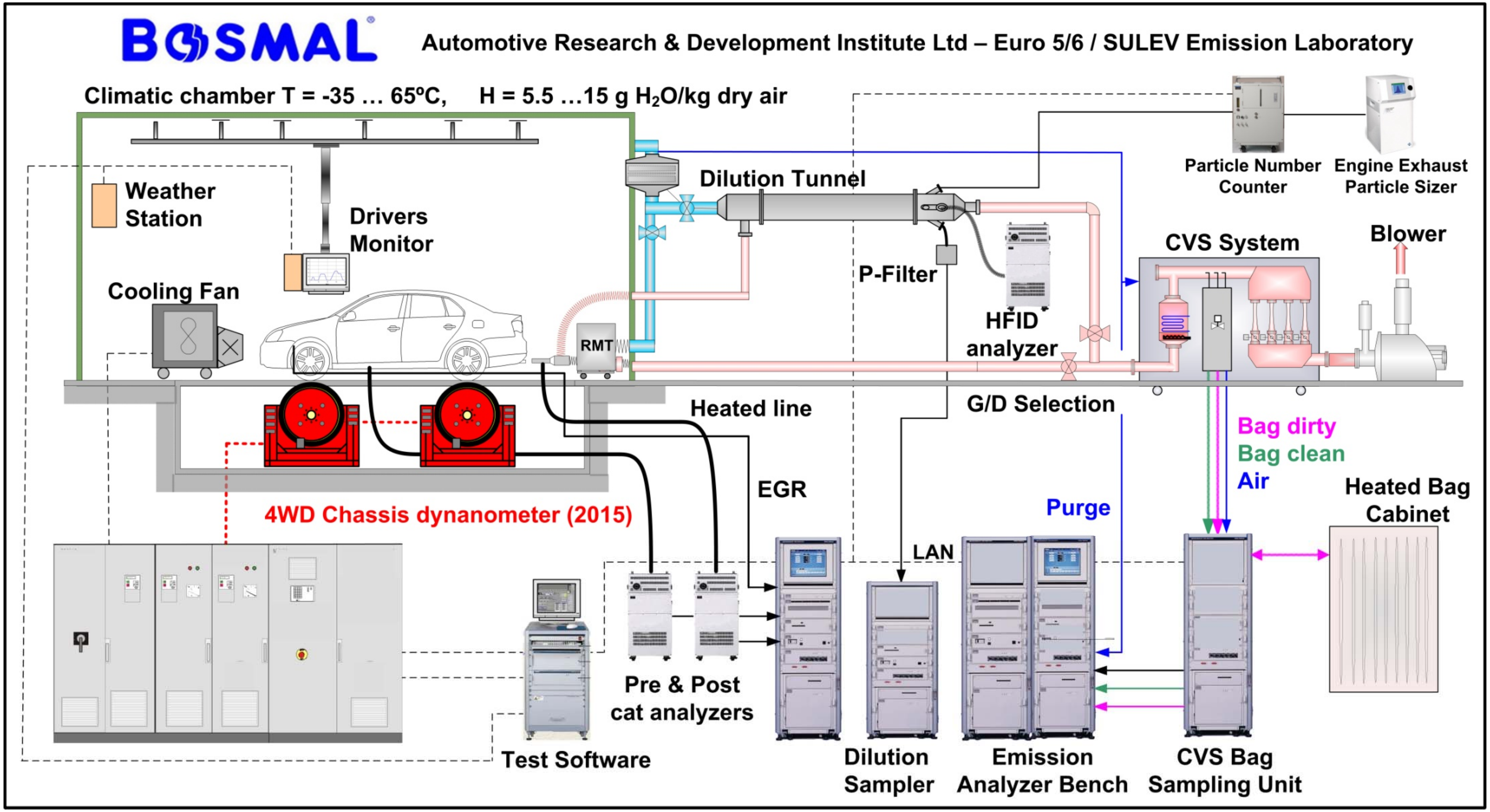
- Conceptual and structural similarities with the Diesel engine; three main types: spray/wall/air guided
- However, the particulate formation process is quite different (see Eastwood, '*Particulate emissions from vehicles*', 2008.) **Pool fires** may play an important role, though perhaps less in spray guided DISI engines
- Multiple advantages over indirect injection SI engines
- The **main disadvantage** is particulate emissions, which at present are **only regulated in the EU at the 'normal' test temperature (20°C-30°C) for PM and soon PN too**

Filters following cold start



Test facility / equipment / vehicles / procedures (1)

Schematic diagram of BOSMAL's emissions measurement setup, as used to measure emissions from the test vehicles – see also [bit.ly/19kvVI3] and [bit.ly/11EcDCd]



Test facility / equipment / vehicles / procedures (2)

Some further information on the experimental setup

BOSMAL's climate-controlled test chamber (-35 °C to +60 °C) housing a chassis dynamometer and windspeed fan

Filter holder and TX40 filter

Dilution tunnel and particle counter

- Testing carried out in accordance with EU & PMP test requirements.
- Test temperatures: +25°C, -7°C, -15°C
- Driving cycle: NEDC (Reg. No. 83)

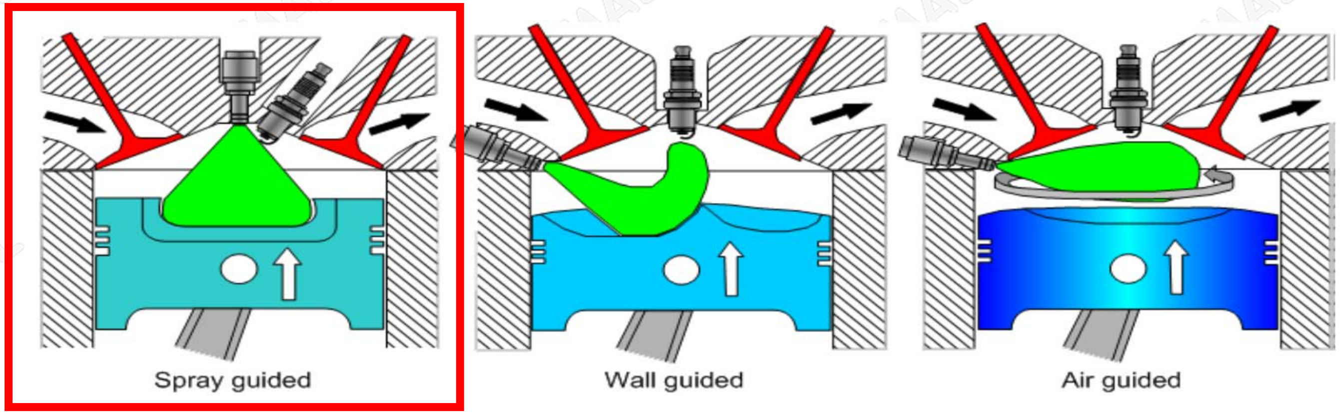
Three fuel types tested at each temperature (low influence; mean values presented here)

2 tests performed at 25°C

3 tests performed at -7°C, -15°C

Test facility / equipment / vehicles / procedures (3)

- The test vehicles (2) were both **Euro 5 vehicles of European manufacture**
- Engine displacement was approximately **1.6 dm^3** in both cases
- Both vehicles featured the same type of fuel injection system for **DISI operation**
- Both vehicles were (at least nominally) stoichiometric **(λ1)**
- **The test vehicles did not feature a dedicated particle filtration device (GPF)**
- Spray guided →
- Centrally-mounted injector →



- Vehicles were **preconditioned and heat soaked** according to UNECE Regulation No. 83
- Full thermal stabilisation was achieved: ambient air, engine block, coolant, engine oil and fuel

Results and analysis (1)

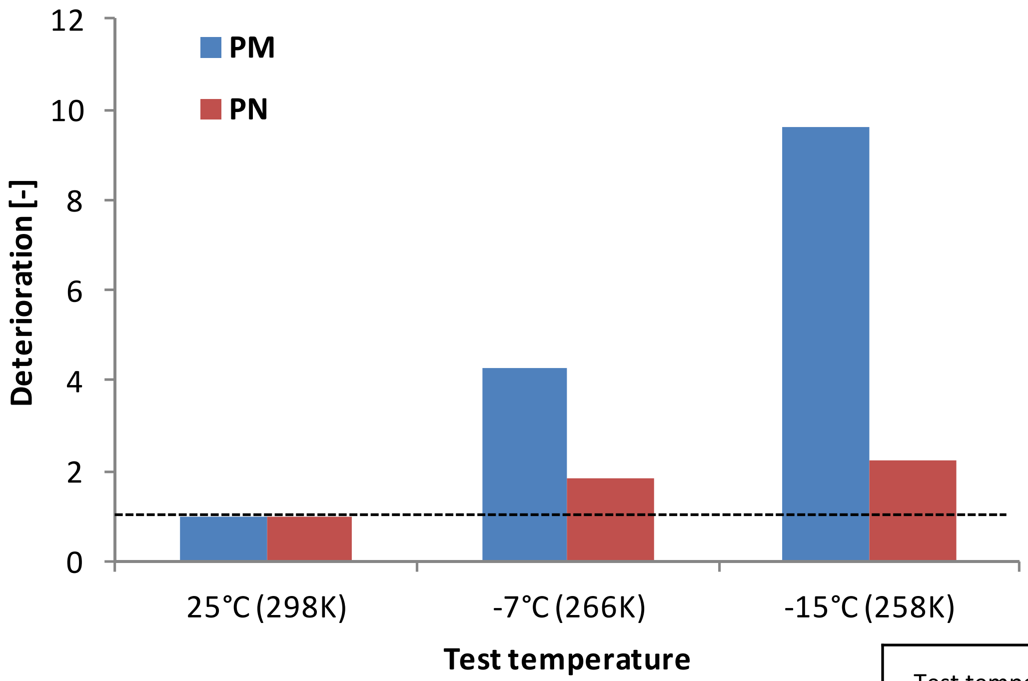
- As expected, particle mass (PM) and number (PN) **greatly increased at the two sub-zero test temperatures**, compared to +25°C
- Deteriorations were greater for PM than for PN: **up to 10 times more PM**!
- The results implied changes in the propoerties of the particles (PM/PN ratio)
- **Excess emissions greatest over the first phase of the cycle** (the UDC): cold start, followed by 'cold→warm' operation, significant enrichment, low speed/load
- The second phase (the **EUDC**), which is 'warm→hot' still showed **excess emissions of both PM and PN**
- Emissions over the NEDC were **very 'startup heavy'**, with a significant emissions penalty over the first phase, especially at sub-zero temperatures. At -15°C, **around 88% of PM and 77% of PN** emitted during the entire cycle were emitted **over the first 4 km**. (*So the remaining 7 km had relatively little impact on total particulate emissions, even though it represented 64% of the distance covered*)

Results and analysis (2)

Deterioration in emissions

Question: ‘How many times higher are PM/PN emisions at the sub-zero test temperatures?’

Answer: ‘Between 2 and 10 times higher, over the entire NEDC!’



The form of the trend is different for PM and PN, but the increases are clear and unambigious

Graph shows mean results from both test vehicles as single values; table shows values for each test vehicle

Test temperature	PM deterioration [-]		PN deterioration [-]	
	Vehicle 1	Vehicle 2	Vehicle 1	Vehicle 2
25°C (298K)	1	1	1	1
-7°C (266K)	4.01	4.53	1.72	1.96
-15°C (258K)	8.44	10.77	1.97	2.49

Results and analysis (3)

While there were only 3 datapoints, emissions increases appeared to follow a power law relationship:

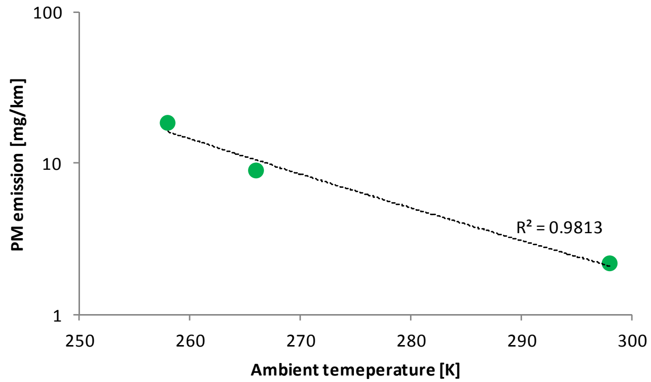


Figure 1. PM emissions from vehicle 1 at three ambient temperatures (two of which were sub-zero). Note the $\log_{10}$ scale on the y-axis

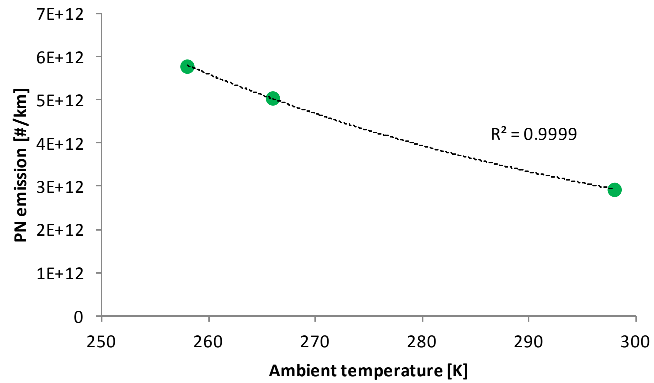


Figure 2. PN emissions from vehicle 1 at three ambient temperatures (two of which were sub-zero)

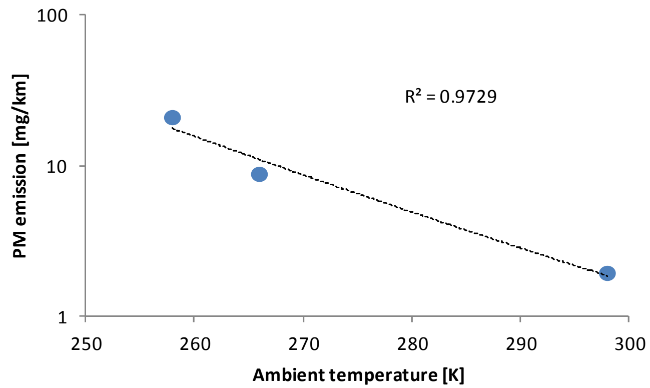


Figure 3. PM emissions from vehicle 2 at three ambient temperatures (two of which were sub-zero). Note the $\log_{10}$ scale on the y-axis

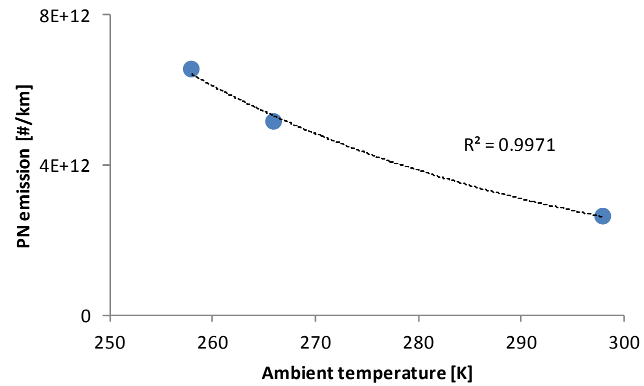
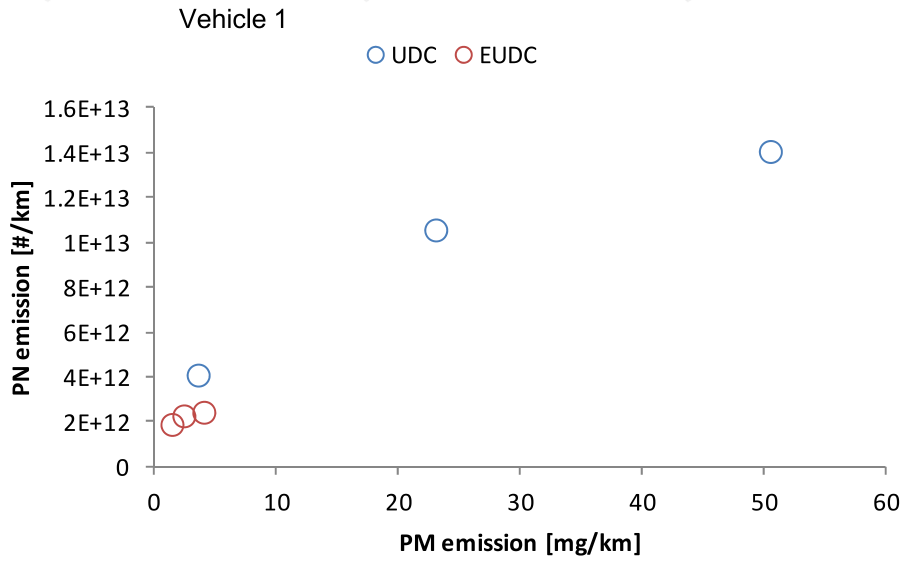
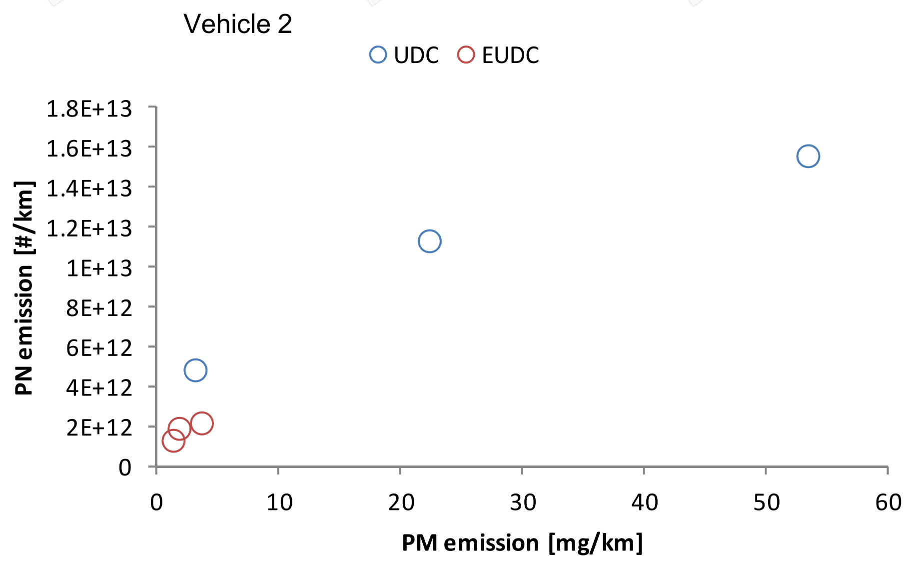


Figure 4. PN emissions from vehicle 2 at three ambient temperatures (two of which were sub-zero)

Results and analysis (4)

Comparing the values of PM and PN results at the three test temperatures:





PM and PN emissions over the EUDC at -15°C are *lower* than emissions over the UDC at +25°C!

Impact of ambient temperature very clear; even for the EUDC differences statistically significant and repeatable.

PM/PN ratio changes somewhat with temperature – particle properties changing?

Heavier particles created as hydrocarbons adsorb onto their surface?

Results and analysis (5)

What precisely causes these excess emissions?

The **difference in thermal energy** can be calculated based on the absolute (Kelvin) temperature: e.g**. -7°C** vs +25°C: 266 K / 298 K = 0.893 = 10.7% **<u>less</u> thermal energy in the system; -15°C** vs +25°C = 13.4% **<u>less</u> thermal energy**

The **excess fuel consumption** can be calculated by comparing values with those measured at +25°C: varies with temperature and cycle phase (UDC/EUDC), but from **10% to 30% <u>more</u> fuel consumption**

These differences are at least order of magnitude smaller than the observed deteriorations in PM and PN emissions over the entire NEDC

However, results over the **EUDC**, **when corrected for ambient temperature AND excess fuel consumption**, started to **normalise**

Results and analysis (6)

Applying the thermal and fuel consumption corrections normalised PN emissions for one vehicle, but only over the EUDC

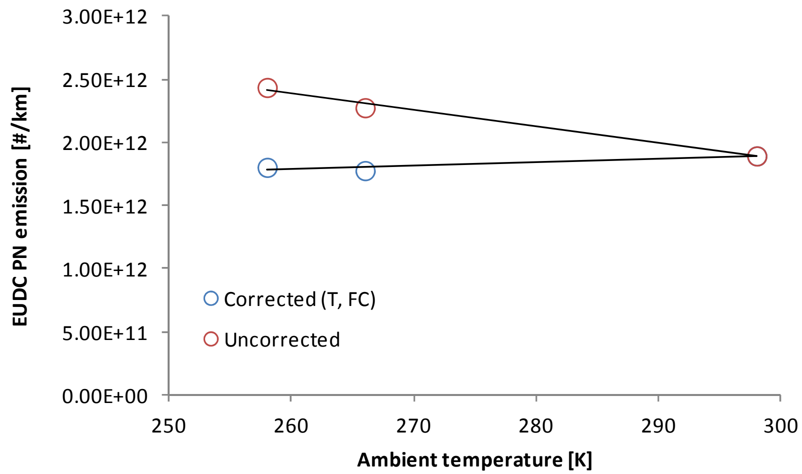


Figure 5. Uncorrected and corrected PN results for vehicle 1 over the EUDC. When corrected using the thermal and fuel consumption coefficients, the results normalised to an almost flat line, in contrast to the uncorrected results

In order to normalise PM emissions and attempt to predict excess emissions over the UDC, further investigations and more complex analysis of results at multiple sub-zero test temperatures would be required (subject of future research/publications)

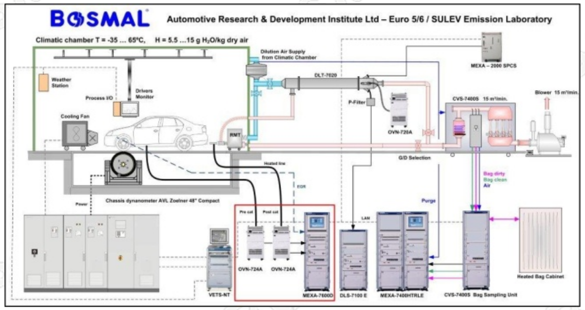
Models can lead to more accurate predictions of particulate emissions released during different driving cycles

Conclusions

A series of laboratory experiments revealed the following general conculsions:

1. Emissions of PM and PN (PM more so) experience massive increases at sub-zero temperatures. PM emissions were reasonbaly low at 25 °C (<5 mg/km), but increased rapid at sub-zero ambient temperatures
2. The deterioration trend may not be linear (power law), so *emissions at temperatures even lower than -15°C may be significantly worse*
3. The proportion emitted during the first phase of the cycle (the UDC) increases as ambient temperature decreases. *Short journeys show massive excesses at very low temp*
4. For one test vehicle, PN emissions during the EUDC phase appeared to be mathematically explicable by ambient temperature and excess fuel consumption
5. *These excess emissions are an obvious air quality threat*. Setting emissions limits for PM and PN from DISI vehicles in the EU Type VI test (-7°C) would appear reasonable
6. Further research at other ambient temperatures would allow further analysis of the type attempted here

Thank you for your attention – any questions?



Contact: piotr.bielaczyc@bosmal.com.pl

www.bosmal.com.pl