10th ETH-Conference on Combustion Generated Nanoparticles

Particulate Emissions from a Gasoline Homogeneous Charge Compression Ignition Engine

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Introduction

Particulate Emissions from Homogeneous Charge Compression Ignition (HCCI) combustion are routinely assumed to be negligible. It is shown here that this is not the case when HCCI combustion is implemented in a direct injection gasoline engine.

HCCI is of interest primarily because it offers the potential for significant improvements in thermal efficiency and low emissions of oxides of nitrogen at steady state operating points compared to conventional spark ignition engines. Thermal efficiency is higher in HCCI engines because they operate unthrottled, the load being controlled by dilution, in this case, with residual exhaust gas. Dilution is also responsible for the reduced emissions of oxides of nitrogen; the combination of dilution and raised heat capacity decreases the peak burned gas temperature, and this has the effect of decreasing the rate of thermal NO formation. It also decreases the energy release rate, keeping the rate of pressure rise to an acceptable level.

Direct Injection enables a higher compression ratio to be used, thus extending the HCCI light load limit, and it means that the injection timing can be used as a control parameter for combustion phasing.

In the experiments described here, the engine was a Jaguar V6 with a wall guided direct injection combustion system. The valvetrain was modified to permit operation in HCCI mode. Modifications include two profile camshafts for inlet and exhaust valves, both with 60 degree cam phasing systems. More details can be found in Xu *et. al.* The conditions needed to sustain HCCI operation were realized using the negative valve overlap method for trapping high levels of residual exhaust gases in the cylinder. Measurements of emitted particle number concentration and electrical mobility diameter were made with a Cambustion DMS500 over the entire HCCI operating range. Emissions of oxides of nitrogen, carbon monoxide and unburned hydrocarbons were also measured. These data are presented and compared with similar measurements made under conventional spark ignition (SI) operation in the same engine.

Under both SI and HCCI operation, a significant accumulation mode was detected with CMDs between 80 and 100 nm. Where comparisons were possible, the number concentrations from HCCI combustion were slightly higher than from SI. Moreover, the number concentration of accumulation mode particles varied inversely with the amount of residual gas trapped, and hence in direct proportion to the nitric oxide emissions. This is the opposite of the well known particulates-NO tradeoff that can be observed in conventional compression ignition engines, and is thought to be because the extra heat in the intake and compression strokes improves the mixture preparation. A nucleation mode was also observed with CMDs between 10 and 20 nm. The nucleation mode was most concentrated when the levels of residual gases was very high (c55%), correlating to the lowest temperatures in the expansion stroke and highest emissions of unburned hydrocarbons.

The suggested contributors to PM formation in DI gasoline HCCI engines are:

- **Wall wetting:** A significant proportion of the PM formed in DI engines can be attributed to the impingement of fuel on the combustion chamber surfaces. Locally rich regions occur as fuel diffuses from these surfaces.
- **Gas to particle conversion of unburned hydrocarbons:** Emissions of UHCs are high because the temperature in the expansion stroke is too low for effective oxidation of the HCs diffusing out of the crevice volumes back into the bulk gas. This HC vapour becomes super-saturated when the exhaust cools and liquid particles form by condensation nucleation. The contribution to the total PM from this mechanism is expected to be higher in a HCCI engine than in SI.
- **Charge inhomogeneity:** In DI engines, the time available for mixing is only a few tens of ms, and so the local air-fuel ratio can vary significantly even in *homogeneous* charge engines. Pyrolysis is dominant in the locally rich regions and so carbonaceous particles are formed.
- **Lubricating Oil and Fuel Sulphur**. As in an SI engine, sulphates and lube oil particles are likely to contribute particularly to the nucleation mode.

In summary, it was shown by experimental measurements that the number concentrations of emitted particles from HCCI combustion in a gasoline direct injection engine are similar in size and concentration to those from conventional direct injection gasoline operation, and thus are non-negligible.

References

Xu, H. *et. al.*, Modelling of HCCI Engines: Comparison of Single-zone, Multi-zone and Test Data. SAE Technical Paper 2005-01-2123.

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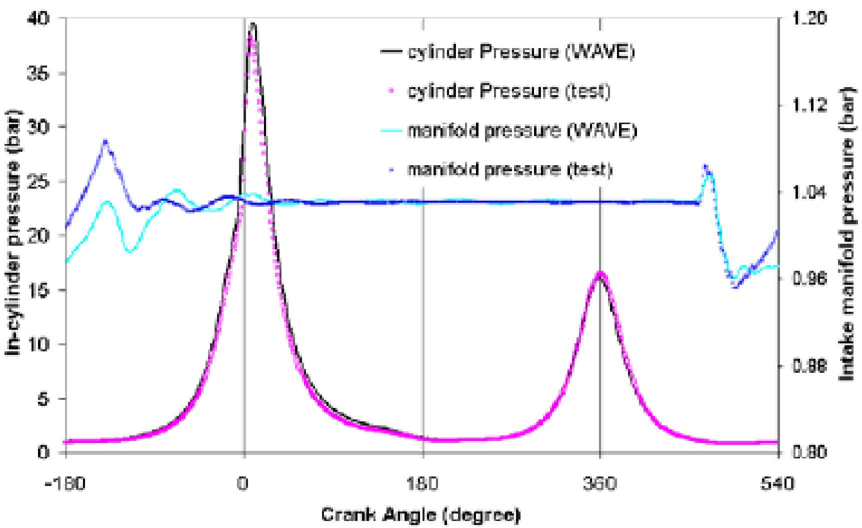
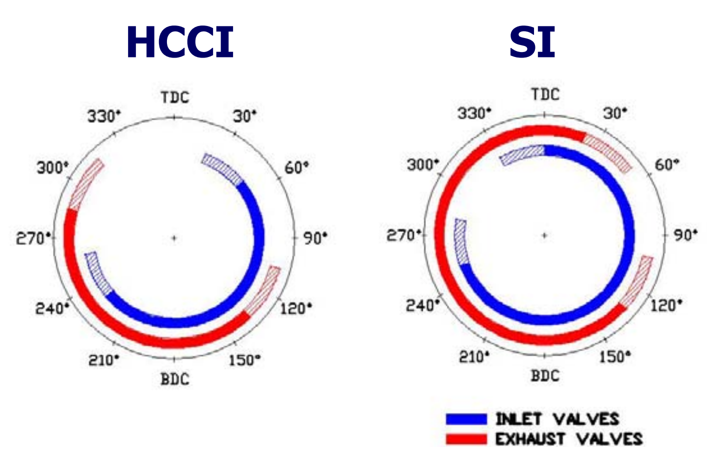
Background: Negative Valve Overlap HCCI

- HCCI: Auto-ignition of a homogeneous mixture through compression.
- Very low throttling loss. → Up to 20% improvement in fuel economy has been demonstrated.
- Combustion temperatures are low, so there is not much production of thermal NO. For the same reason, emissions of CO and HC are higher than from conventional combustion.
- Load controlled by varying the residual gas fraction in the cylinder.



Valve Timing



HCCI Particulate Emissions?

Direct fuel injection is likely to be because:

- charge cooling at high load hence higher volumetric efficiency
- Injection timing is a control parameter for combustion phasing
- Enables a higher compression ratio, so extends the HCCI light load limit

Wall wetting is inevitable, followed by diffusive burning from surfaces.

Time for mixture preparation limited -→ Local Air Fuel ratio variations.

High residual gas fraction leads to lower combustion temperatures -→ Reduced HC Oxidation rate & less effective post normal combustion oxidation -→ High HC emissions

If HC emissions are increased we might also expect an increase in the VOF formed by gas-to-particle conversion of unburned or partially burned fuel.

Contribution from lubricating oil and Sulphur in the fuel.

Gasoline HCCI Engine

Engine:

Bore & Stroke: 89 x 79.5 mm

Compression Ratio: 11.2: 1

Fuel: Reference ULG

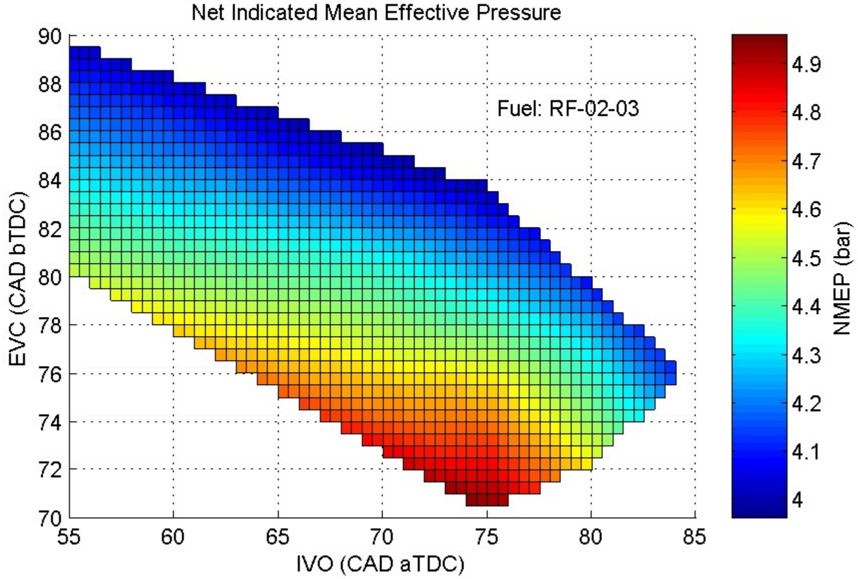
Instrumentation:

Cambustion DMS500: PM number & size

Cambustion fastFID: Unburned HCs

Non-Dispersive IR: [NO], [CO], [CO_2]

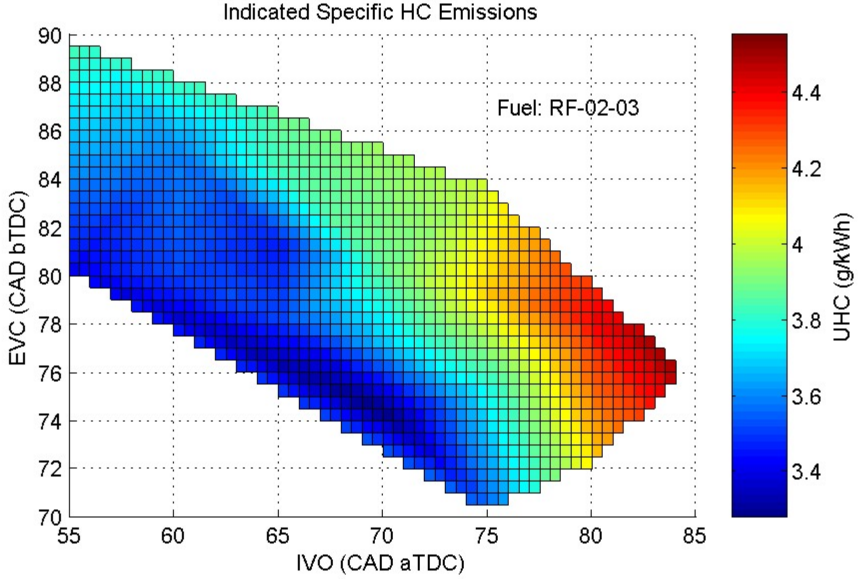
Load and Gas Phase Emissions

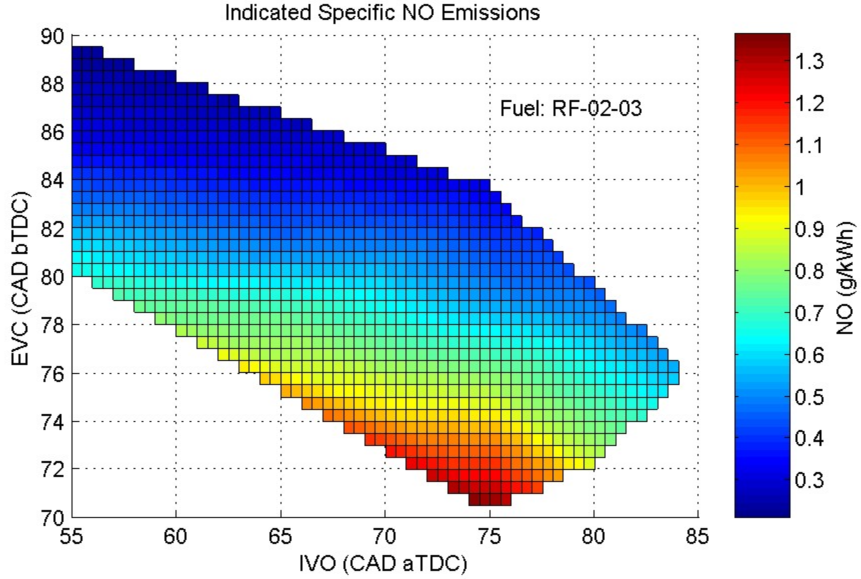


1500 rpm, λ=1.0

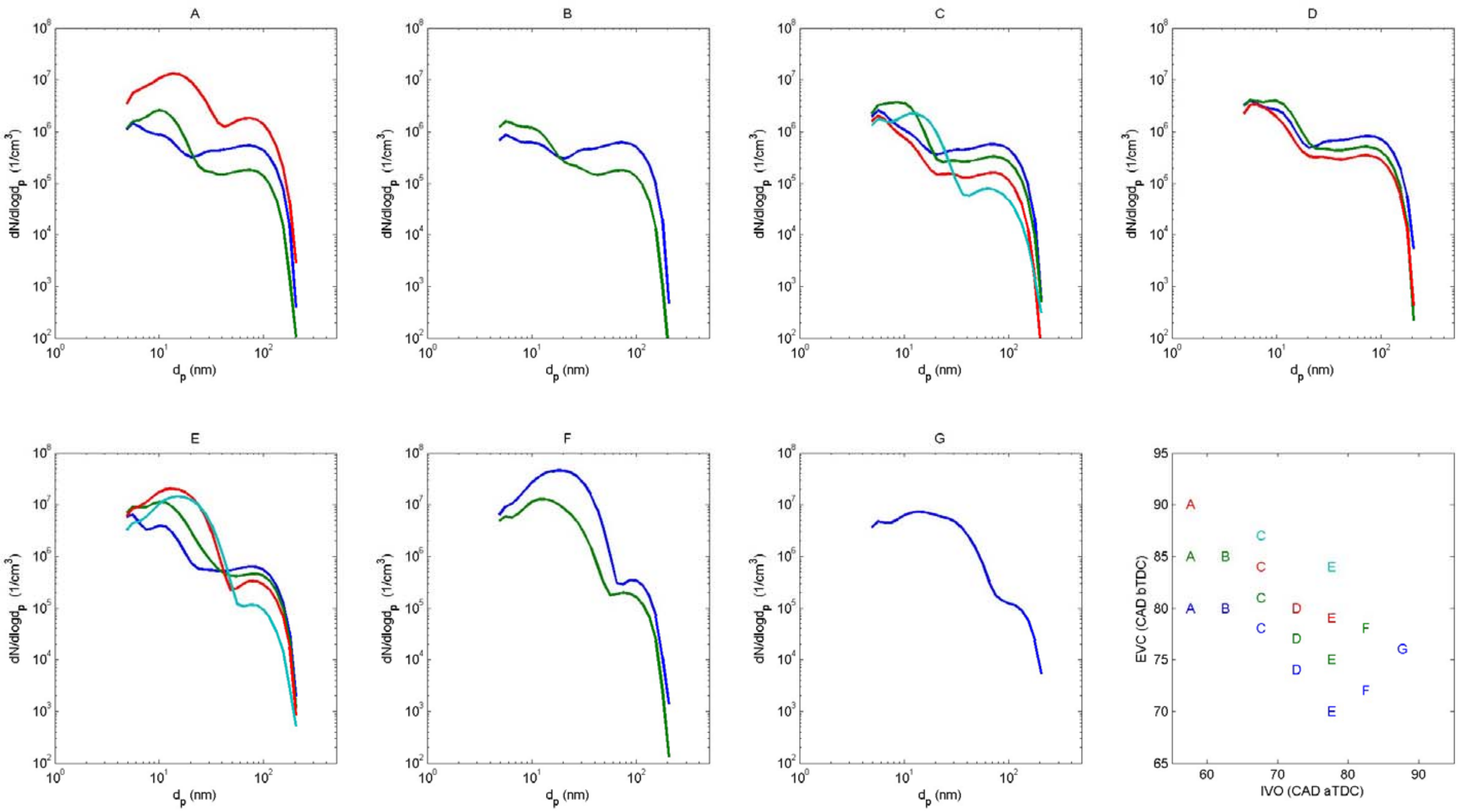
Reference ULG

IMEP is nearly a sole linear function of the trapped residual gas quantity.





PM size distributions - HCCI

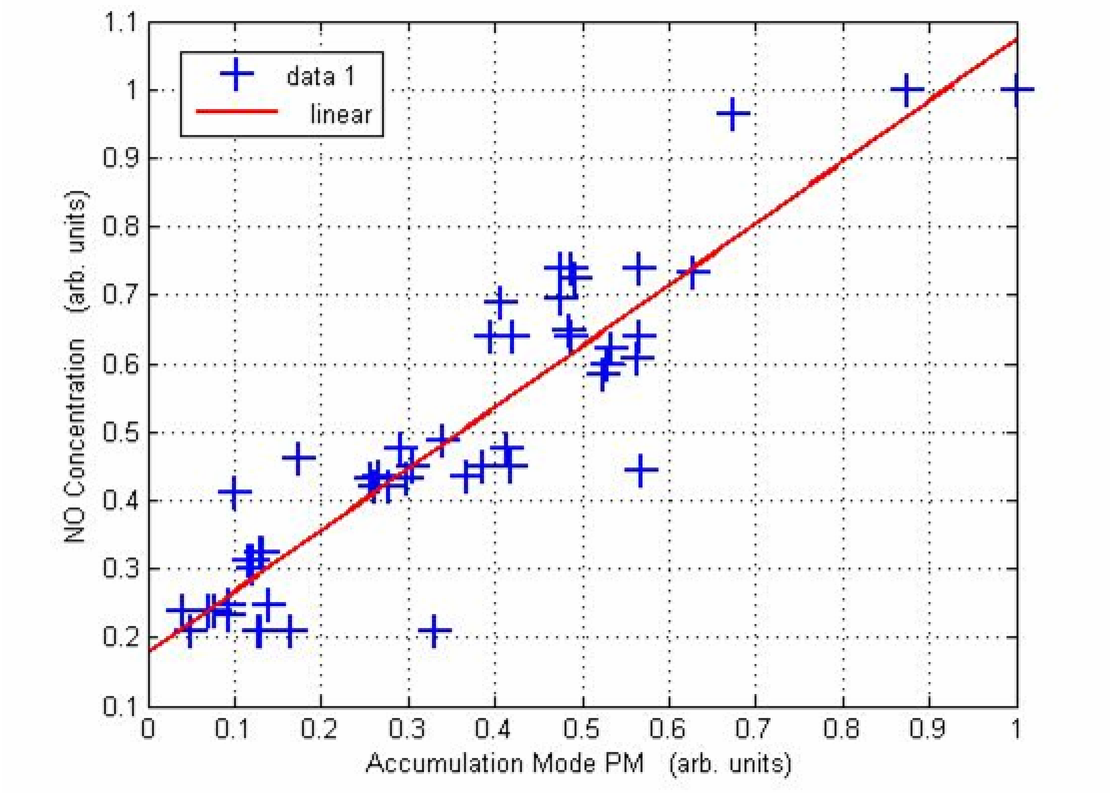


1500 rpm, λ=1.0, Reference ULG

Particulates – Nitric Oxide

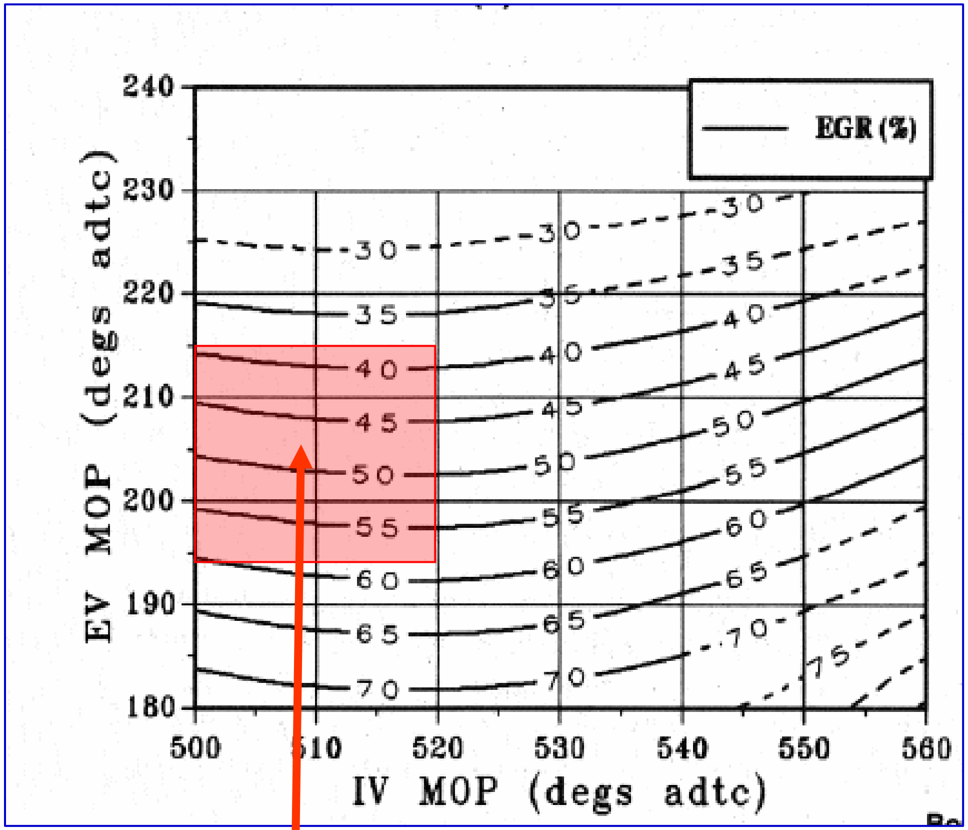
Rate of thermal NO formation α peak burned gas temperature (T)

Residual gas decreases T but this usually increases PM because it slows the oxidation rate and leads to partial burns.



With auto-ignition (HCCI), residuals improve mixture preparation, but decrease oxidation in the expansion stroke. Burn rates are not diffusion limited PM scales with load, rather than with EGR.

Residual Gas Fraction and Mixture Preparation

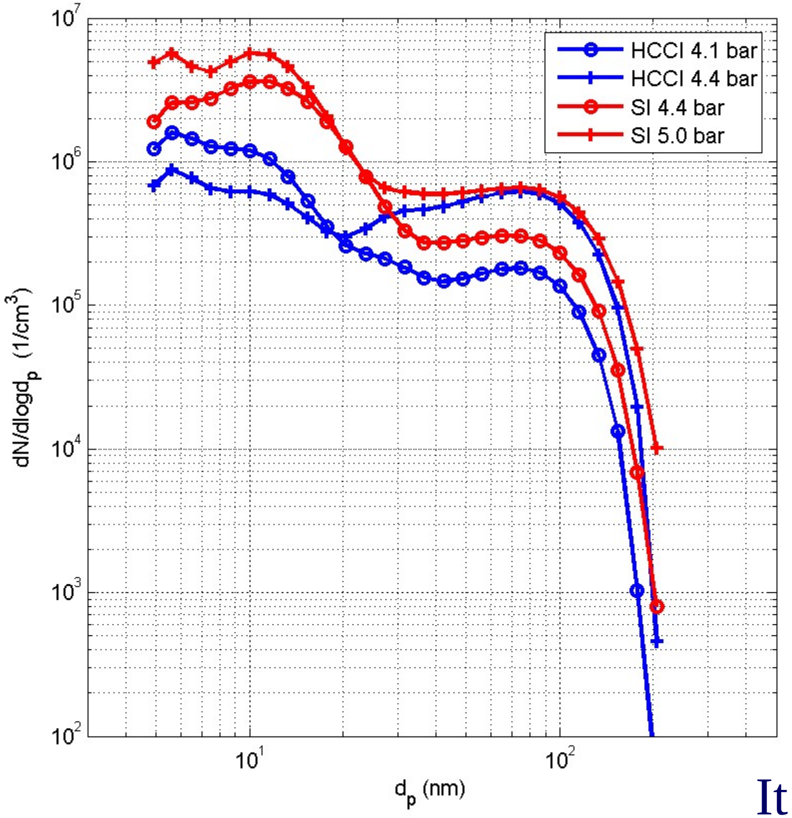


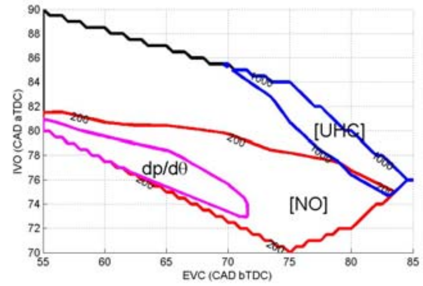
Source: Xu, H *et. al.* JSAE 20030333.

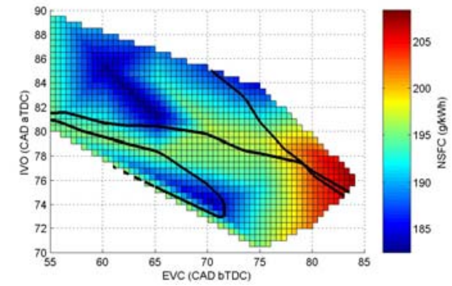
Range used in experiments

Temperature in the intake stroke: 200 < T< 400 degC

PM size distributions – HCCI and SI







It is possible to get many different emissions data-sets for the same load with HCCI

At the same load (4.4 bar), the # concentration of the acc' mode from HCCI is a factor of ~3* > than from SI

However, the # concentration of the nuclei mode is ~4 times lower

Conclusions - Particulates

- Meaningful comparison with SI requires caution because of there are several combinations of valve timing that can give the same operating point, each with different emissions
- PM emissions have been measured and were <u>non-negligible</u>
- Compared to SI at the same operating point, PM Number concentrations were found to be higher in the accumulation mode by about a factor of 3, but the nuclei mode number concentrations were lower.
- These levels put HCCI somewhere between first and second generation early injection DISI. This is still one or two orders of magnitude lower than diesel
- With HCCI, the accumulation mode PM concentration varies inversely with the amount of residual gas. Since NO emissions vary proportionally to residuals, this leads to the opposite of the well known PM-NO_x trade off in diesel engines

Thank you for listening

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Fuel Composition

-	RF*	ULG**
Density (kg/m^3)	751.6	739.8
Sulphur Content (mg/kg)	<1	19
Olefins (% vol.)	2.9	11.53
Aromatics (% vol.)	33.2	32.29
Saturates (% vol.)	59.3	43.82
Benzene (% vol.)	<0.1	0.72

Table 1: Fuel Properties

* Reference Fuel CEC RF-02-03. Analysis by Petrochem Carless Limited.

* Birmingham University Pump ULG. Analysis by Shell Global Solutions.