Lubricant Formulation Influences Nanoparticle Emissions From Light- and Heavy-duty Diesels

Results and Measurement Experiences

SCAQMD Conference on Ultrafine Particles:

The Science, Technology and Policy Issues

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Introduction

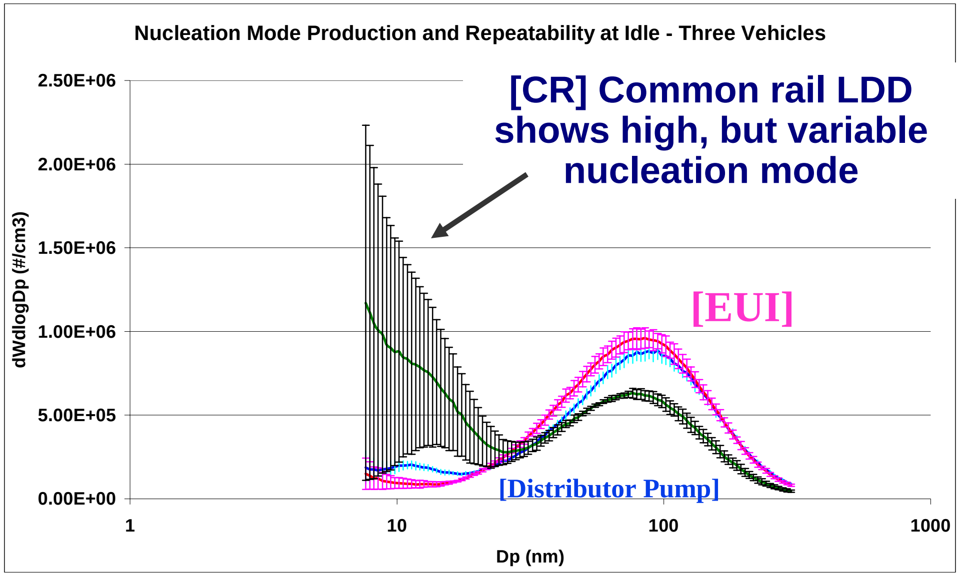
- Experiences and results of measuring and discriminating particle emissions from different lubricants on Diesel engines
- Contents
  - Key Elements of the Experimental Approach
  - Light-duty Diesel Results
  - Heavy-duty Diesel Results
  - Conclusions

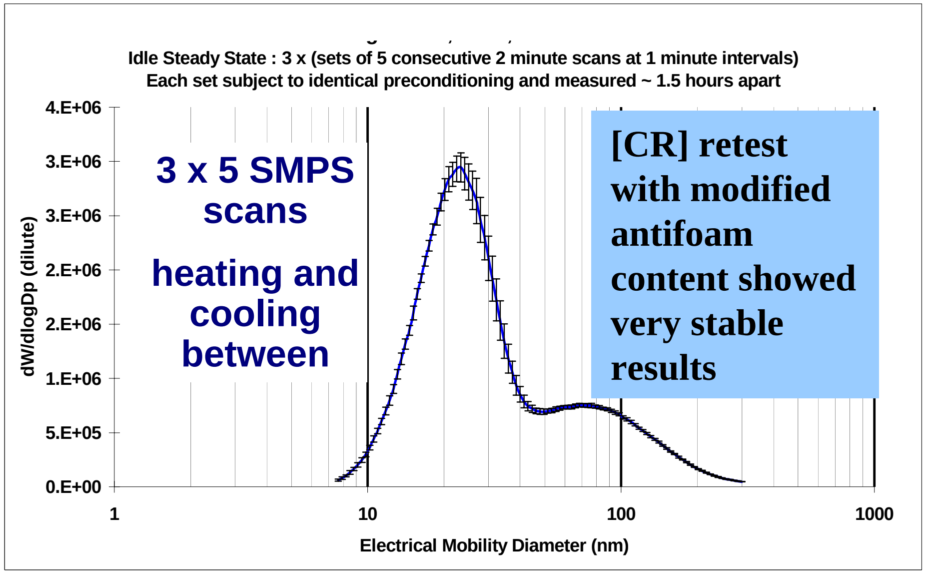
The Experimental Approach Is Key in Enabling Lube-to-Lube Discrimination

- Assume that you're looking for small effects
  - But you might be surprised!
- Source a suitable particle generator
  - Low soot levels to maximise any nucleation mode production
  - Stable operation to limit variability and enable statistical comparisons
- Experimental design
  - Use previous experience to optimise the experiment
  - Rigorous test protocols to ensure repeatable operation test-to-test
    - Closest possible similarity in oil-to-oil testing required
  - Specially formulate the oils to highlight properties for comparison
- Measurements
  - Employ most sensitive measurement techniques available
    - For particles: CNC based, including SMPS
- Statistical Analyses
  - Determine fundamental variability in the system as reference
    - Engine, sampling and measurement system
  - Compare oils within repeatability framework

Selection of particle generators

- Carbonaceous particles are known to suppress nucleation
  - Low soot conditions are required
- Light-duty Diesel vehicle shows nucleation mode at idle
  - Common rail FIE ensures stable particle production
  - Lower soot mode from common rail vehicle led to higher nucleation mode
- Heavy-duty Diesel with efficient wall-flow DPF shows minimal soot at any conditions
  - Majority of particles likely to be nucleation mode
  - Test-bed engine permits very close control of operation





Test protocols

- **Light-duty and heavy-duty Testing**
  - **System Conditioning**
    - LD: exhaust, oxi-cat, transfer tube, CVS tunnel
    - HD: System Conditioning: exhaust, oxi-cat, DPF, dilution tunnels
  - **Regulatory reference tests**
    - LD: Cold start NEDC, Hot starts for repeat data, Idle for size distribution discrimination between oils
    - LD: Hot idle provides the right mix between limited soot, thermal release of volatiles
    - HD: ETC transients for regulatory reference, ESC for 13 mode size distribution discrimination between oils
    - HD: Repeat tests split across 2 days
    - HD: High temperature conditioning with oil change to purge the measurement system
  - **Precise timing for repeatable exhaust temperatures for both LD and HD**

Heavy-duty test protocol

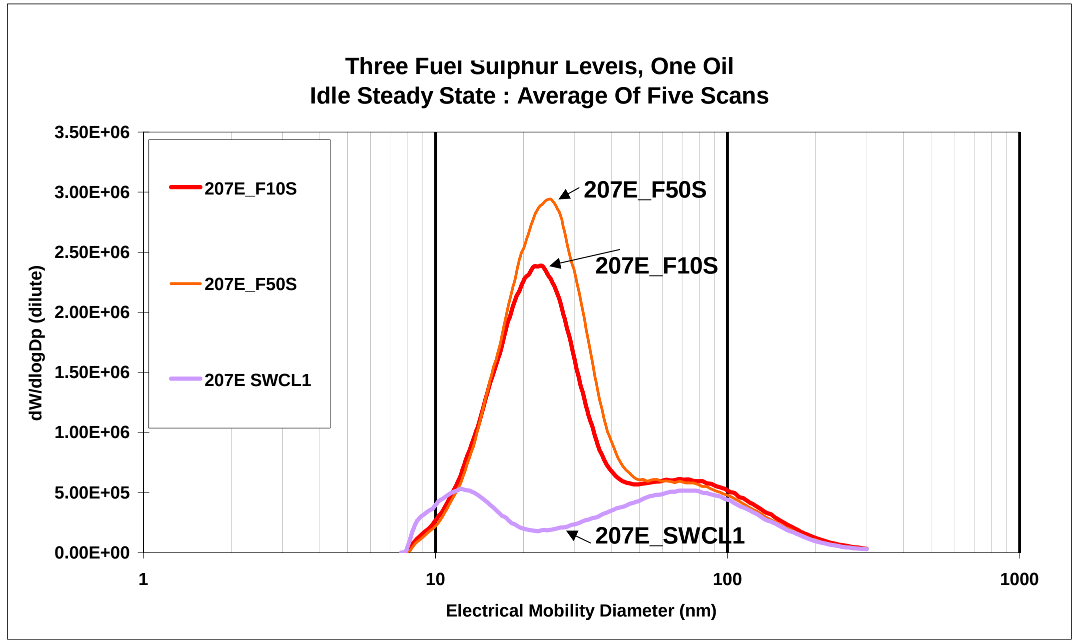
Protocol - Day 1	Protocol - Day 2
4 x ESC, 2 x ETC	**4 x ETC, 2 x ESC**
Warm-up	Warm-up
Power curve	Power curve
ESC	ESC
Stabilisation: ESC Mode 4	Stabilisation: ESC Mode 4
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ESC 1	**ETC 3**
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ESC 2	**ETC 4**
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ESC 3	**ETC 5**
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ESC 4	**ETC 6**
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
Precondition Mode 4	Precondition Mode 4
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ETC 1	**ESC 5**
Continuity: Modes 1 and 4	Continuity: Modes 1 and 4
ETC 2	**ESC 6**
Oil Change (if required)	Oil Change (if required)

Light-duty Results and Experiences

Three Fuels Evaluated: Nucleation Mode highest with highest S Fuel

- Fuel sulphur effect on nucleation mode expected
  - Three Fuels were tested
    - F10S (EN590, 10ppm S)
    - F50S (EN590, 50ppm S)
      - F10S doped
    - Swedish Class 1
      - High volatility: low T95
      - Low sulphur (~3ppm)

	SWCL1	F10S	F50S
density (kg/m3)	812	824.6	824.6
T10 (°C)	197.8	202	202
T50 (°C)	226.3	250	250
T95 (°C)	**280**	**340**	**340**
S (ppm)	3	10	50
H:C	2	1.79	1.79

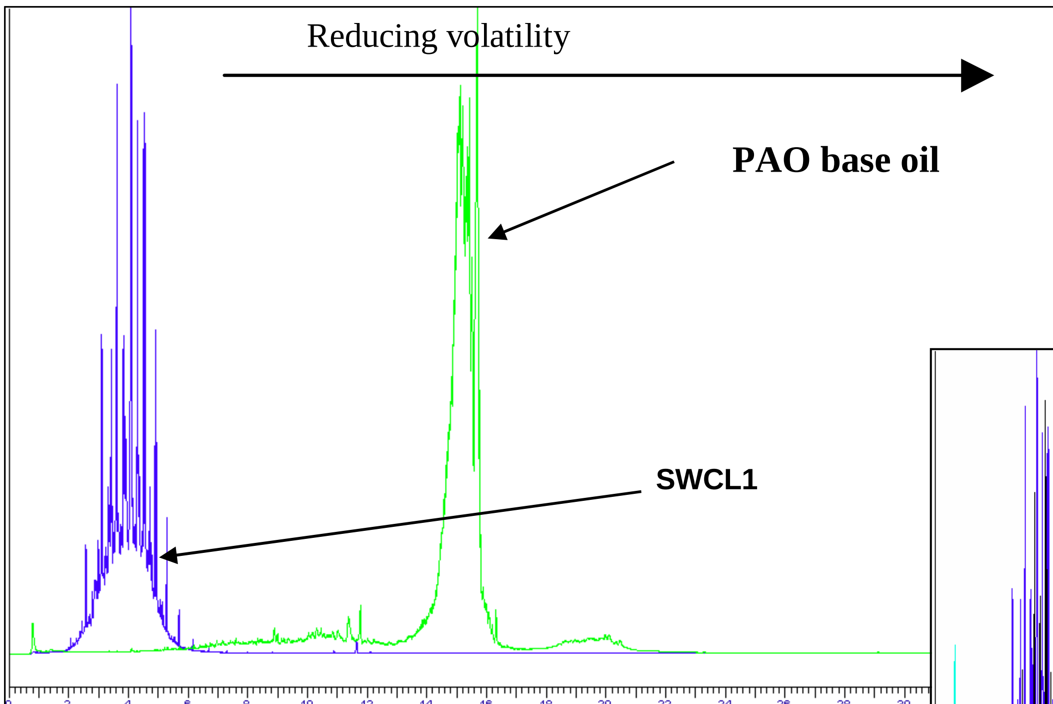


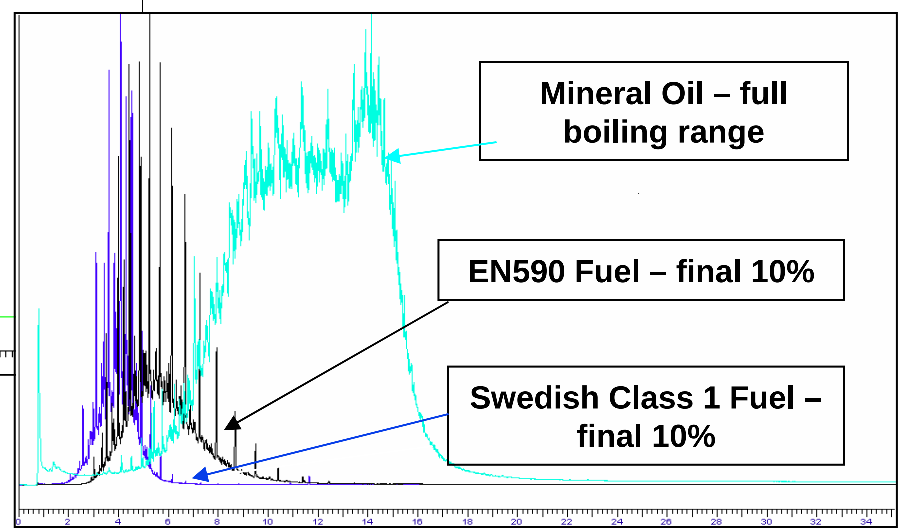
- Several experiments were conducted
  - Difference between nucleation modes from F10S and F50S was relatively small when one oil tested
  - Lube tests on ‘extreme’ oils proved difficult to discriminate on F10S despite ‘low sulphur’
  - SWCL1 nucleation and accumulation modes were smaller than F10S; so lube effects appear larger compared to fuel effect
- Sulphur is not the only driver for nucleation mode formation, T95 appears to be important

Swedish Class 1 (SWCL1) fuel selected

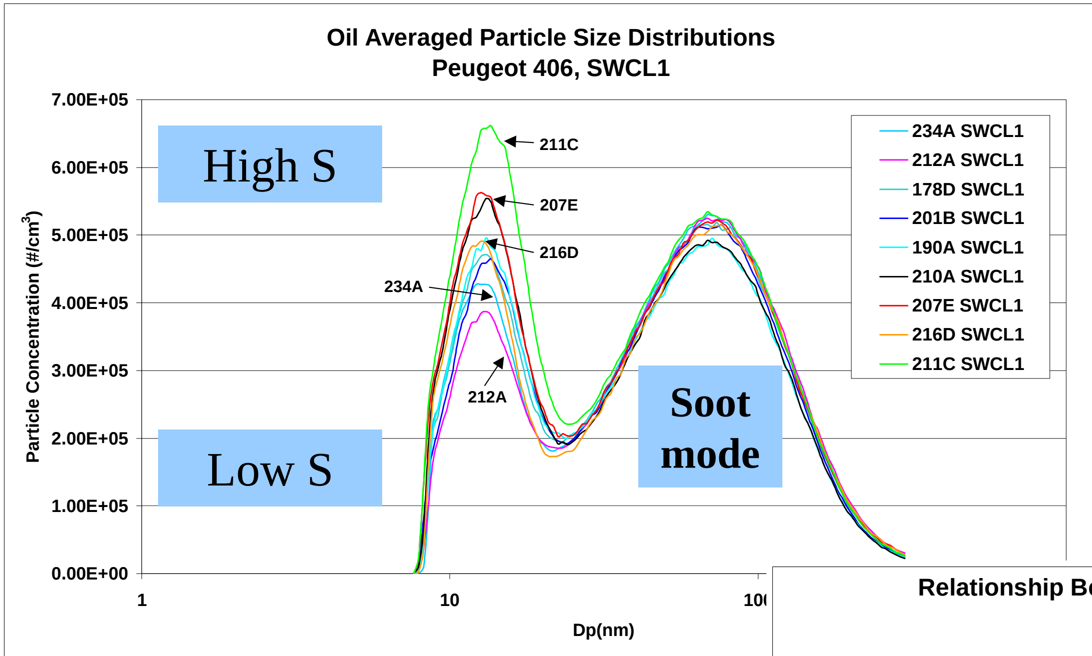
- Assumptions that sulphur and lubricant basestock may be major influences on particle production
  - Greatest differential between fuel and lubricant volatility desirable
  - Low sulphur fuel required (<3ppm)

- SWCL1 Enables:
  - **Volatility effects of lubricants to be elucidated**
  - **Sulphur effects of lubricants to discriminated from fuel effects**



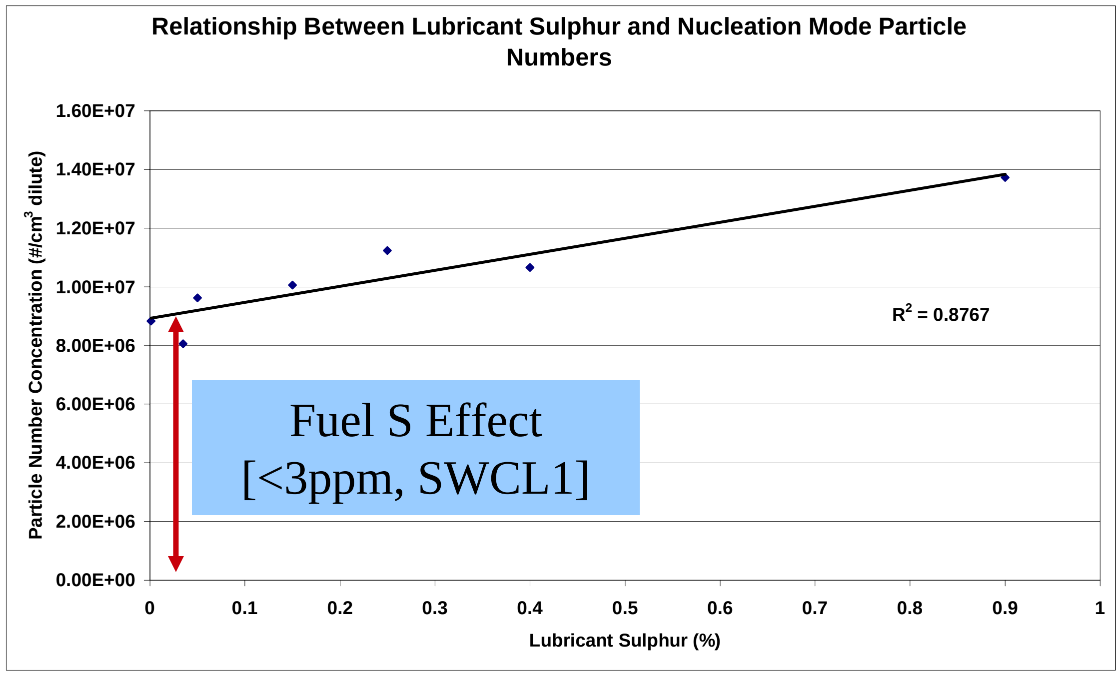


Magnitude of Nucleation Mode Scales With Lubricant Sulphur level



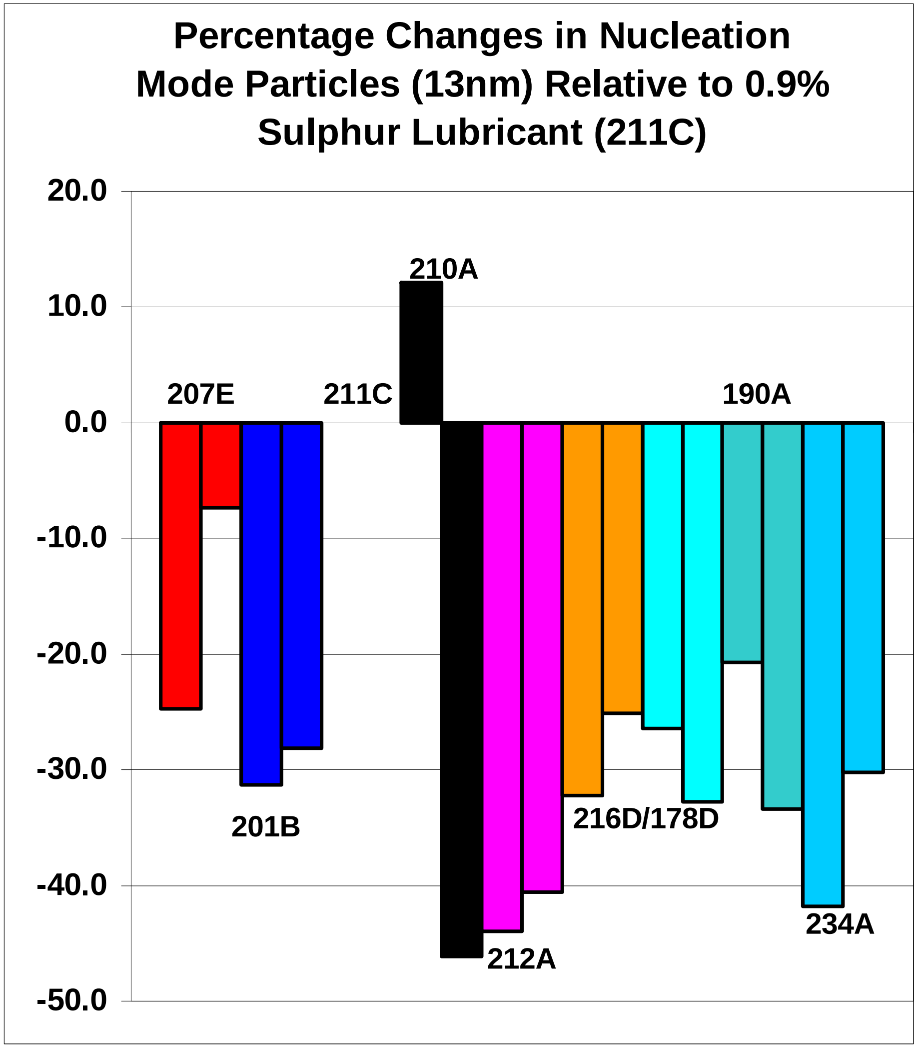
- Highest S lubricants (0.9%, 0.4%) show highest <30nm particle numbers
- Lowest S lubricants (zero, 0.05%) show lowest <30nm particle numbers
- Soot mode differences small and not directly linked with lube properties

Linear Relationship between Sulphur and Integral of Nucleation Mode Particle Numbers



Statistical Analyses Show Reductions in Both Sulphur and Phosphorous can Reduce Particle Number Emissions

- **Multiple regression analyses showed**
  - A reduction in nucleation mode particle numbers of > 40% proved possible with a reduction in lubricant sulphur from 0.9% to 0.02%
  - These data also show that an independent reduction in particle numbers of up to 15% can be achieved by a reduction in lubricant phosphorus from 0.1% to zero
- **Data were significant at 99% confidence**
- **On a mass basis the phosphorus effect was greater than the sulphur effect**



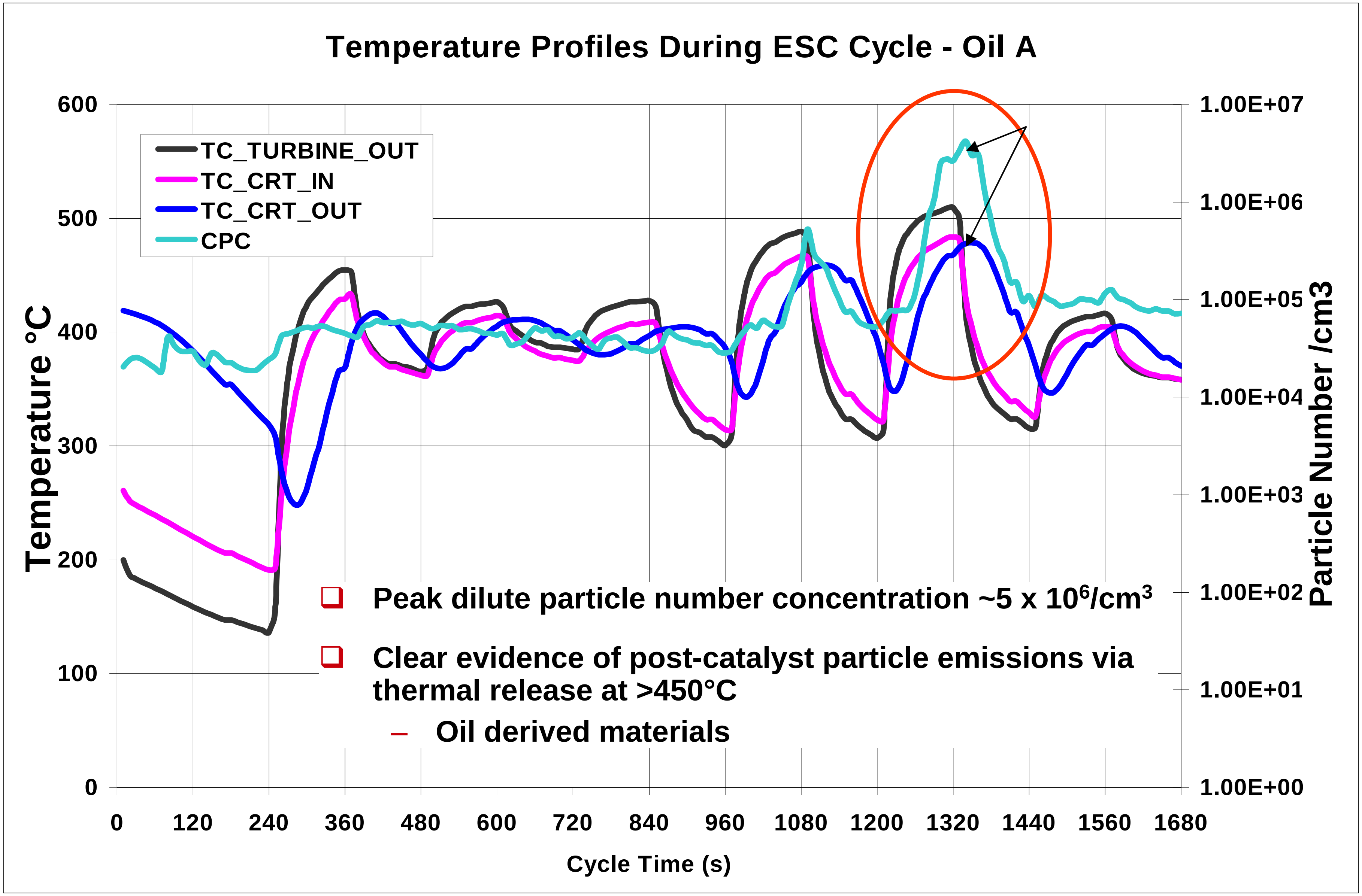
Heavy-duty Results and Experiences

Condensation Particle Counter Measurements

Swedish Class 1 Fuel

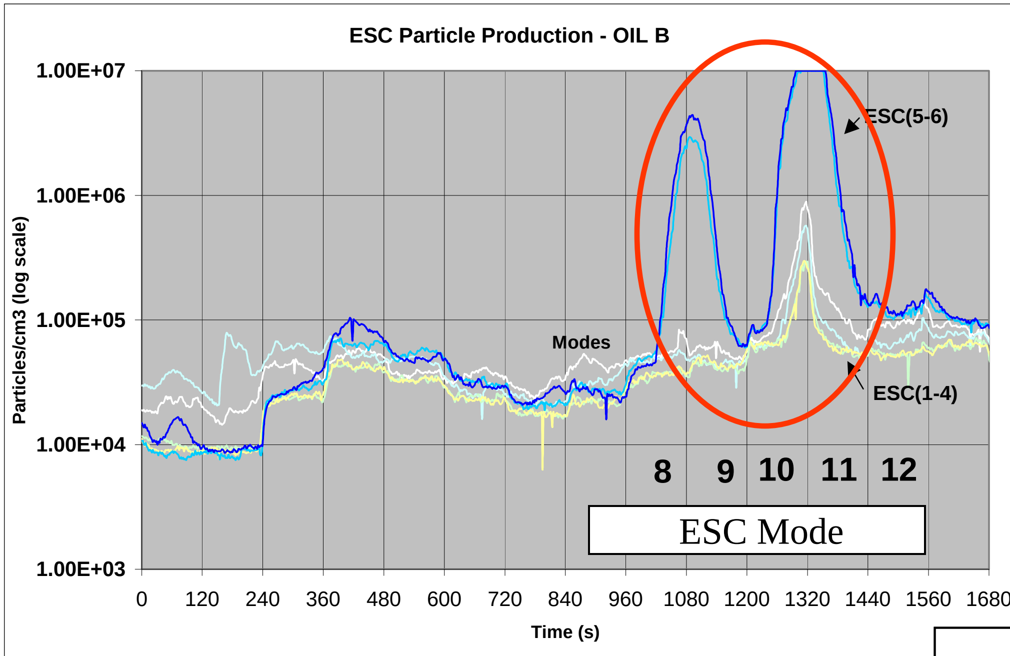
HD Diesel Engine equipped with a DPF

During latter part of ESC cycles, particle number emissions were in response to catalyst-out temps; cooler ETC did not show this effect

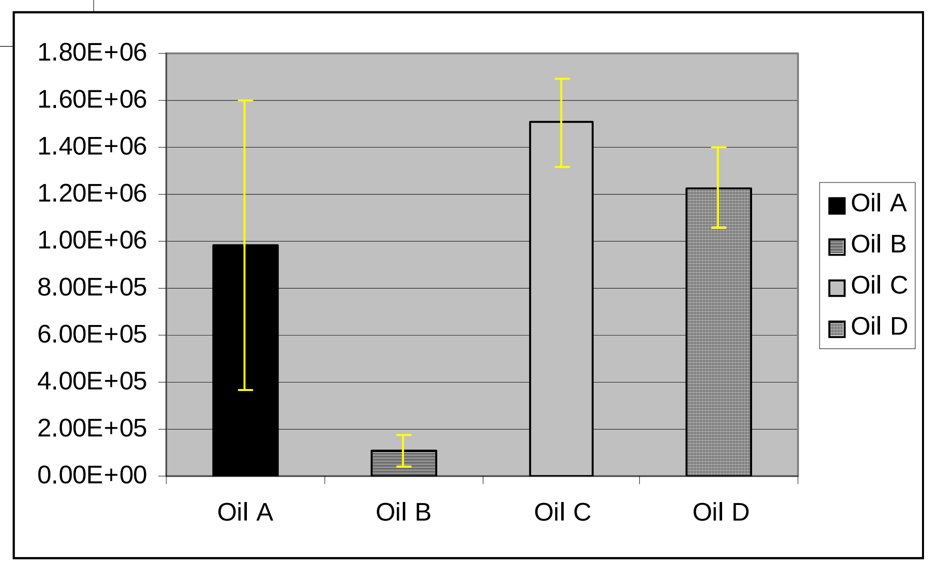


- Peak dilute particle number concentration ~5 x 10^6/cm^3
- Clear evidence of post-catalyst particle emissions via thermal release at >450°C
  - Oil derived materials

Particle number emissions from ESC show large influence of test protocol

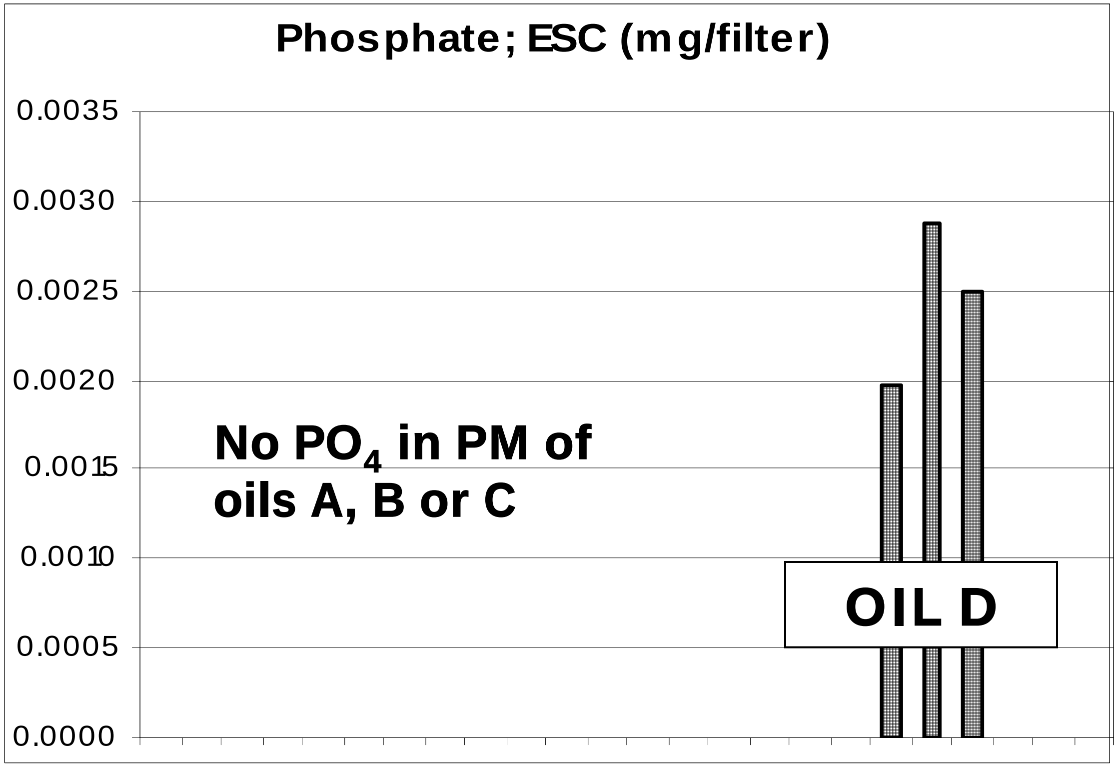


- ESC Cycles which precede ETC cycles have lower emissions levels
- ESC cycles which follow ETC tests emit materials stored during those cooler cycles



- Comparisons between oils omit the high tests and address the weighted ESC Cycle
- Oil B emissions are then shown to be significantly lower than other oils at 95% CI (2-sigma)
  - Oil B is Low SAPS with synthetic base

Simple elemental analyses of oils do not predict tailpipe oil related emissions



- Phosphates were only detected in the particulate phase during operation on Oil D, but this was not the highest phosphorus containing oil
  - Oils C and A both contained substantially more phosphorus

Summary

Light-duty Diesel Vehicles

- Lubricant derived sulphur was found to be a statistically significant influence on nucleation mode particle number at the 99% confidence level.
  - This analogous to the well recognised fuel sulphur effect.
- Unexpectedly, oil derived phosphorus also had an adverse effect on nucleation mode particle production at the 99% confidence level.
  - The phosphorus effect was greater on a mass basis than the sulphur effect.
- Increasing fuel ‘back-end’ volatility (T95) has an unexpectedly large effect on increasing nucleation mode particle production
  - A lower final boiling point fuel gave the best lubricant discrimination.
  - There are additional lubricant factors present other than S and P which effect nucleation mode particle production

Heavy-duty Engines

- Test cycle impacted significantly on particle production with the hotter ESC conditions appearing to give best conditions for lubricant discrimination for nucleation particles.
  - Running cooler cycles prior to hot ones leads to storage and release phenomena
- A low SAPS oil with a synthetic base was found to give statistically significantly lower nucleation particle numbers than a mineral and other formulations
- Formulation effects leading to the reduction in nucleation particles could not be fully explained by elemental compositional analysis.
- A DPF gave significant reductions in both nucleation and accumulation mode particles.

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