Shell Global Solutions

Fuel requirements in engines using premixed and partially premixed compression ignition combustion

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Premixed compression ignition for low-NOx and low-smoke

- Promoting mixing of fuel and air before ignition to reduce smoke
- Low-temperature combustion to reduce NOx – lean mixtures + EGR, heat release after TDC….
- Engine Ignition Delay, EID = CA50 –SOI, measure of mixedness
- HCCI is one end of this spectrum (high EID)– fully premixed, lean (flame front not sustainable). Low load, high HC and CO, difficult to control.
- Practical implementation in diesel engines – Toyota UNIBUS system (early fuel injection/HCCI), Nissan MK (late injection + EGR) “premixed enough” combustion.

Fuel Quality for Premixed Autoignition

Primary quality is the autoignition quality –

The mixture should autoignite – a problem at low load

Heat release rate should not be excessive – a problem at higher loads

Fuel should also be volatile enough for it to be fully mixed with air – otherwise no HCCI, excessive smoke

Engine control can be used to overcome deficiencies in fuel quality to some extent.

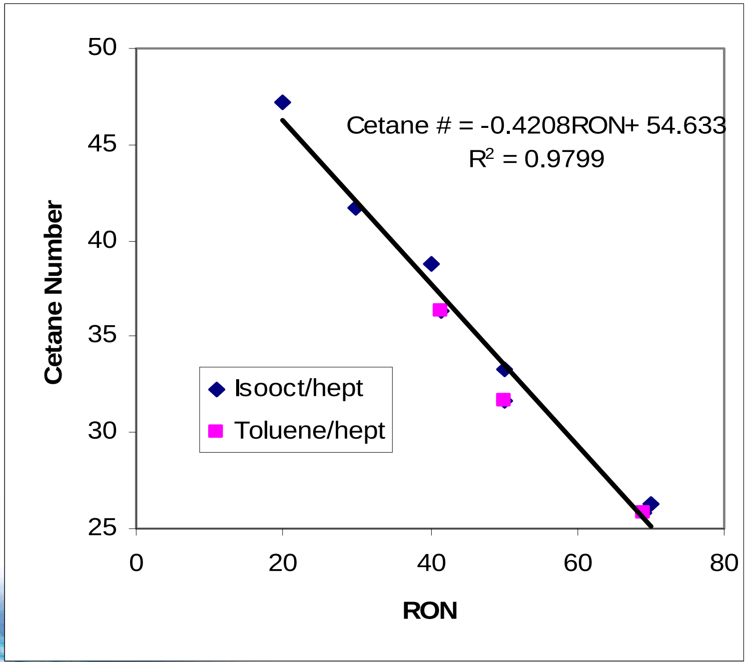
Auto-ignition quality, the critical property

This is true for partially pre-mixed case as well

Autoignition quality – empirical approaches

Conventionally measured by

- RON and MON for gasolines
- Cetane Number (CN) or Derived Cetane Number based on an ignition delay measurement for diesel fuels



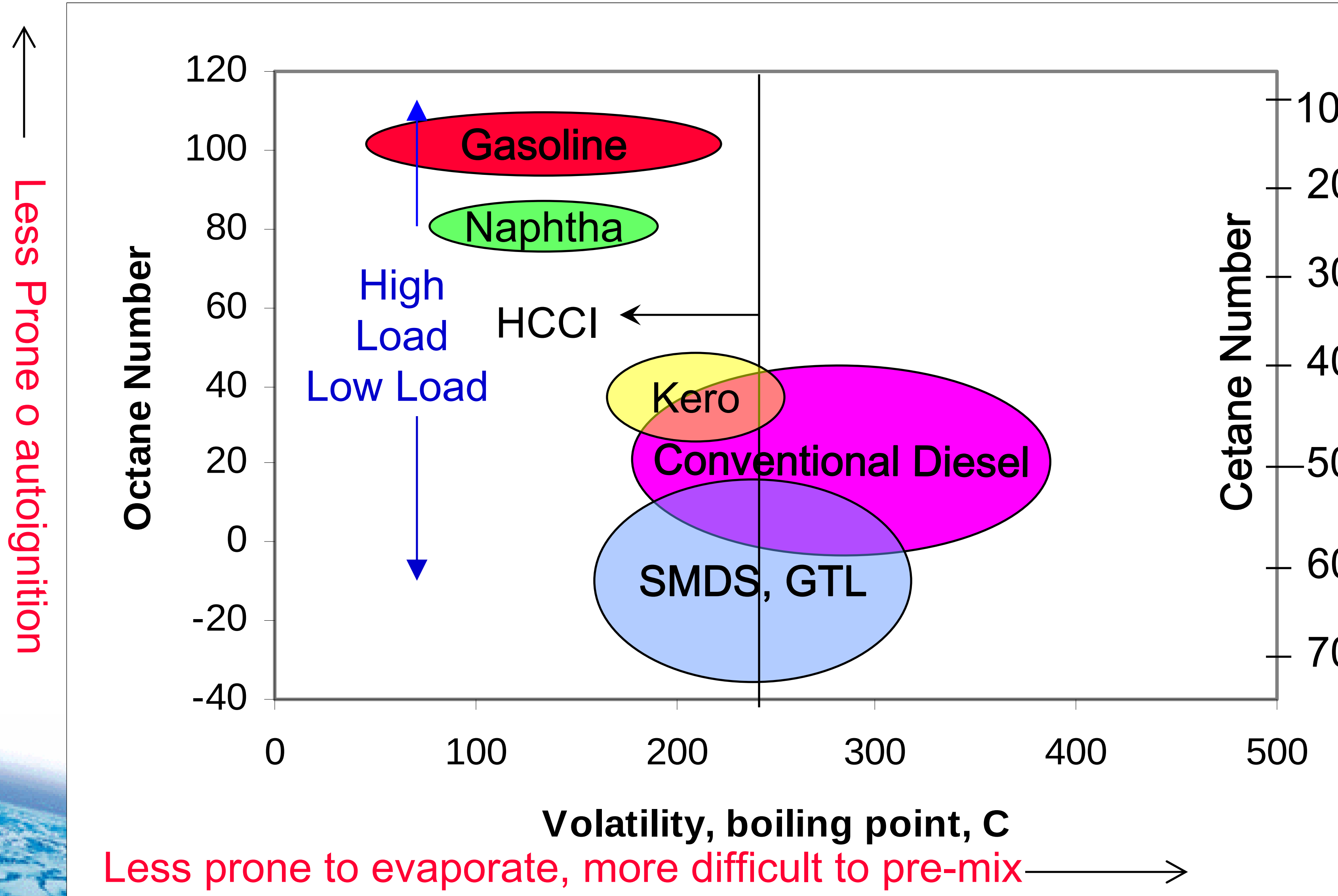
Good correlation between different measures where comparison is possible.

If RON <~60, CN >~30, Diesel-like fuel

Autoignition Quality of Practical Fuels

- For gasoline-like fuels (RON >60) defined by the Octane Index, OI = RON – KS, S is sensitivity = RON – MON, K is a constant depending on pressure/temperature in the gas and varies widely for the same engine.
- The requirement, OI_0, of the engine varies widely.
- The same sensitive (non PRF) fuel can behave like different PRF depending on the value of K. OI of a sensitive fuel changes in the same direction as OI_0. Also with high temperatures differences between fuels decrease.
- For diesel-like fuels, Cetane Number (CN) > 30, CN is a good measure of autoignition quality.

Autoignition Quality vs Volatility



Fuel for premixed CI

An engine can be run in such a mode on almost ANY fuel if the operating conditions are chosen properly

A good fuel is one which enables a wider range of operation

Fuels which are more resistant to auto-ignition can be made to auto-ignite by raising the initial temperature by say using a lot of internal EGR at low load – easier in bigger engines

The real challenge is to get premixed combustion at high loads.

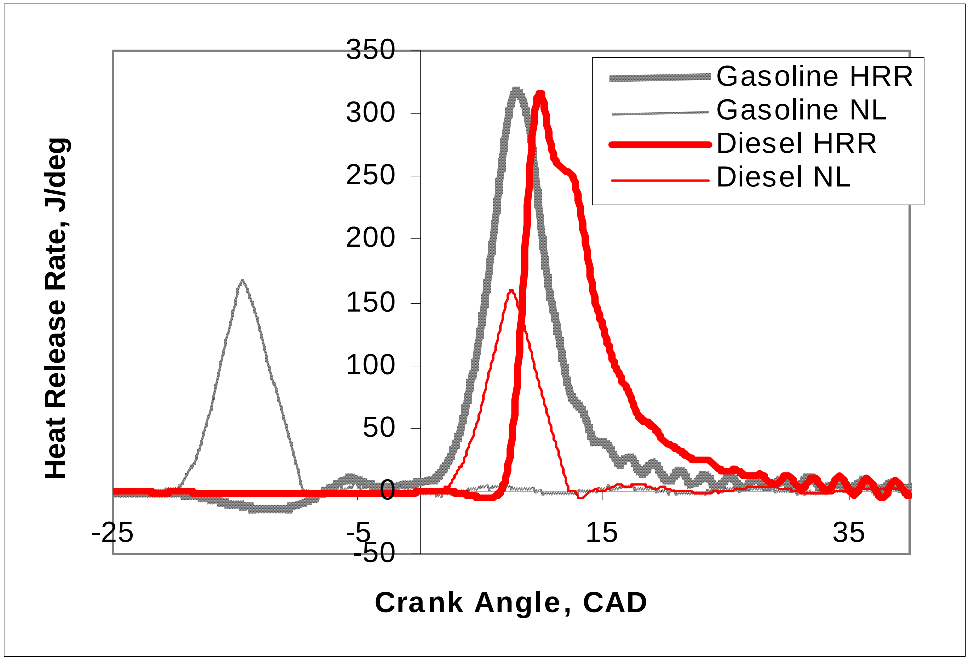
Stratification (partial premixing) helps.

Partially Premixed – "Premixed Enough" Compression Ignition (CI)

- In practice, HCCI obtained by early injection of fuel
- In HCCI, no control over phasing of heat release which is determined entirely by chemical kinetics. High heat release rate restricts high load.
- With much later injection, near TDC, enough premixing of fuel and air can be achieved to reduce smoke and NOx while regaining control on combustion phasing. This enables much higher loads to be achieved.

Fuels with more auto-ignition resistance are much better because of higher Ignition delay

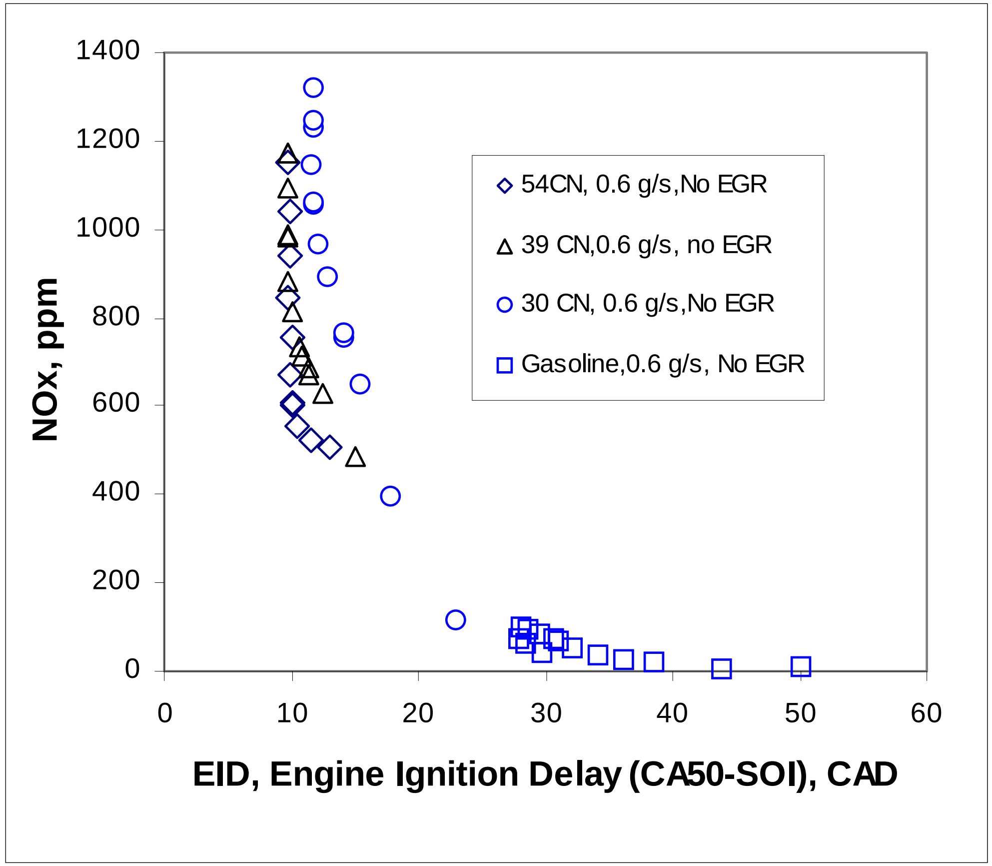
Comparison between gasoline and diesel (Swedish MK1) heat release patterns



0.6 g/s, No EGR, Pin =1.5 bar abs, Tin = 40 C, 1200 RPM

Low smoke (< 1% AVL opacity) because of high oxygen for both fuels concentration but higher NOx with diesel.

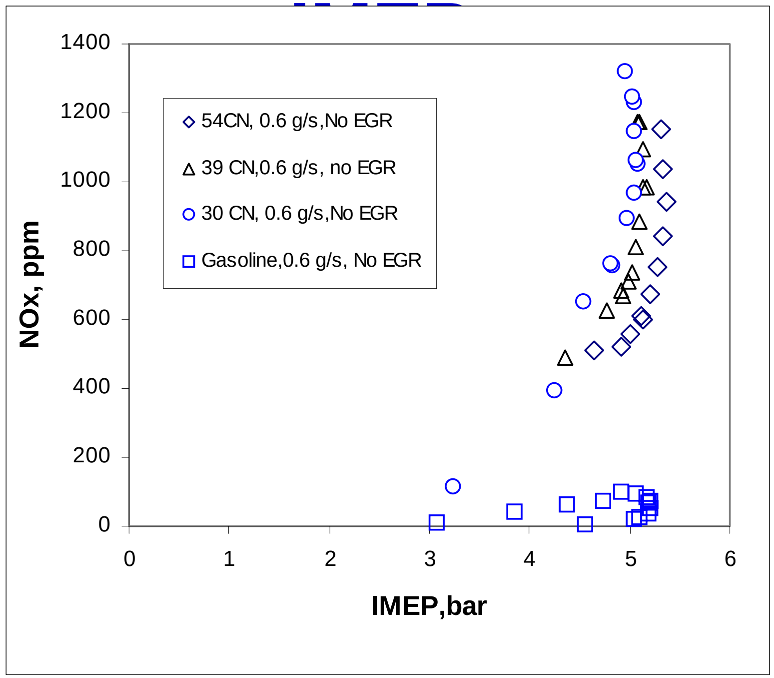
Comparison between different fuels - NOx



0.6 g/s, No EGR, Pin =1.5 bar abs, Tin = 40 C, 1200 RPM

NOx decreases with ignition delay

Comparison between different fuels– NOx and

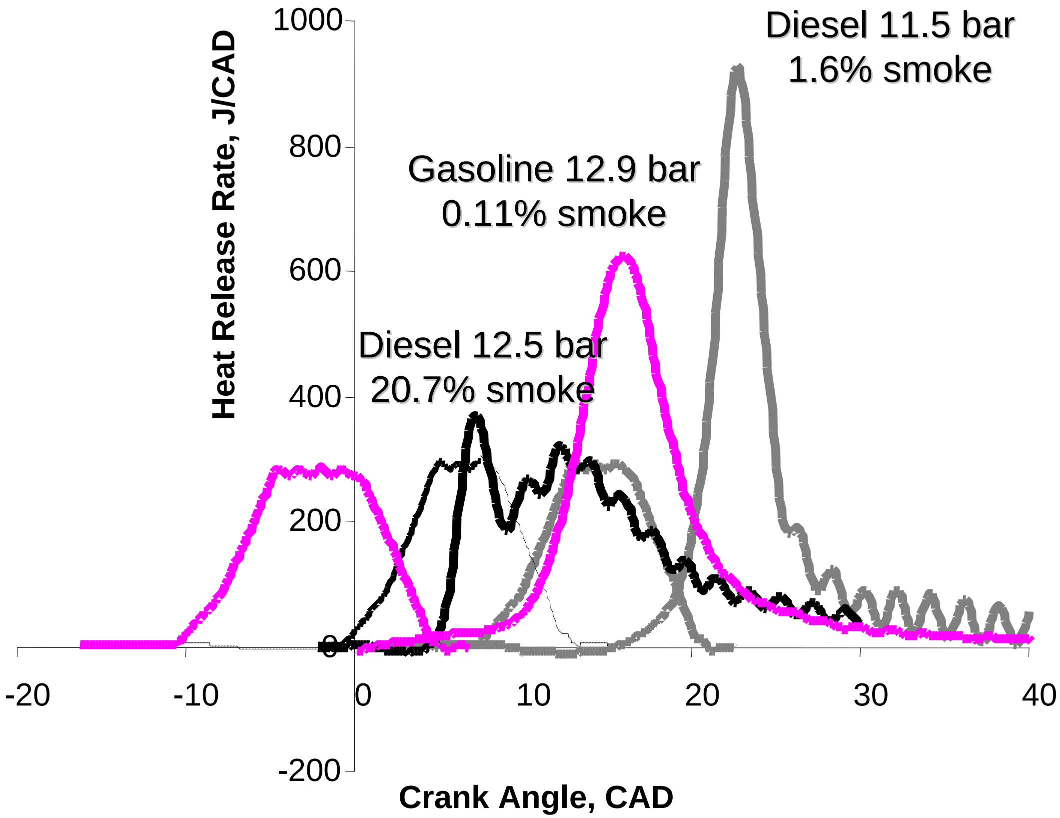


Very much lower NOx for the same IMEP for gasoline because of higher EID.

Increasing injection rate will increase IMEP but also smoke for the diesel fuel and NOx for all fuels. NOx can be reduced by EGR

IN THE REST OF THE PRESENTATION SWEDISH MK1 DIESEL WILL BE COMPARED WITH GASOLINE with Pin = 2 bar abs, EGR ~ 25% stoich

Examples of Heat Release and Needle Lift

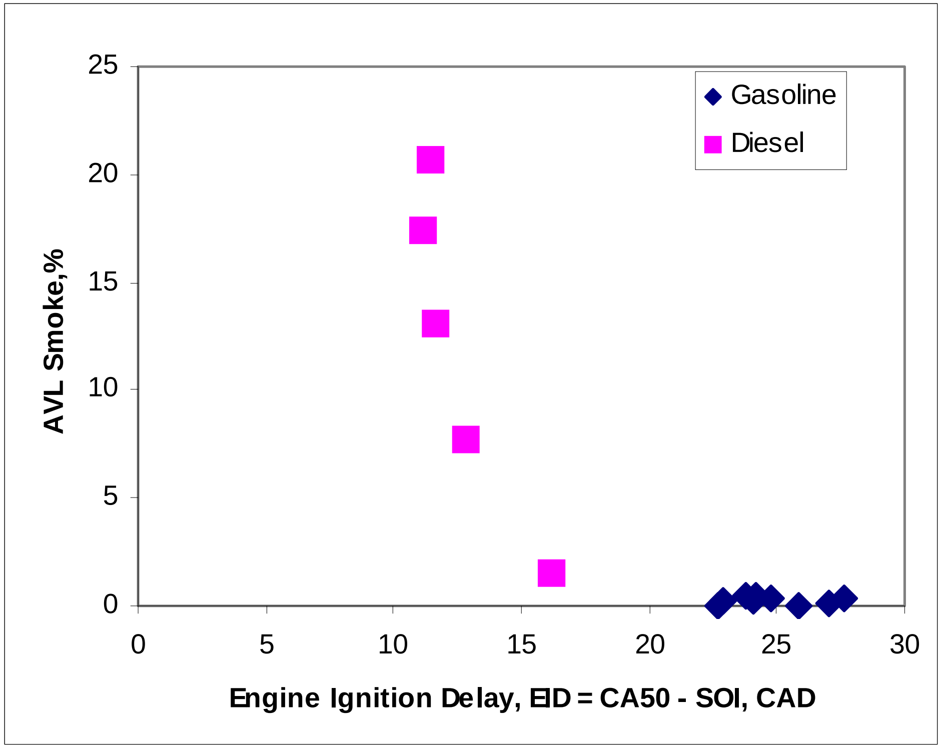


Pin = 2 bar abs, 1200 RPM
EGR ~ 25% stoich
Fixed fuel rate (1.2 g/s) in a
Single pulse

Smoke can be reduced by separating the heat release from the injection – increase ignition delay.
NOx can be controlled through EGR

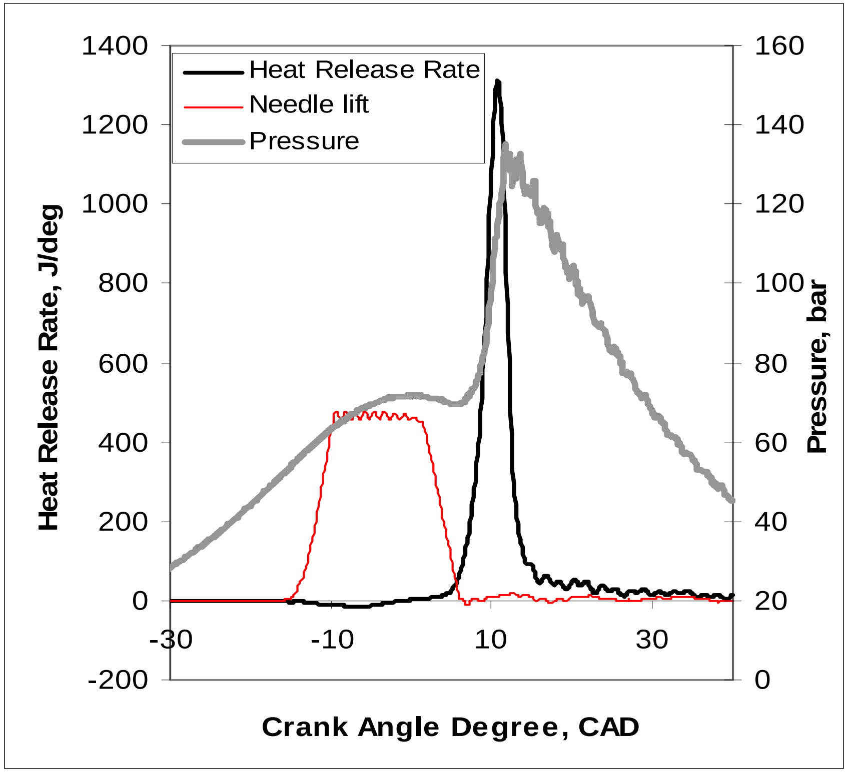
If the fuel is injected very early – HCCI mode – no control on combustion phasing

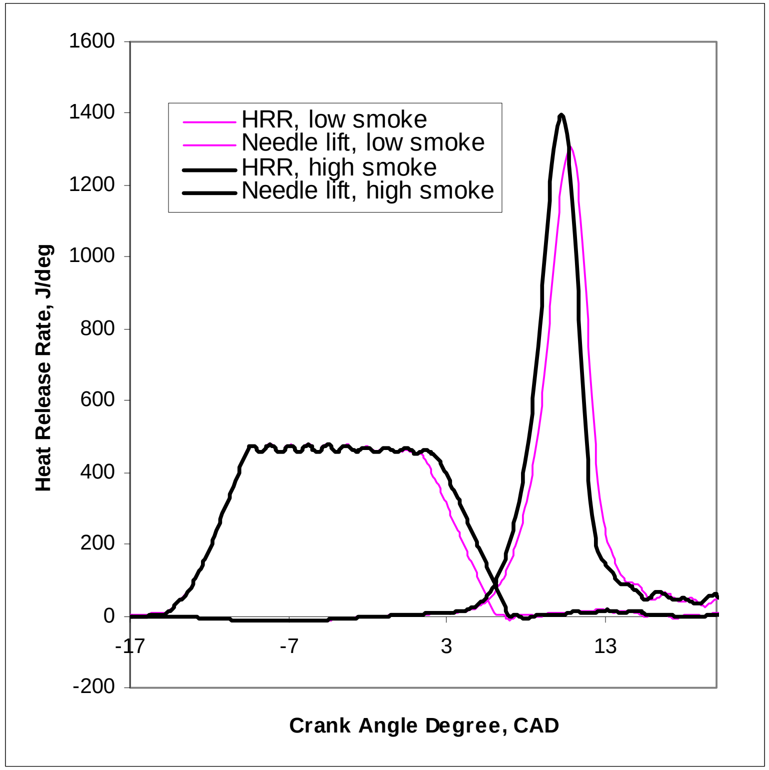
Low smoke for gasoline because of higher EID



Pin = 2 bar abs, 1.2 g/s fuel, EGR ~ 25% stoich (38%)

High IMEP point with gasoline, single injection





Pressure, heat release rate and needle lift curves for gasoline with 14.86 bar IMEP (0.115 bar std), 1.8% smoke and ISNOx , ISFC, ISCO and ISHC of 1.21 g/kWh, 178 g/kWh, 3.4 g/ kWh and 3.6 g/kWh respectively. Needle lift, arbitrary scale.

More overlap between heat release and injection event for high smoke case

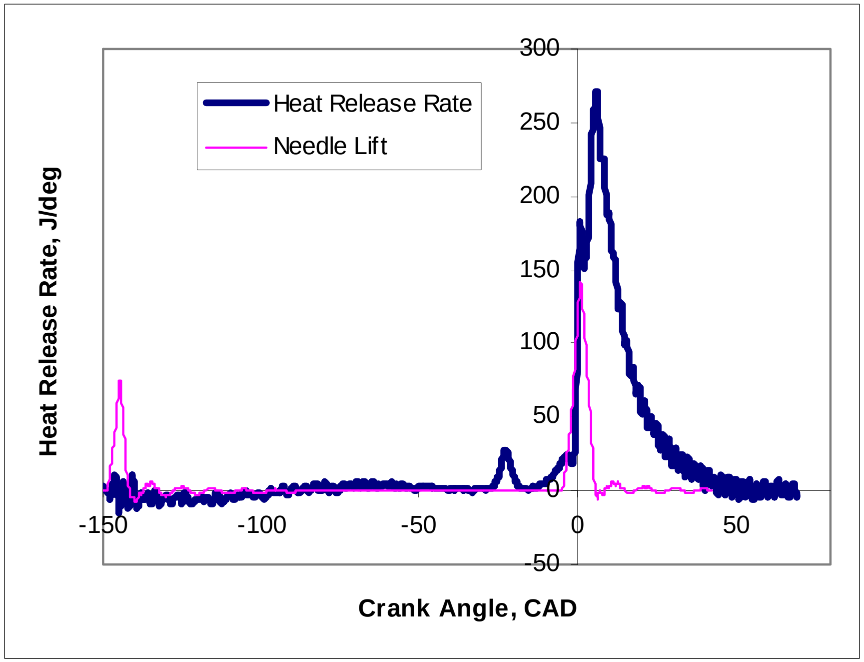
Double Injection Strategies Used

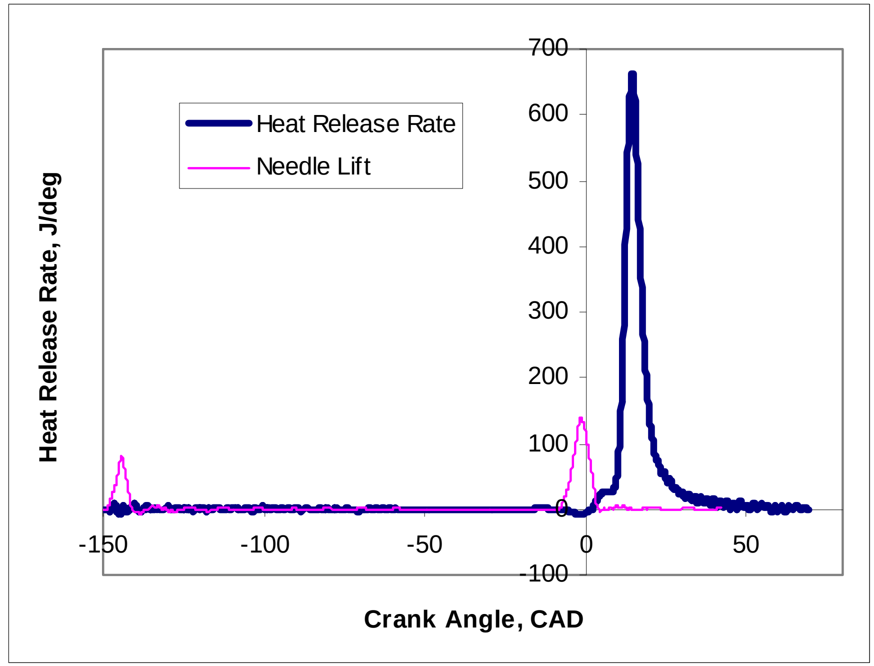
- Total injection of 1.2 g/s. Pilot injection at fixed injection rate and SOI of 150 CAD before TDC (when the valves close), sweep of SOI of main injection near TDC of fixed injection rate - at two different fractions of the total fuel mass in the pilot for gasoline
- For the diesel fuel, for a total injection rate of 1.2 g/s, the main injection was fixed at 0.84 g/s at TDC and the SOI of the pilot was varied
- Main injection was fixed at 1.19 g/s with SOI at 11 CAD before TDC in most cases, and the pilot injection quantity, with SOI fixed at 150 CAD before TDC, was varied for gasoline.

The two limits are too early combustion and high smoke

Comparison between diesel and gasoline

Total fuel rate 1.2 g/s, 70% in main injection. Lowest possible smoke with diesel was 7.8%

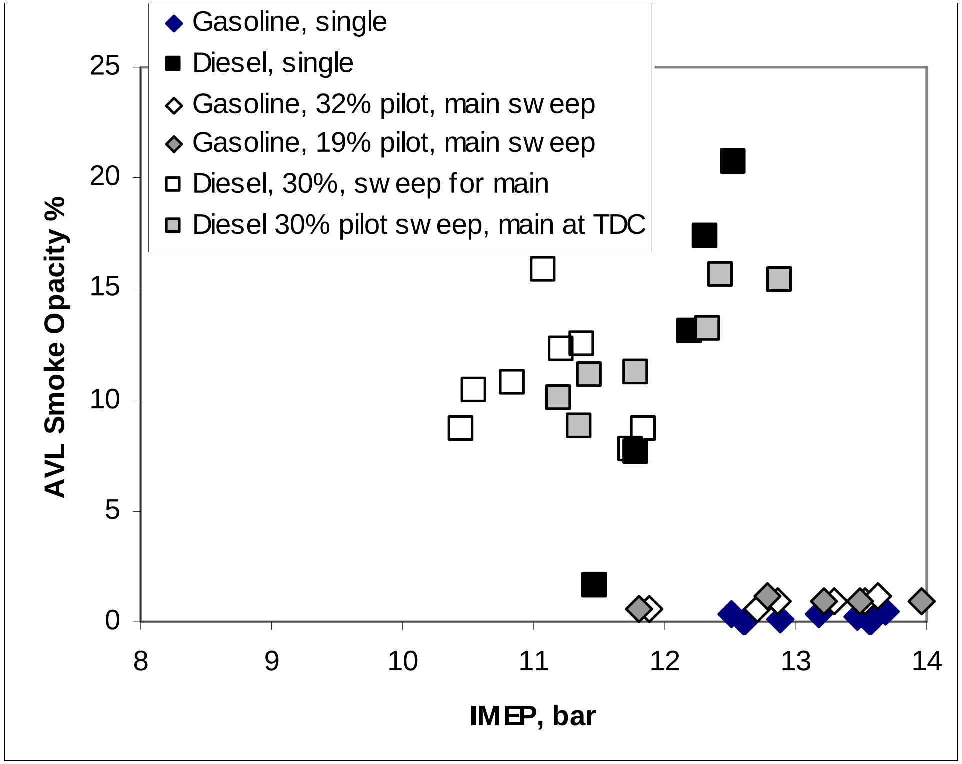




Swedish MK1 diesel. Main injection SOI at – 6 CAD. Mean IMEP 11.84 (std 0.115 bar) bar. AVL smoke opacity 8.7%. In g/kWh, ISFC= 183, ISNOx = 0.3, ISHC = 11.3, ISCO = 10

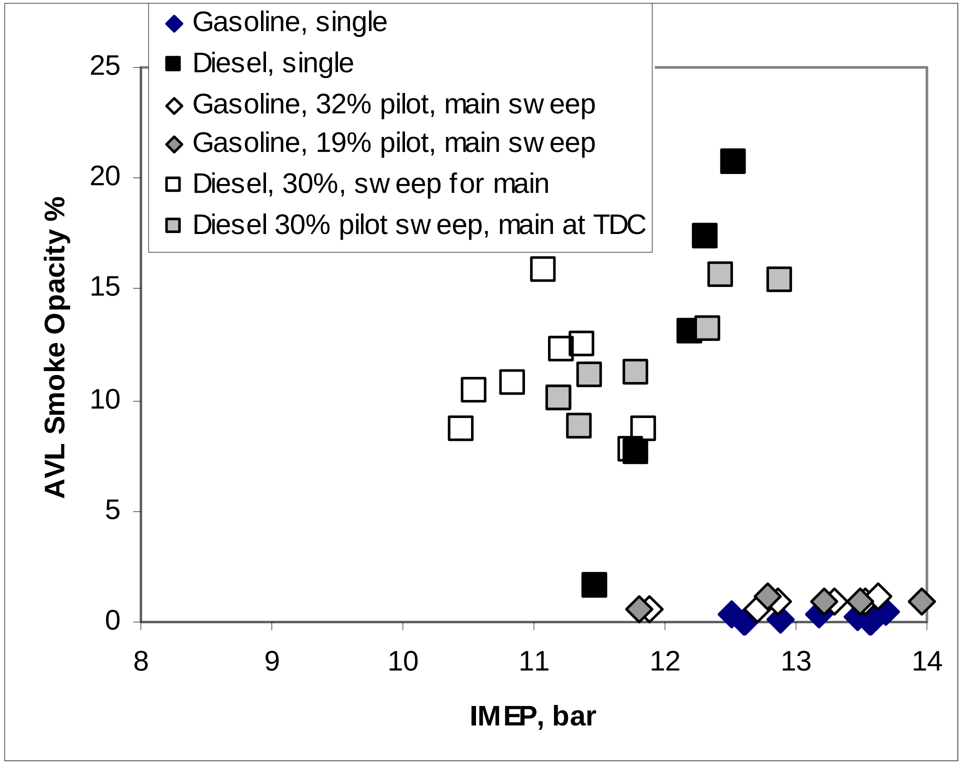
Gasoline. Main injection SOI at – 9 CAD. Mean IMEP 12.86 (std 0.108 bar) bar. AVL smoke opacity 0.9%. In g/kWh, ISFC= 174, ISNOx = 0.39, ISHC = 6.8, ISCO = 9

Smoke – total fuel rate 1.2 g/s different injection strategies



- Lowest smoke possible is lower with single injection for diesel
- Smoke level much lower for gasoline at high IMEP

Smoke – total fuel rate 1.2 g/s different injection strategies



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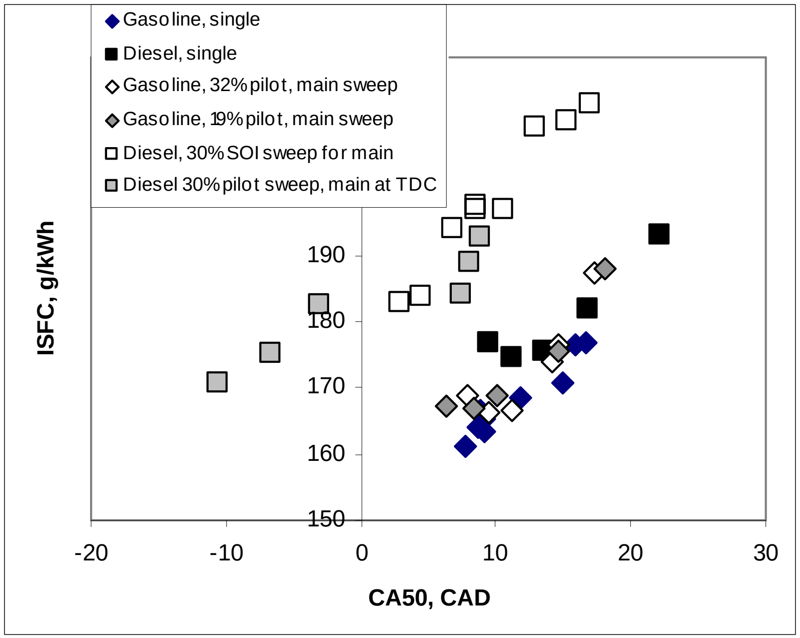
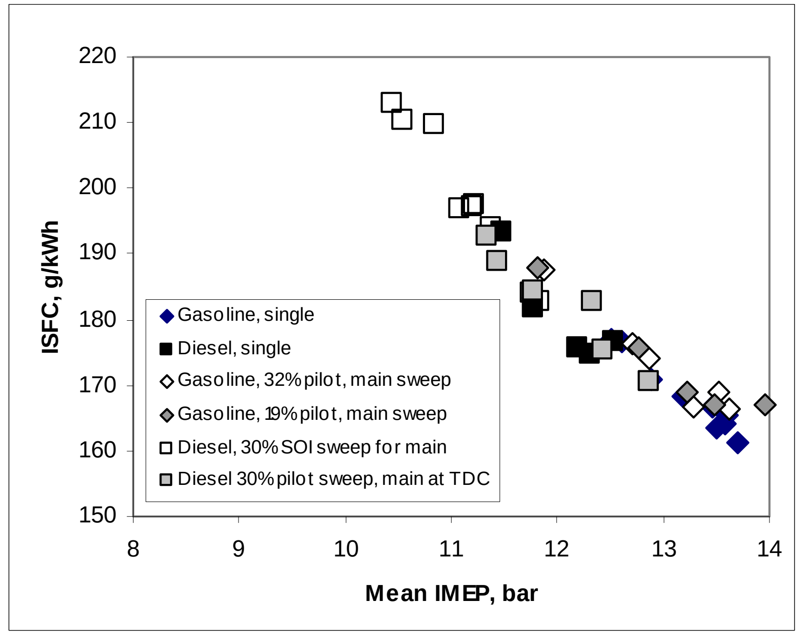
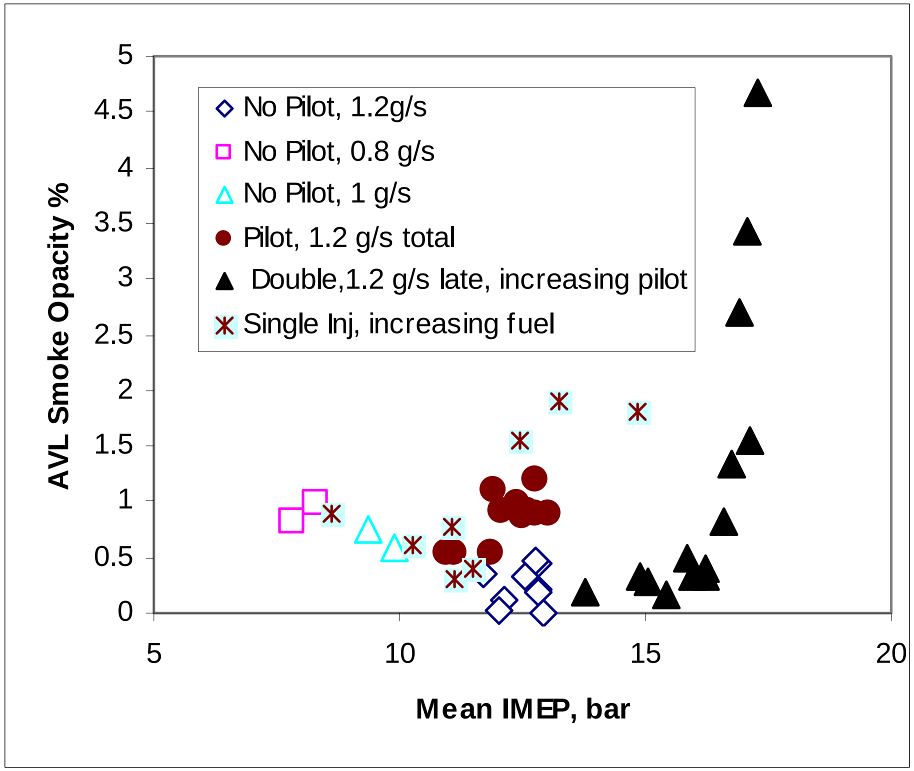
Fuel consumption – total fuel rate 1.2 g/s different injection strategies





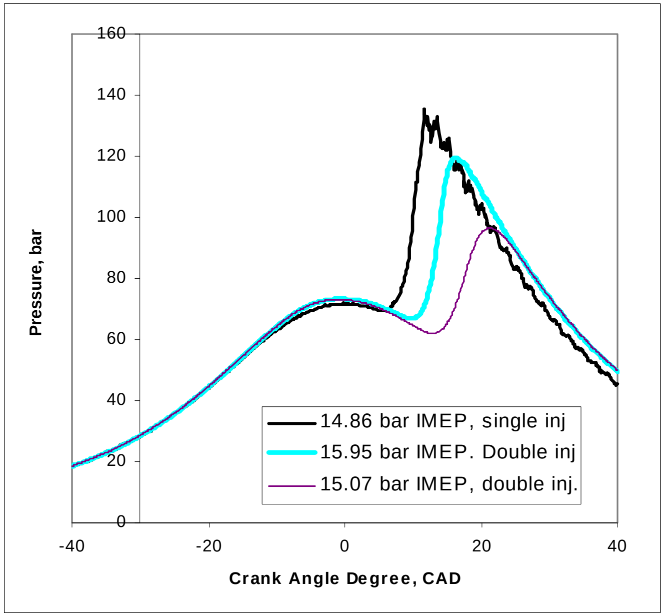
- **With diesel fuel, double injection increases ISFC compared to single injection**
- **With gasoline, double injection does not increase ISFC**
- **ISFC decreases as IMEP increases**

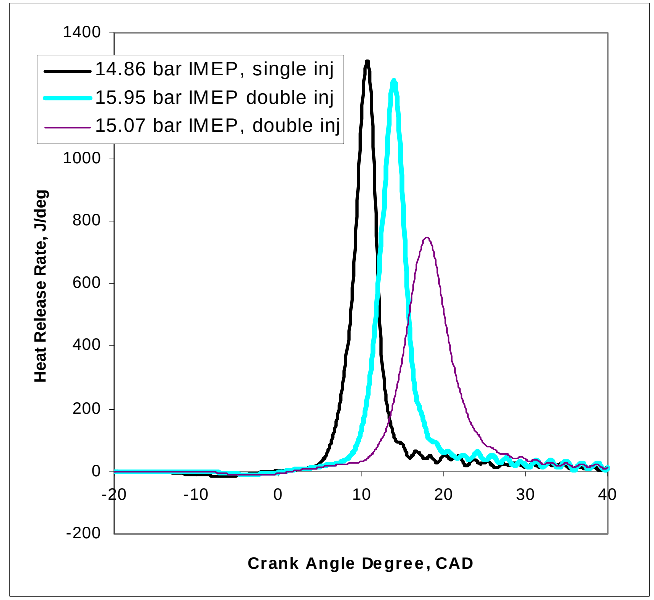
Smoke at high IMEP with gasoline



- **With gasoline, double injection helps reduce smoke at high load**
- **Even with double injection smoke increases eventually at high load**

Gasoline – single vs double injection





Double injection allows MHRR to be reduced and delayed without increasing cyclic variation and at lower emissions.

All experiments at 2 bar abs. inlet pressure, 40 C inlet temp. ~35% EGR based on actual exhaust.

The highest IMEP at such low levels of smoke with diesel < 6.5 bar

Injection	Fuel Rate Mean g/s	CO2 Intake %	IMEP* Mean bar	IMEP* std bar	AVL smoke % opacity	ISNOx g/kWh	ISFC g/kWh	ISHC g/kWh	ISCO g/kWh	MHRR* J/deg	Angle of MHRR* CAD
Single**	1.436	4.05	14.86	0.115	1.81	1.21	178	3.6	3.4	1446	10.8
Double***	1.46	4.14	15.07	0.138	0.28	0.59	179	3.0	5.8	817	18.2
Double* **	**1.549**	**4.16**	**15.95**	**0.112**	**0.33**	**0.58**	**179**	**2.9**	**6.8**	**1393**	**14.1**

* Mean from 100 cycles
** SOI @ -16 CAD
*** 1.19 g/s @ -11 CAD and rest at -150 CAD

Conclusions

- The engine can be run on gasoline in partially pre-mixed mode even when it cannot be run in HCCI mode.
- Much higher ignition delay for gasoline compared to diesel at a given set of operating conditions and hence lower smoke (and lower NOx).
- Double injection helps reduce maximum heat release rate while maintaining IMEP,low emissions and fuel consumption for gasoline
- Much higher IMEP possible with gasoline compared to diesel for low smoke and NOx
- IMEP = 15.95 bar, smoke < 0.07 FSN, ISNOx, ISCO, ISHC and ISFC of ~ 0.6, 6.8, 2.9, 179 g/kWh. This was with 23% pilot, 2 bar abs. Pin and 35% EGR (actual).
- Highest IMEP possible with diesel fuel for this low smoke < 6.5 bar
- Further improvements should be possible with optimisation of injection and mixture preparation (multiple injections, more injector holes….)

Practical scenario – dual mode

Practical engines will run in pre-mixed mode where they can and switch to conventional mode where they cant.

Diesel / HCCI – As volatile as possible, minimum cetane that can still support diesel mode. A fuel in the Kero range with moderate cetane number (~ 40). GTL cut of moderate cetane number (~ 40).

SI / HCCI – Such an engine will necessarily have a higher compression ratio than normal (12-14?). Requires high octane quality – high RON (~100) and as ***low*** a MON as possible.

High sensitivity will help with HCCI mode. Handle through engine management (e.g. internal EGR) at low load.

Idealised "Full HCCI" Scenario

- **Conventional Diesel Fuels** – Too involatile and too prone to autoignition. Involatility constraint can be overcome by improved mixture preparation strategies but difficult to make the fuels less autoignitive. Also likely to be less sensitive and hence less flexible than gasolines.
- **GTL** – Better volatility than diesels but more autoignitive
- **Conventional Gasoline Fuels** – Volatile. Higher loads can be attained more erasily. Difficulty with autoignition e.g. at low loads can be overcome by engine management e.g. large amounts of hot internal EGR – easier with larger engines. Sensitivity leads to flexibility.

Gasolines are best for "FULL" HCCI

Conclusions – Fuel Requirements of HCCI Engines

- First generation HCCI engines will be dual-mode – Fuel determined by conventional mode.

Diesel/HCCI - a volatile (GTL components?) mid range cetane (~40) fuel seems to be optimum.

SI/HCCI – High RON, high sensitivity

- For "full HCCI" (or partially premixed CI) engines gasoline type fuels are better suited than conventional diesels. GTL fuels, at least some cuts, will have suitable volatility but might be too prone to autoignition.
- For the same RON, more sensitive gasoline fuels (lower MON) will increase the operating range of an HCCI engine.