A Comparison Of Real-Time On-Road Diesel Particulate Emission With Chassis Dynamometer Measurements

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Introduction

A Peugeot 406 2.2l HDi passenger car was driven around Cambridge and its environs whist monitoring the particulate size spectrum in real-time using a Cambustion DMS50 mobile fast particulate spectrometer. As well as the full spectrum, nucleation and accumulation mode number, CMD and GSD and accumulation mode mass were calculated. Using the logged road speed, the tests were then repeated on a more traditional chassis dynamometer ("rolling road") facility to compare real world emissions with those in a laboratory environment.

Instrumentation and Experimental Details

The DMS50 is a new differential mobility analyser which classifies aerosol particles from 5 nm to 560 nm from their electrical mobility, producing both a size spectrum and multi-lognormal fits to instrument response in real time, with a time response of around 500 ms and data rate of up to 10 Hz. Particles are charged with a unipolar diffusion charger and pass into a classification column, where a radial electric field diverts them from a sheath air flow until they land on any of 22 detection rings, each connected to an electrometer circuit. The instrument transfer function is used generate a 34 channel size spectrum from the 22 electrometer signals, as well as a lognormal parameterisation which distinguishes between nucleation and accumulation modes.

The DMS50 samples directly from the exhaust of the vehicle, post Diesel Oxidation Catalyst (DOC) (except for drive "C"). The Diesel Particulate Filter (DPF) was removed for these tests. A DLC50 dilution controller provides a heated primary dilution factor of 4 at the point of sampling to reduce condensation. The aerosol passes through heated conductive silicone tube to the DMS50 in the vehicle. The instrument contains an integrated rotating disc diluter, for these tests set to give a factor of 100, giving a total dilution factor of 400:1 (corrected by feedback).

The logged road speed was presented on screen to a driver in the chassis dynamometer facility, so the cycles could be repeated as closely as possible. An on road "coast down" test was performed to establish the speed-load relationship for the dynamometer. For these tests, as well as the in-car DMS50, a DMS*500* (non-mobile, 200 ms, 5 nm – 1 μm antecedent of DMS50) sampled from the constant volume sampler (CVS) of the dynamometer facility.

Results and Discussion

Each of the two main road tests ("A" and "B") were preceded by a short warm-up drive. An alternative route ("C"), sampling pre-DOC was also undertaken (with no chassis dynamometer repeat). Speed repeatability on the dynamometer was excellent, though slight differences in fuelling were observed.

Considering drive "B" first, the cumulative soot mass trace shows some difference between the real-world drive and the dynamometer repeat. Comparison of accumulation mode number and size shows that whilst the concentration is very similar, the on-road particles tend to be slightly smaller (concentration weighted mean CMD of 61.8 nm) than those on the dynamometer (65.2 nm). Accelerating down the slip road onto the A14 generates around 10% of the total particulate mass emission of the 26 minute drive. Whilst accumulation mode concentrations are very similar in all three examples, more nucleation material is generated in the direct sampling system than in the CVS system.

Nucleation mode bursts seem in general to be correlated with high engine load (fuelling), even more so than for soot bursts. Where there is a lack of correlation between particulate emissions and fuelling it is probably due to the indeterminate effect of Exhaust Gas Recirculation which whilst reducing NO_x can promote P.M. formation.

Drive "A" shows much better repeatability between the on-road and dynamometer tests. A repeat of the dynamometer test for this drive was attempted, however during the extra-urban section the engine management system tried to regenerate the (not fitted) DPF, by instigating post-injection fuelling designed to raise the temperature of the DPF and oxidise the soot. This caused a large amount of nucleation material to be formed (especially in the CVS tunnel), with size of up to 50 nm. A previous study on this vehicle with the DPF fitted also saw such an effect, which could have been due to thermal desorption of volatiles from the DPF. In this case with no DPF fitted, the nucleation material could be due to desorption from the DOC (known to absorb sulphate) or possibly from un-burnt post-injected fuel.

Drive "C", on a different route but similar traffic conditions, sampling pre-DOC shows much higher average levels of nucleation material than the post-DOC tests.

Conclusions

These experiments show rapid acceleration and deceleration to be the biggest cause of urban transient P.M. emission, whilst high speed cruises generally produce more soot mass than low speed cruises. The use of an oxidation catalyst reduces nucleation matter. DPF regeneration events can cause large amounts of nucleation material. It is remarkable how closely it is possible to reproduce on-road tests in a laboratory environment. This is probably especially true in Cambridge due to the lack of gradients on the roads. The vehicle easily complies with Euro Stage III particulate emissions (~0.03 g/km cf. 0.05 g/km), even when not driven on a legislated drive cycle.

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Introduction

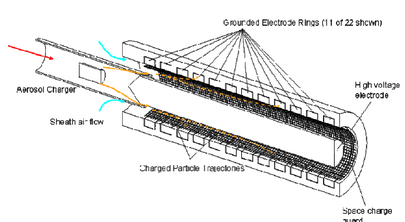
- Real-time particulate size spectrometer on-board Peugeot 406 2.2l Diesel car
- Diesel Particulate Filter (DPF) removed, Diesel Oxidation Catalyst (DOC) present for most tests
- Log road speed and fuelling on drives around Cambridge, U.K., and its environs.

- Reproduce drive on chassis dynamometer ("Rolling road")
- Additional spectrometer in standard *Constant Volume Sampler* (CVS) tunnel
- Compare particle size, concentration and mass
- Can we successfully reproduce real-world driving in the laboratory?
- Does the vehicle meet legislative requirements "off-cycle"?

Instrumentation

- Cambustion DMS50: Real time particle size spectrometer
- Based upon DMS*500* (Reavell 2002, Reavell *et al.* 2002)
- 5 – 560 nm
- 10 Hz data rate, ~500 ms $T_{10–90}$ response time
- Built-in rotating disc diluter
- 12 V operable for mobile use

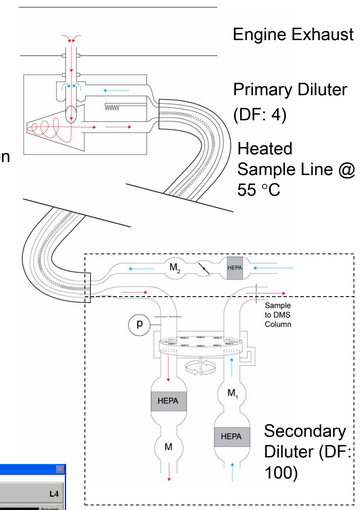
- *DLC50* controls primary dilution at sampling point and drives heated line

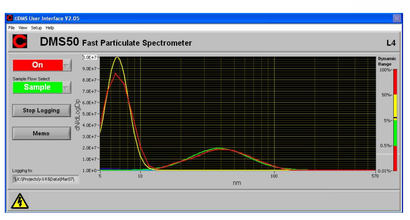


- Aerosol sample drawn through corona discharge charger
- Charged aerosol enters classifier surrounded by clean sheath airflow
- Strong electric field causes particles to drift towards sensitive electrometer detectors
- Larger particles with more drag drift more slowly and are detected further downstream.
- Particle sizing on the basis of charge:drag ratio (electrical mobility)

Sampling & Data Processing

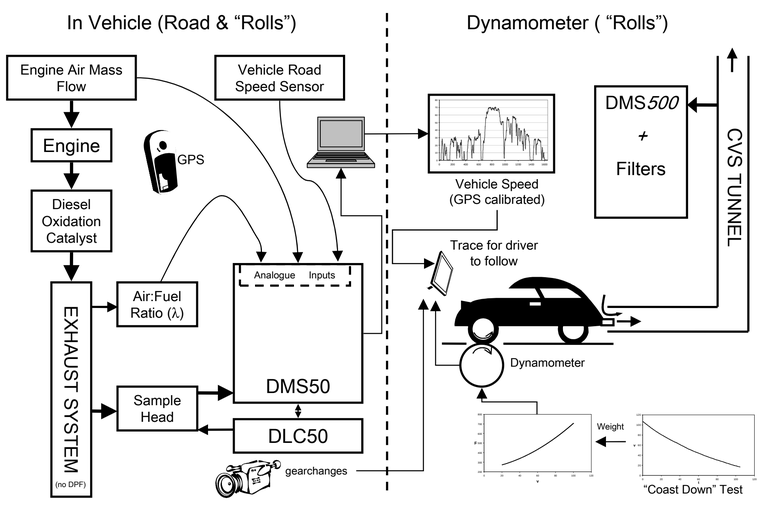
- DMS50 has built-in rotating disc diluter
- DLC50 adds primary dilution and heated line control – dilution correction feedback provided to DMS
- Primary dilution
  - Inhibits agglomeration and condensation
  - Mass flow controlled HEPA filtered compressed air.
  - Dilution factor of 4 used here
  - Heated to 55°C by sample line
- Secondary high ratio diluter
  - Extends instrument cleaning interval
  - Rotating disc type
  - Dilution factor: 100
- **Total dilution factor 400** used here





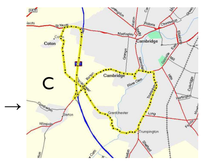
- Instrument gives 34 channel size spectrum *and* a lognormal parameterisation which automatically distinguishes between nucleation and accumulation modes
- Accumulation mode lognormal parameters used to calculate mass (Symonds et al. 2007)

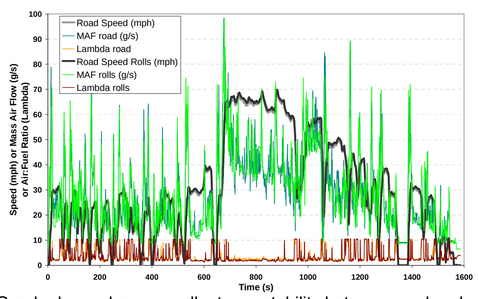
Experimental



- DMS 50 analogue inputs used to log speed, λ, and air intake mass flow. Video camera records gear changes, GPS plots route and calibrates speed.
- Vehicle speed trace and gear change map played back to driver in chassis dynamometer. Latter has been calibrated for force using a coast down test. We assume no major gradients in Cambridge (a good assumption).

- Day 1:
  - Warm-up
  - **A**: Newnham →"The Backs" → A14 → Newmarket Road → Cherry Hinton
  - Both urban and extra urban driving. Wind: 6.2 mph, S.E. (head)
- Day 2:
  - Warm-up
  - **B**: As A but slightly longer at start.
  - Wind: 10 mph, W (tail)
- Day 3:
  - **C**: Sampling **pre-DOC**
  - Newnham → M11 → Coton → Granchester → Trumpington

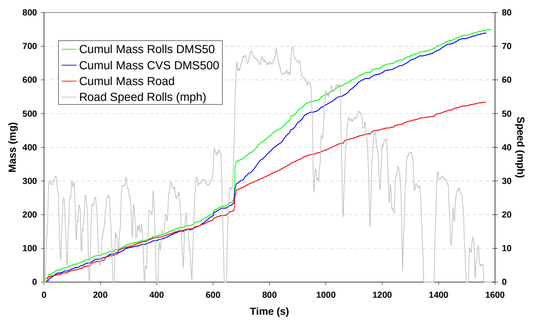




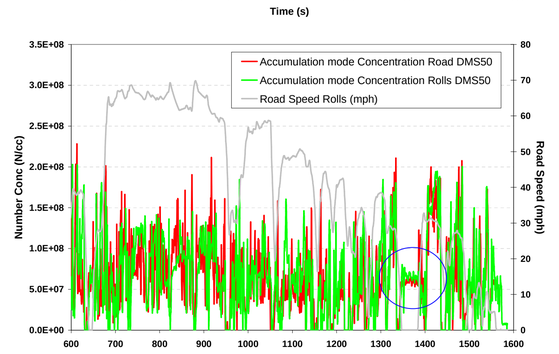
- Graph above shows excellent repeatability between road and laboratory of (e.g.) drive "B".

Drive "B"

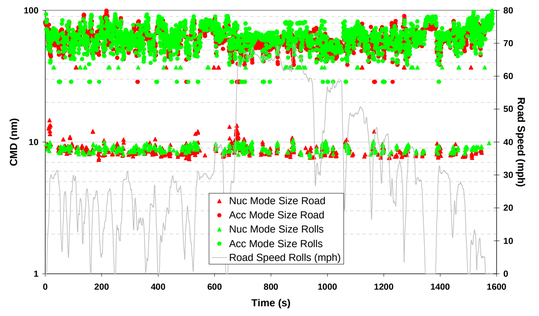
- Mass is a good comparison metric, as it encompasses both size and concentration information. Here we see cumulative mass calculated by the DMS50 (and 500) in real-time using size and concentration data from the lognormal parameterisation. A diameter to mass weighting factor of 3.19 is used — refer to Symonds et al. (2007) for an explanation. The DMS50 (direct sampling) and DMS500 (CVS) in the laboratory show good agreement, whereas slightly less mass is seen in the real world drive.



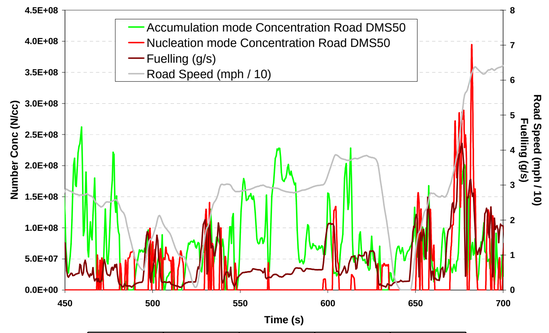
- Some of this reduction is mass is due to slightly fewer particles in the accumulation mode being produced on the road. The idle period indicated, where the vehicle was stopped at traffic lights, shows a clear example of this.



- Here are shown the sizes of particles in the nucleation and accumulation modes, both on-road and from the chassis dynamometer. The accumulation mode particles from the real world drive are slightly smaller (around 5 nm on average) and this also contributes to the reduction in mass seen on the road.



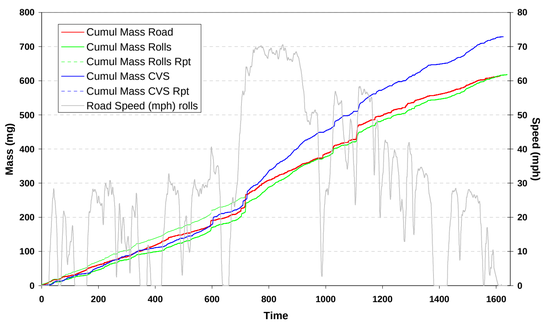
- Fuelling is seen to be correlated with nucleation formation (both on acceleration and deceleration). On deceleration, nucleation material is produced mainly due to the disappearance of the accumulation mode, onto which volatile material will often condense. Less of a correlation is seen between fuelling and the accumulation mode. This is probably due to the effect of Exhaust Gas Recirculation applied by the engine management unit; a parameter which we were unable to measure and as such is an unknown.



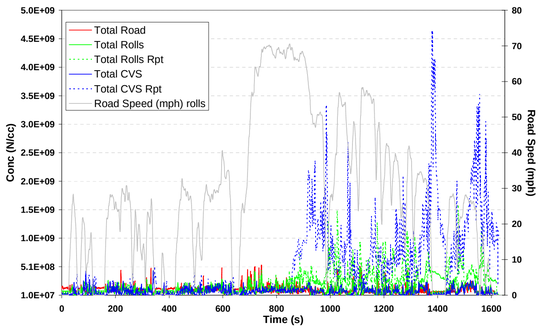
- The vehicle meets the Euro Stage III limit for particulate emission, even with the DPF removed and "off-cycle".

Filter Paper	DMS50 Rolls	DMS500 Rolls	DMS50 Road	Euro Stage III Limit
0.047 g/km	0.034 g/km	0.033 g/km	0.024 g/km	0.05 g/km

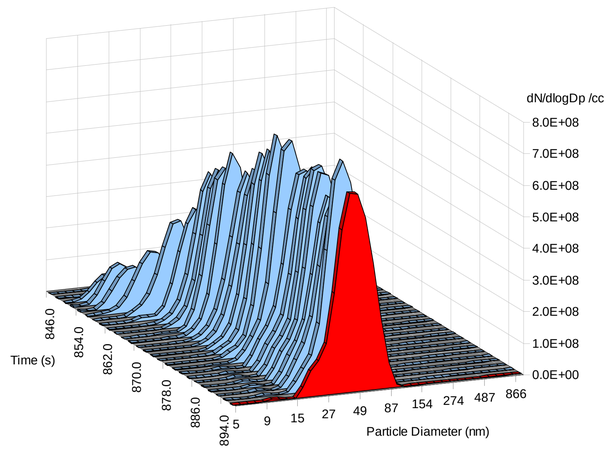
Drive "A"



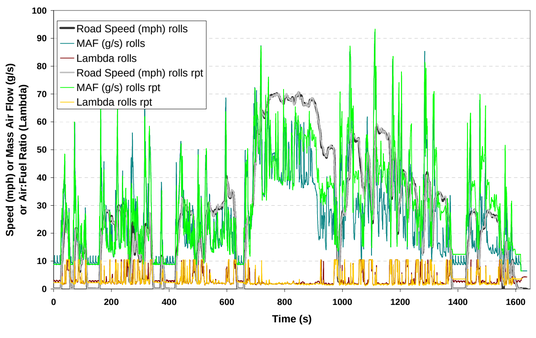
- Mass agreement between the real-world drive and the dynamometer is better on this drive than "B". A further repeat on the dynamometer was performed, and something interesting occurred during the extra urban phase. This is the main subject of the rest of the discussion of this drive. Note the mass calculation fort this further repeat (dashed lines) has been truncated.



- The plot above shows the total particulate concentration. At around 850 s, the repeat on the chassis dynamometer produces many time more particulate than the real-world drive or the initial repeat on the dynamometer. This is especially true of the measurement from the CVS tunnel.



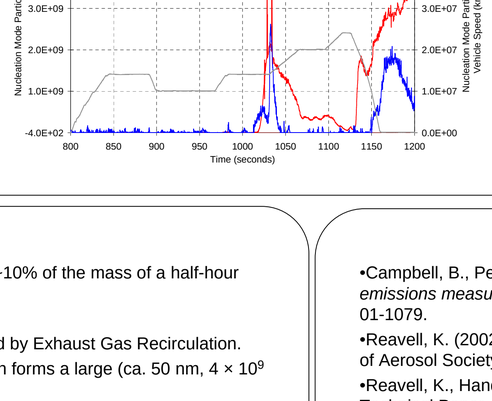
- The above still from a particle size spectrum animation shows in more detail what is occurring. A nucleation mode starting at around 10 nm grows substantially in both size and concentration, until it is over 50 nm in CMD.



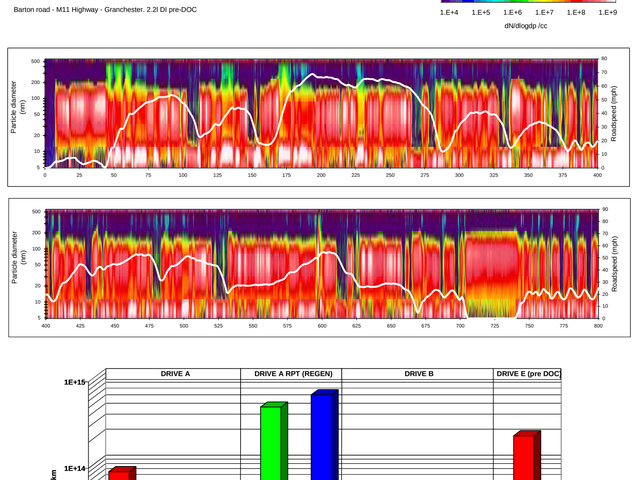
- Also, after this time, the engine air intake and fuelling have subtly changed.

Although no DPF is fitted, the vehicle's engine management system has decided to attempt to regenerate the DPF. It post-injects extra fuel to increase the temperature of the DPF to promote active oxidation. The production of large amounts of nucleation material during regeneration has been observed before, for example the study by Campbell et al. (2006) on this same vehicle (but with a DPF fitted) showed (by chemical analysis) a large amount of sulphate to be produced in the nucleation mode (see graph on right from that publication).

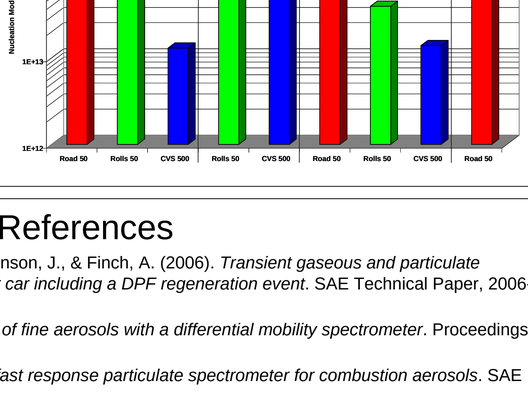
The sulphate is thought to desorb from the hot DOC. Nucleation then occurs in the exhaust system, the DMS 50 sampling system or the CVS tunnel. In this case, nucleation under the conditions of the CVS seems to be more favourable.



Drive "C" and Nucleation Particulate



- Drive "C" (note, a different route), sampling pre- Diesel Oxidation Catalyst, shows much higher levels of nucleation material than drives "A" and "B" (with the exception of the regeneration attempt). The white regions at small particle sizes in the contour plot to the left show the high levels of nucleation material.



- This is summarised in the chart to the left, which shows the number of particles per kilometre, normalised to the tailpipe. In general, the DMS50 sampling system produces more nucleation material than the CVS, with the exception of the regeneration attempt, during which more is produced in the CVS.

Conclusions

- Acceleration and Deceleration responsible for much P.M. emission: Slip road to A14 produces ~10% of the mass of a half-hour drive.
- Correlation between peaks and troughs in fuelling and peaks in nucleation mode emission
- Less correlation between fuelling and accumulation mode emission – unknown factor introduced by Exhaust Gas Recirculation.
- DPF regeneration produces large amount of desorbed (assumed) sulphate from the DOC, which forms a large (ca. 50 nm, 4×10^9 cc^{-1}) nucleation mode.
- However, DOC reduces nucleation material during normal driving, by oxidising un-burnt hydrocarbons.
- Vehicle easily meets Euro III emissions standards, even without a DPF, even "off-cycle".
- Remarkable how closely on-road tests can be reproduced under laboratory conditions.

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