Shell Global Solutions

Is gasoline the best fuel for advanced diesel engines? – Fuel effects in "premixed-enough" compression ignition engines.

Gautam T. Kalghatgi
Shell Global Solutions (UK)

Premixed combustion in CI engines

- Conventional CI (diesel) engines have high efficiency but high particulate and NOx emissions
- Regulations to control these pollutants are getting tighter, particularly for heavy duty engines.
- Promoting mixing of fuel and air before combustion reduces smoke
- Low-temperature combustion reduces NOx – lean mixtures + EGR
- HCCI is one end of this spectrum – no “in-cycle” control over heat release. Engine control very difficult also only low load.

Practical Low-NOx, low-smoke combustion

- Inhomogeneity / Stratification – increases high load limit. Always exists in practical CI engines when combustion phasing is controlled by injection timing.
- We can define, Engine Ignition Delay, EID = CA50 – SOI (Start of injection). CA50 is the crank angle at which 50% of total heat release occurs
- The larger the EID, the more premixed the fuel and air at the time of heat release. This reduces smoke and also NOx if the global mixture strength is sufficiently lean
- Advanced diesel engines aim to increase EID – e.g. Nissan MK (late injection + EGR). "premixed enough" combustion.

Premixed combustion in advanced diesel engines

These systems are usually run on diesel fuels (CN > 40, RON < 40) which are very prone to auto-ignition.

Advanced technology in CI engines is primarily aimed at overcoming the difficulties presented by the ease with which diesel fuel ignites in order to promote premixed combustion

- Enhancing mixing – high injection pressures, more swirl …
- Lots of EGR has to be used to increase EID with conventional diesel fuels.
- Even then, to get low NOx and low smoke at high IMEP is very difficult with diesel fuels

Can we make use of the auto-ignition resistance of fuels to increase EID and improve performance ?

Experiments

- 2L single cylinder engine. CR = 14
- 1200 RPM, Tin = 40º C, EGR using exhaust from stoichiometric SI engine (3-way catalyst), characterised by CO2 content of intake air – e.g 25 % EGR ~ 3.8 % CO2.
- 8 hole nozzle, 1300 bar injection pressure
- Measured CA50, NOx, Smoke, HC, CO etc

Fuel	CN	Density g/cc	IBP ºC	T10 ºC	T50 ºC	T90 ºC	FBP ºC	Aromatics % vol	LHV** MJ/kg
Swedish MK1	54	0.81	195	208	240	273	297	~ 3	43.8
Diesel 1	39	0.81	167	179	196	220	246	34	43.5
Diesel 2	30	0.83	167	179	198	222	246	50	43.3
Gasoline	~15*	0.726	32	50	102	144	176	29	43.2

Three Diesel fuels and one 95 RON gasoline.

** Lower Heating Value

Experimental Detail

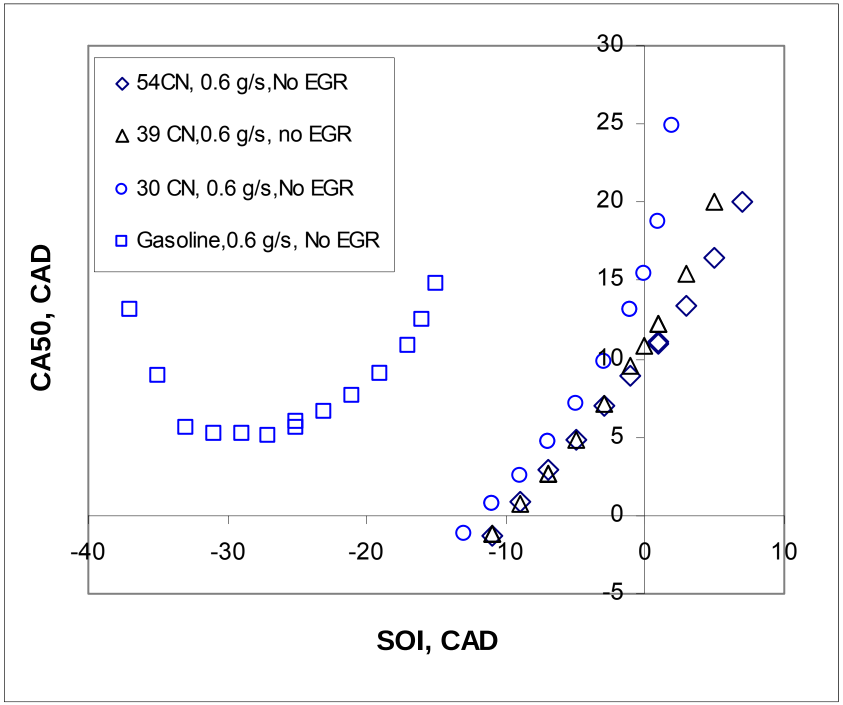
Phase I – Comparison between fuels. All four fuels tested with Pin = 1.5 bar abs. at two conditions –a) 0.6 g/s fuel without any EGR (λ ~ 3.8) and b) 0.8 g/s with 10% EGR* (λ ~ 2.6). Gasoline also tested at 0.8 g/s without EGR (λ ~ 3) and diesels at 0.8 g/s with 25% EGR** (λ ~ 2).

Phase II – Further tests with gasoline with higher inlet pressure, higher fuelling rates and higher EGR to see if higher IMEPs could be reached with low NOx and low smoke.

Phase III – Double Injection with different injection strategies

* 21%   ** 35%

Phase I results – Comparison between Fuels



- Engine will not run on gasoline with very early SOI in HCCI mode

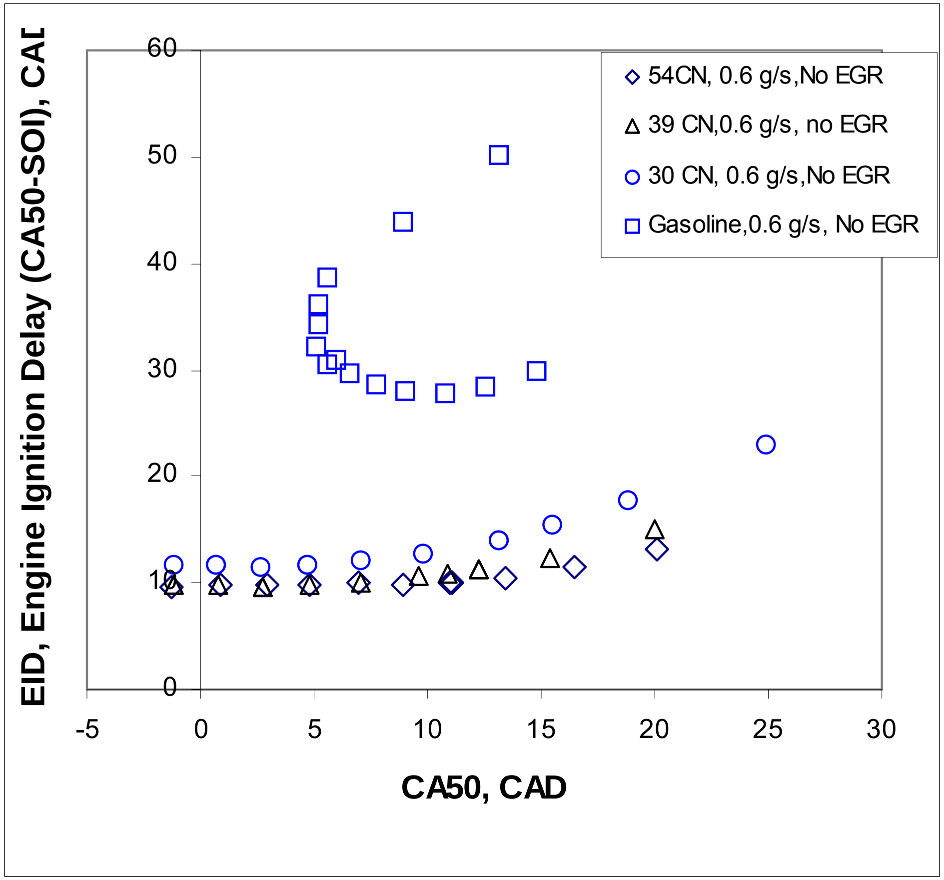
Expected results –

- CA50 decreases with CN

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

λ= 3.8

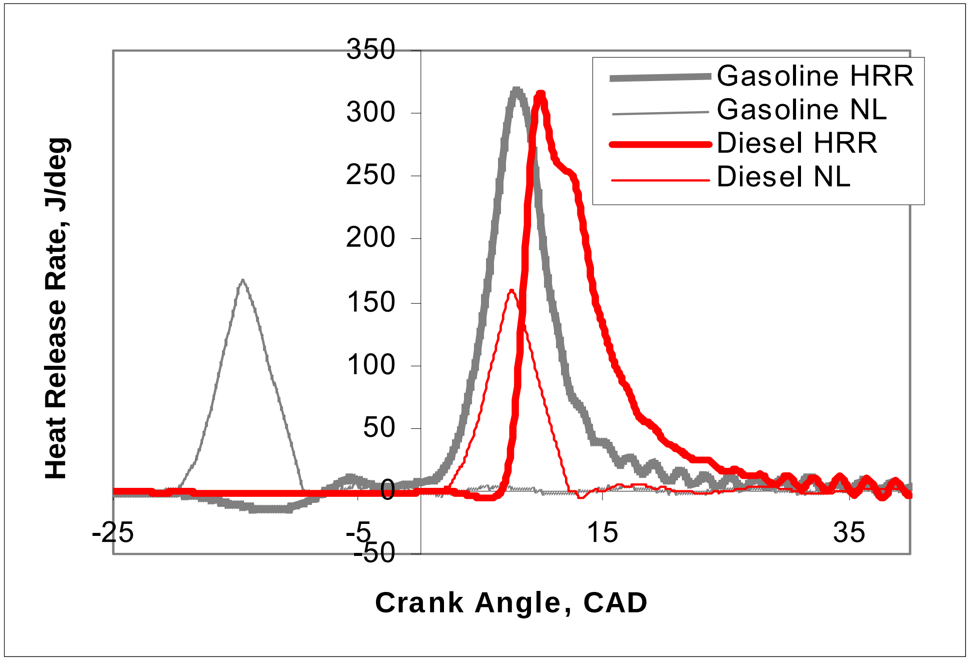
Phase I results – Engine Ignition delay



- Significantly higher ignition delay for gasoline
- Difference between 39 CN and 54 CN less than when CR was 11.4

0.6 g/s, No EGR, Pin =1.5 bar abs, Tin = 40 C, 1200 RPM. λ= 3.8

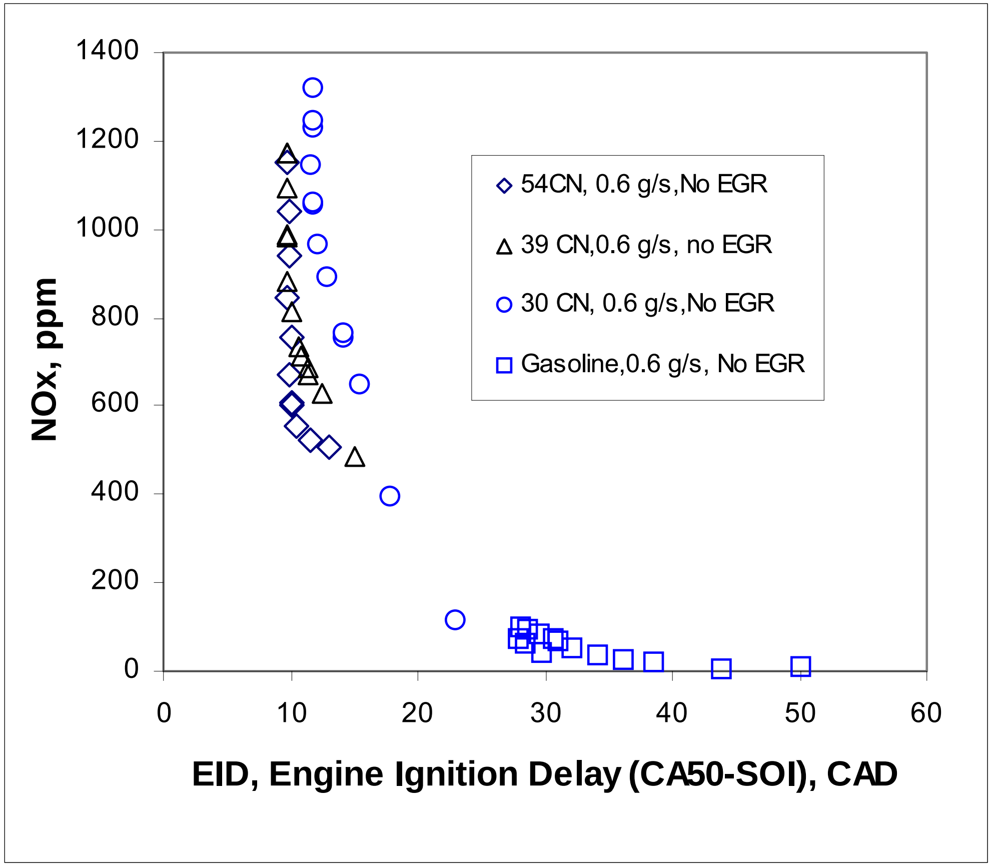
Comparison between gasoline and diesel (Swedish MK1) heat release patterns



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 concentration for both fuels but higher NOx with diesel.

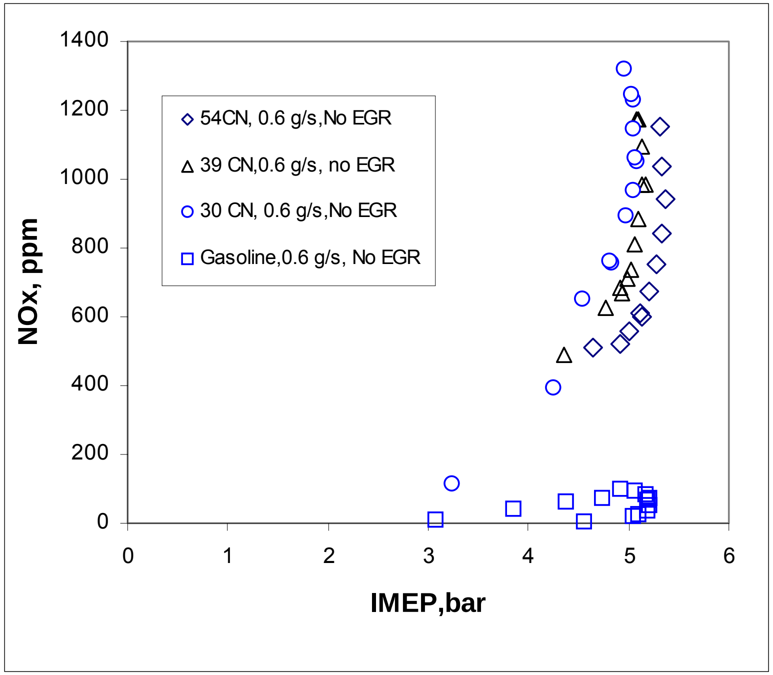
Phase I results - NOx



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

NOx decreases with ignition delay

Phase I results – NOx and IMEP



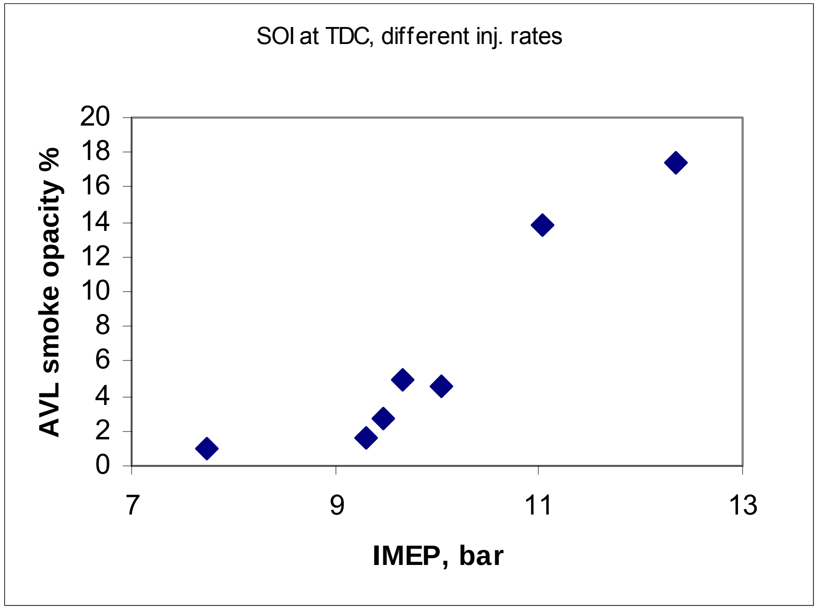
Very much lower NOx for the same IMEP for gasoline because of higher EID.

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

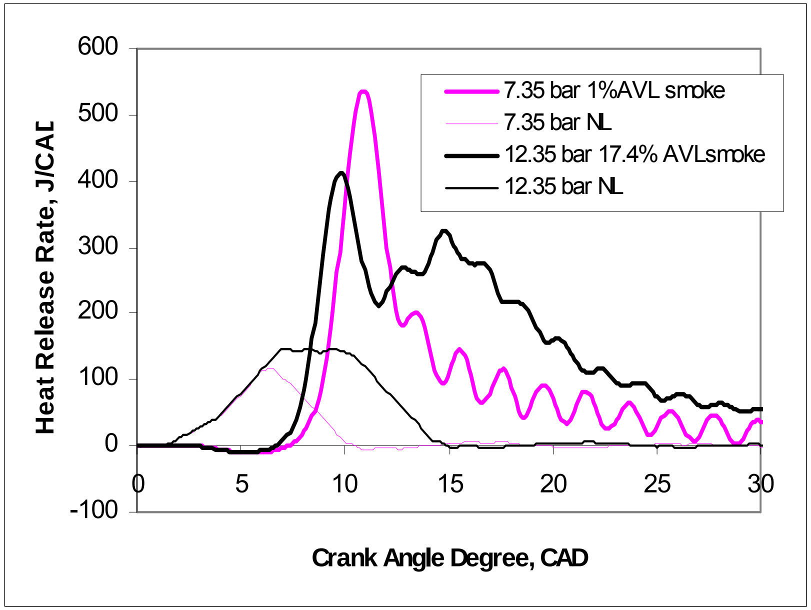
IN THE REST OF THE PRESENTATION SWEDISH MK1 DIESEL WILL BE COMPARED WITH GASOLINE with Pin = 2 bar abs, EGR ~ 25% stoich

Smoke increases with injection quantity

Swedish MK1 diesel fuel, Pin = 2 bar abs, EGR ~ 25% stoich
Single Injection starting at TDC

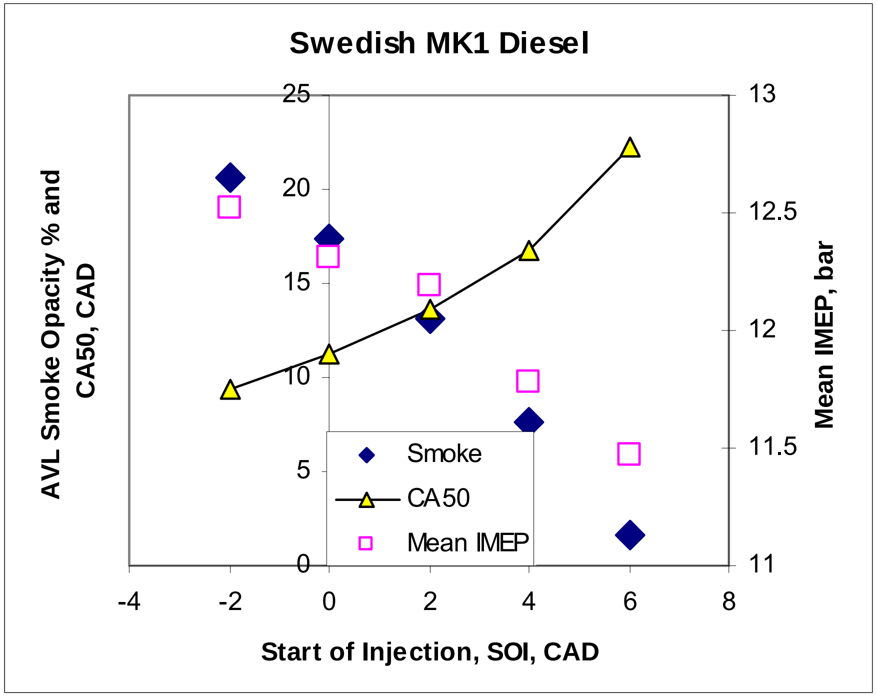


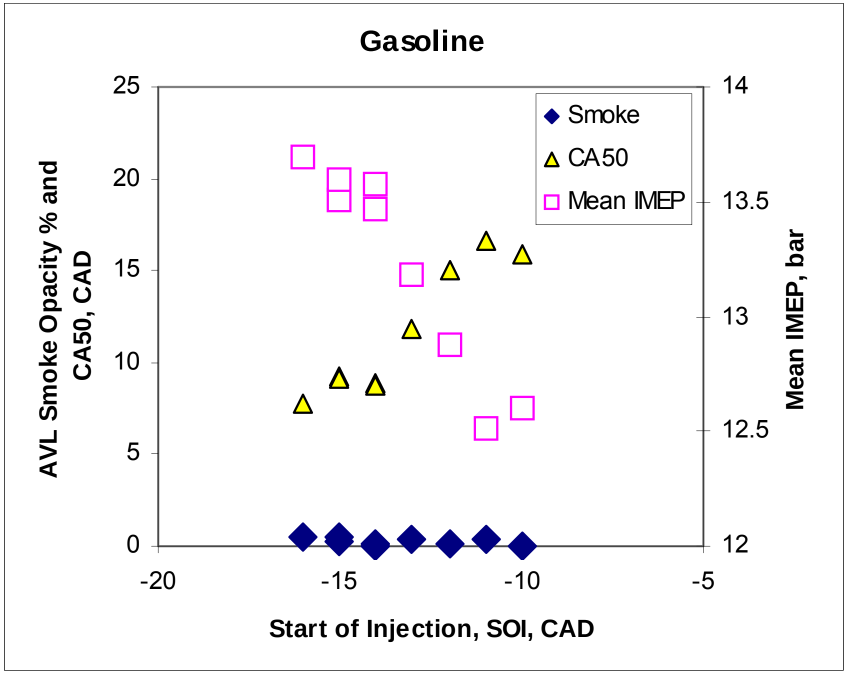
Smoke vs IMEP, SOI at TDC



Heat release rate and needle lift for low and high smoke cases

Injection timing and smoke

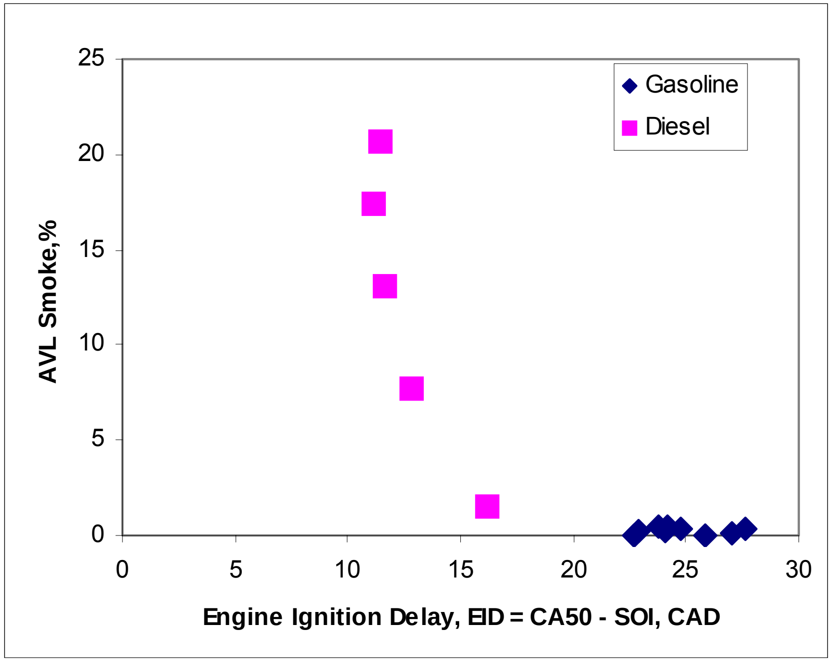




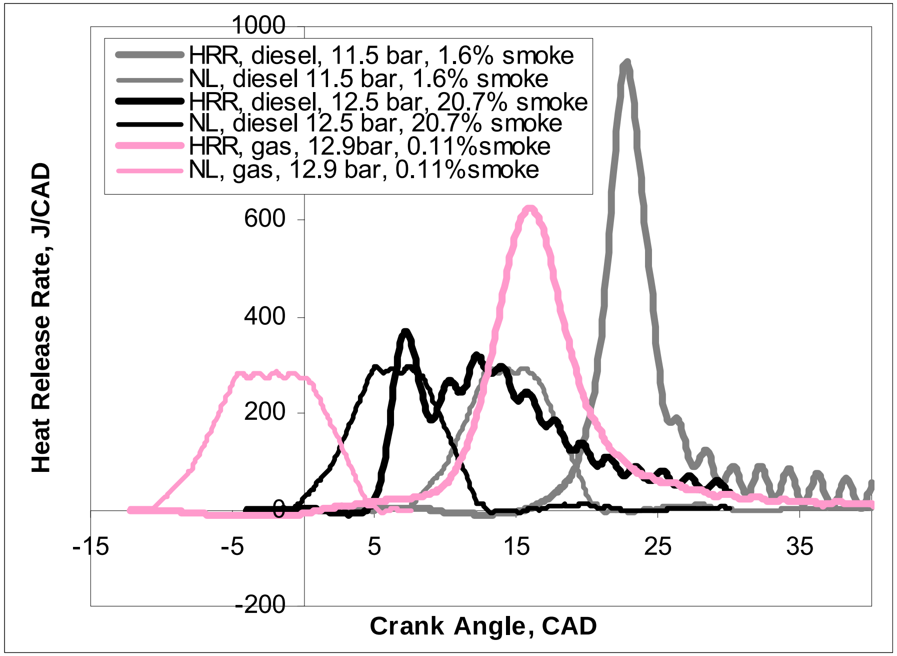
Smoke decreases as injection is retarded for diesel but very low for gasoline

Pin = 2 bar abs, 1.2 g/s fuel, EGR ~ 25% stoich (38%)
Single Injection. λ~1.8

Low smoke for gasoline because of higher EID



Smoke vs ignition delay

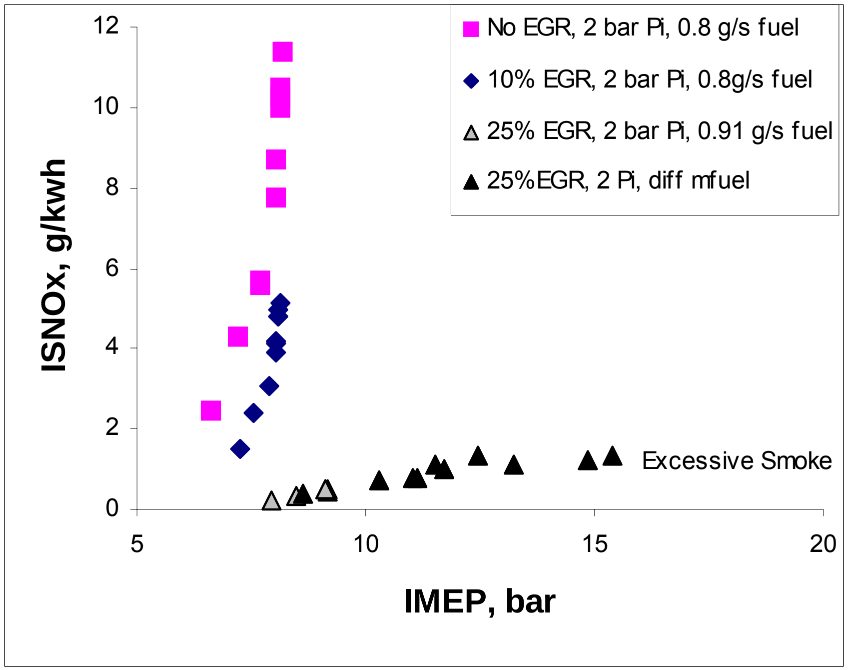


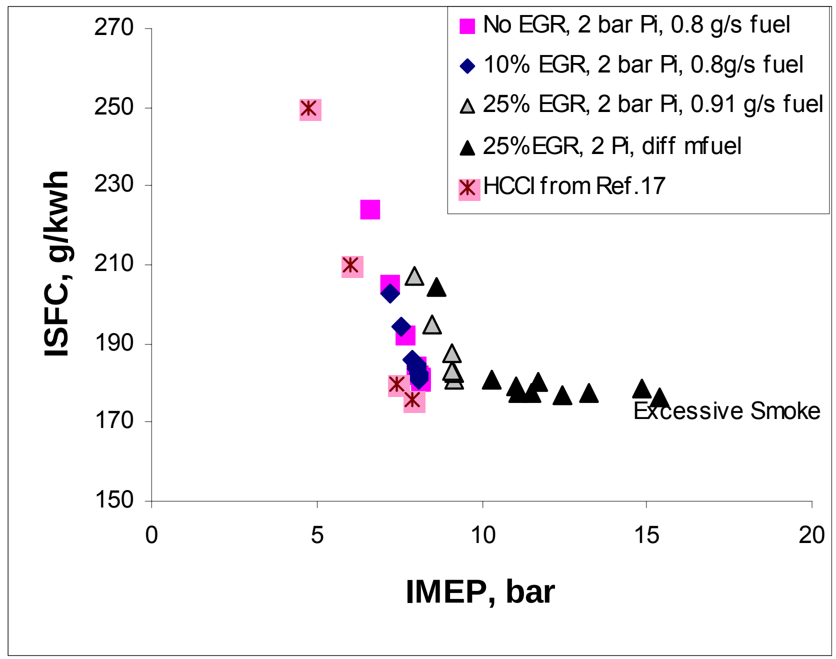
HRR and needle lift for three cases

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

Gasoline fuel rate can be increased up to a point

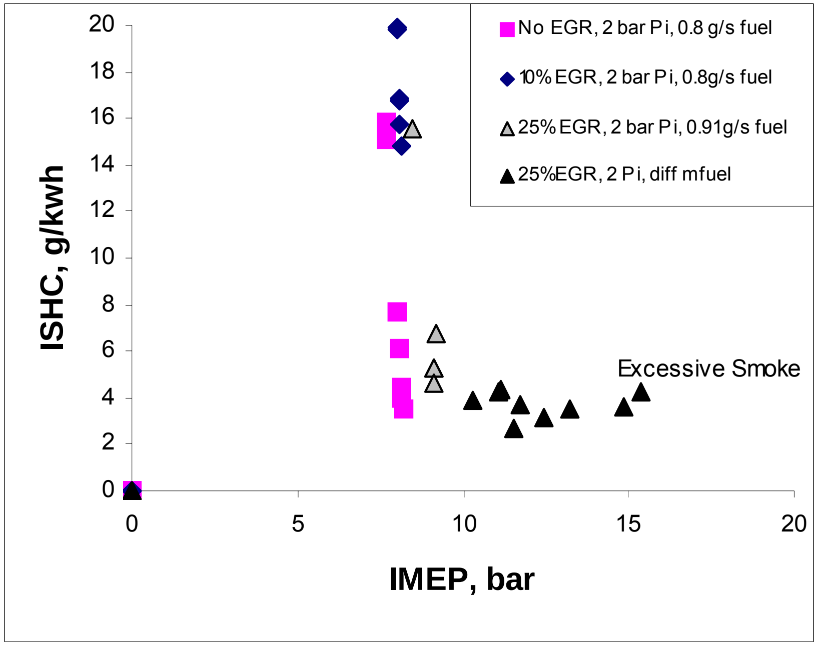
Pin = 2 bar abs, different injection rates and SOI and EGR
Black triangles – fixed SOI, different fuel quantity

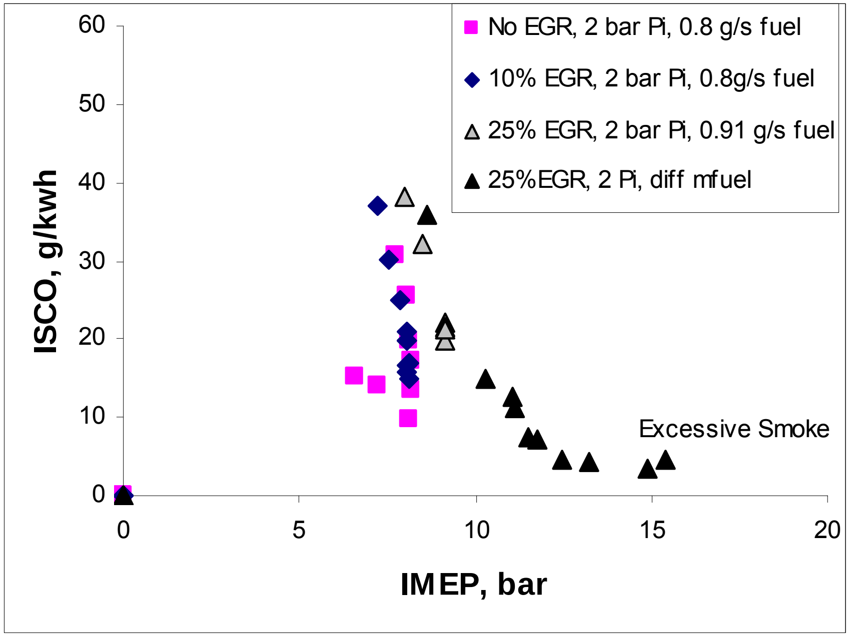




NOx increases with IMEP (fuel rate) but can be controlled with EGR. ISFC decreases with IMEP

HC and CO decrease as fuel rate is increased

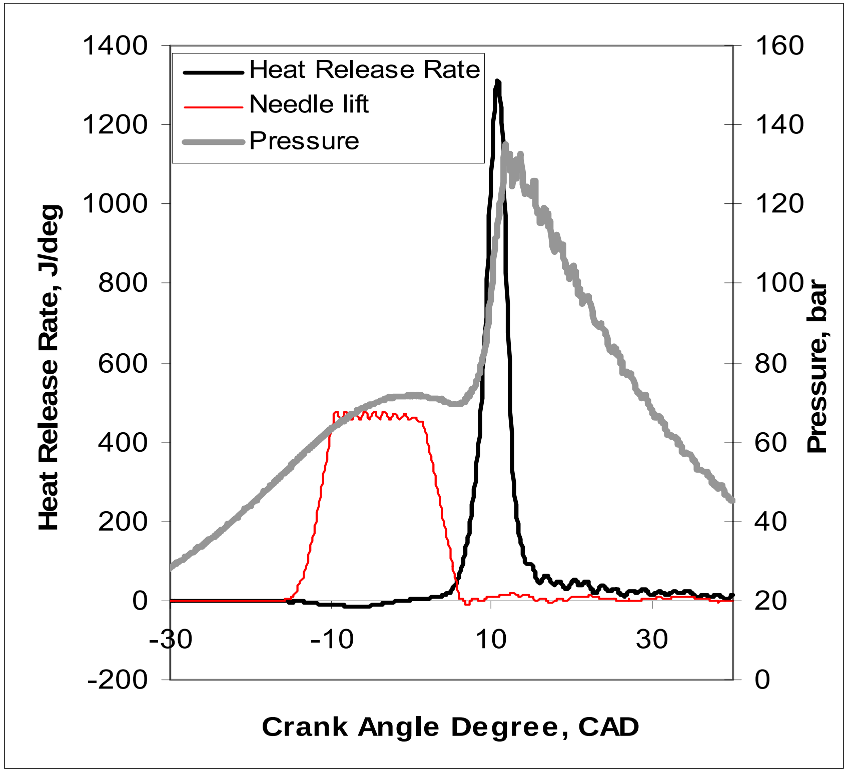


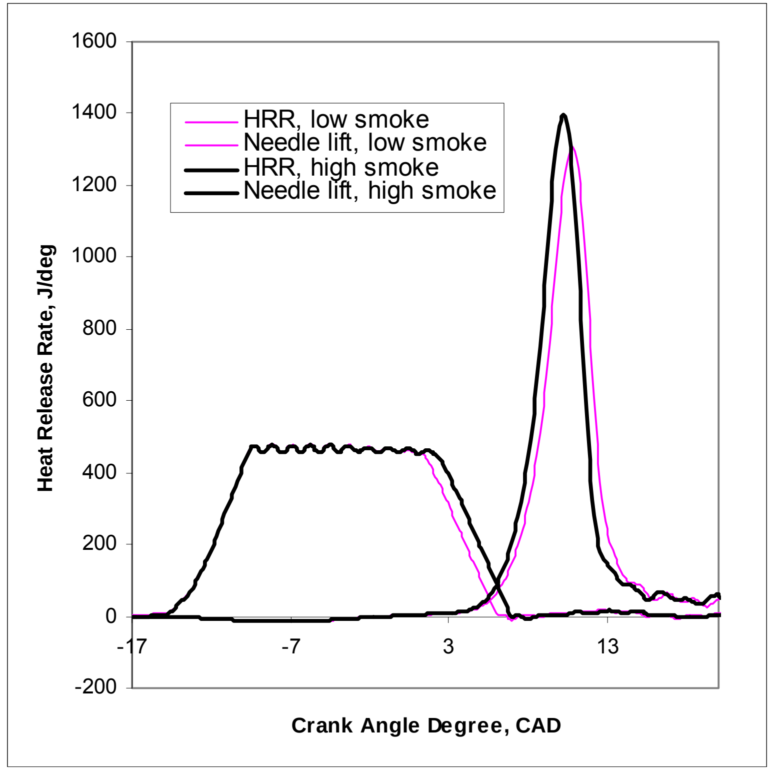


Gasoline

Pin = 2 bar abs, different injection rates and SOI and EGR

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

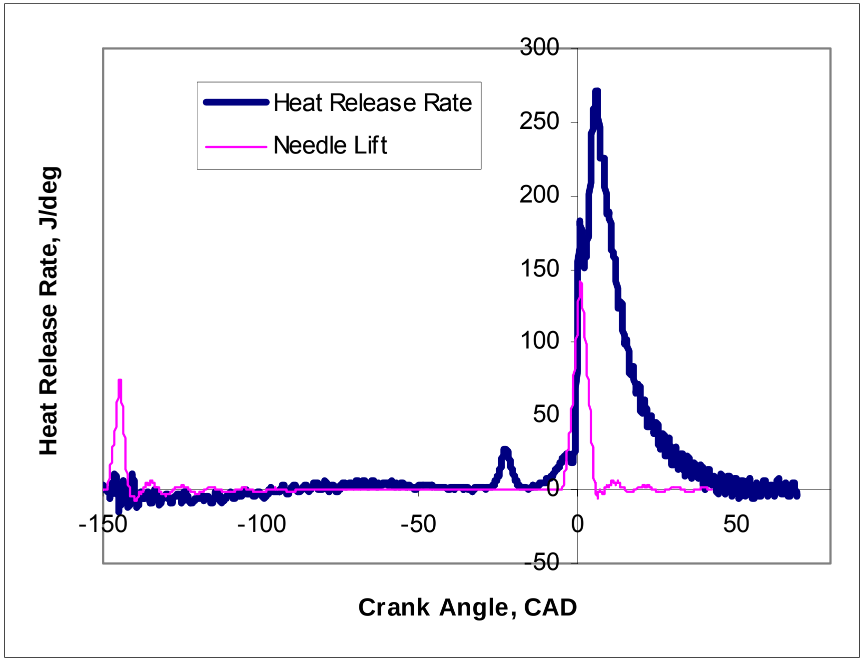
Double Injection Strategies Used

- 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.

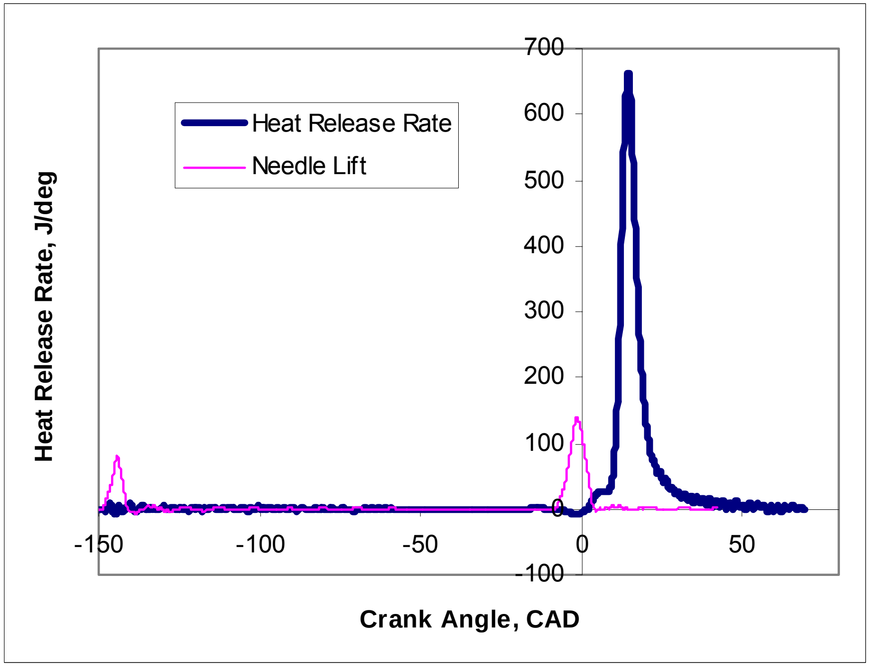
The two limits are too early combustion and high smoke

Comparison between diesel and gasoline

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



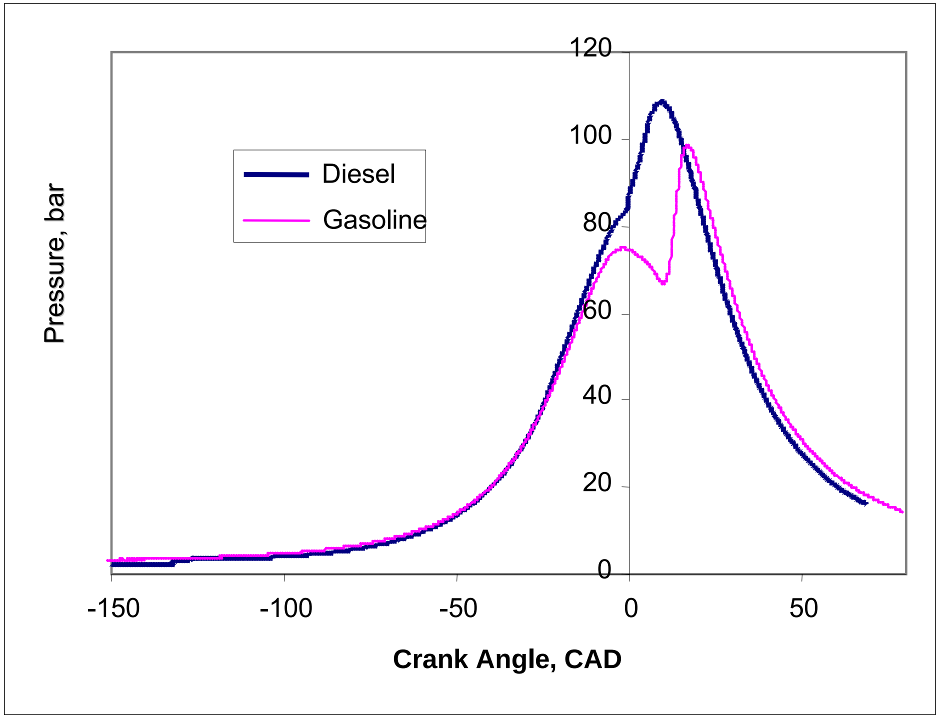
Swedish MK1 diesel. Main injection SOI at – 6 CAD. Mean IMEP 11.84 (std 0.115 bar) bar. AVL smoke opacity 8.7%. In g/kWh, ISFC= 183, ISNOx = 0.3, ISHC = 11.3, ISCO = 10



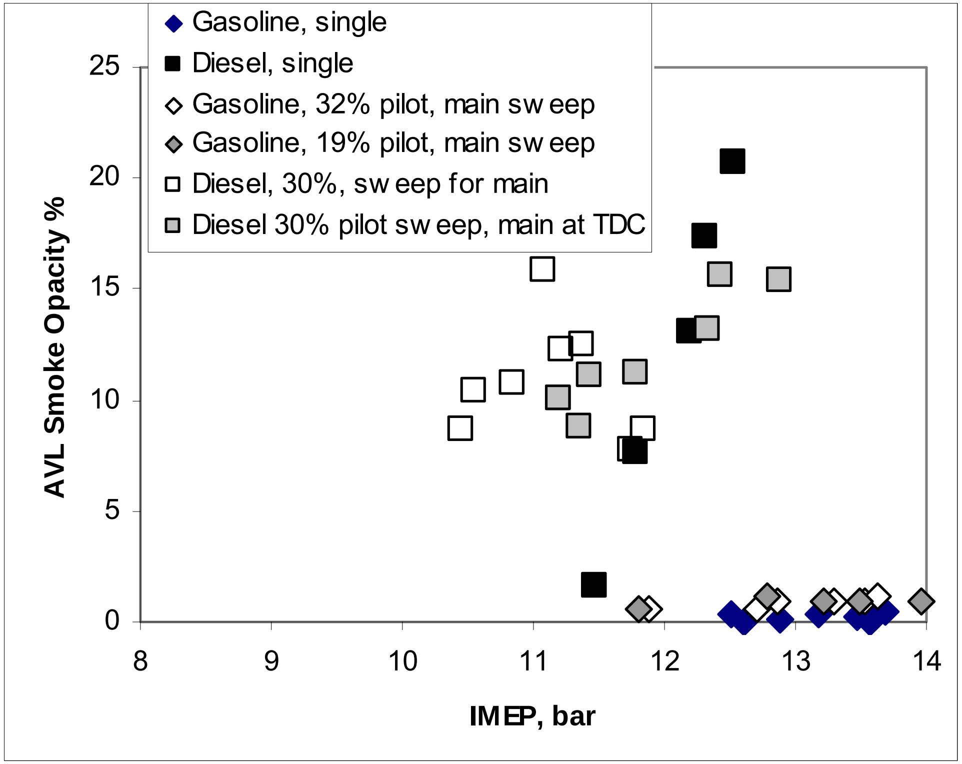
Gasoline. Main injection SOI at – 9 CAD. Mean IMEP 12.86 (std 0.108 bar) bar. AVL smoke opacity 0.9%. In g/kWh, ISFC= 174, ISNOx = 0.39, ISHC = 6.8, ISCO = 9

Comparison between diesel and gasoline - pressure

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



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

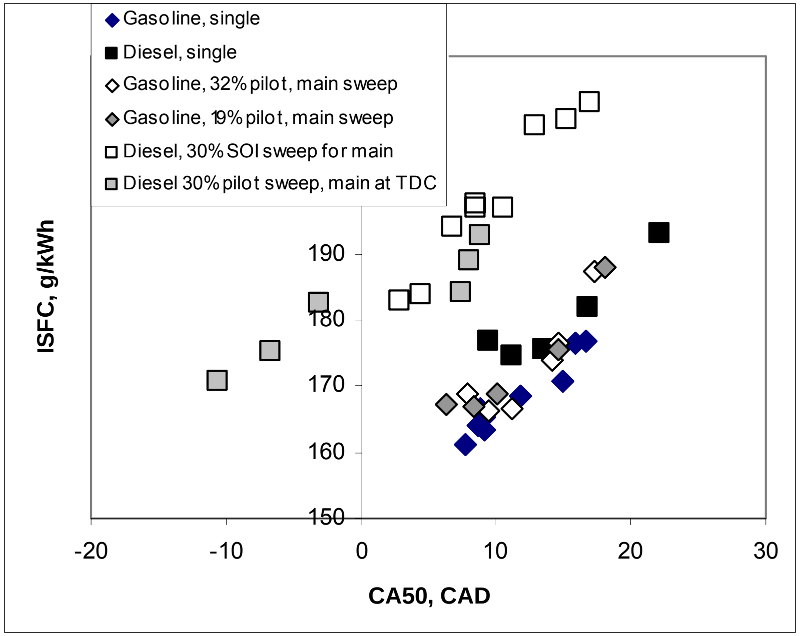


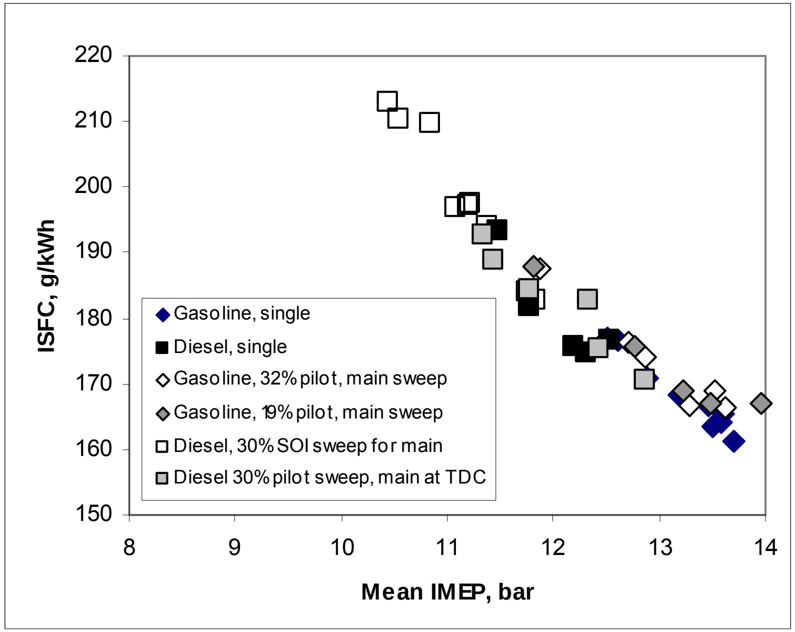
• **Lowest smoke possible is lower with single injection for diesel**

This is because early injection causes heat release during compression stroke – reduces ignition delay for main inj.

•**Smoke level much lower for gasoline at high IMEP**

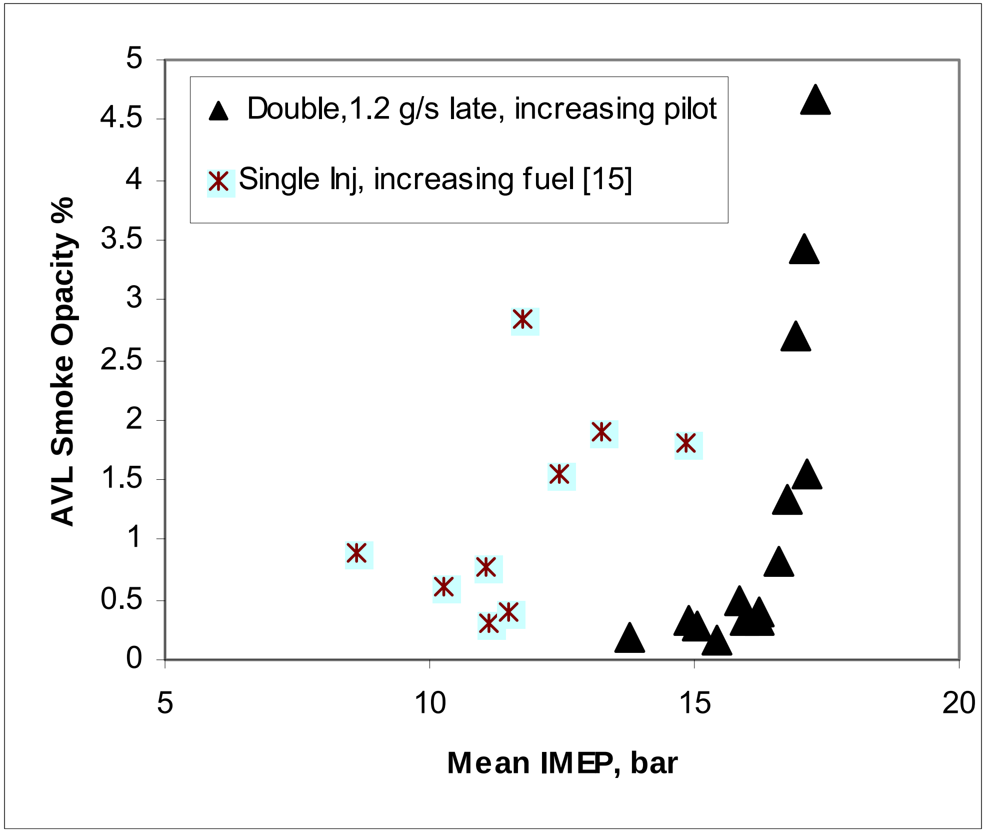
Fuel consumption – total fuel rate 1.2 g/s different injection strategies





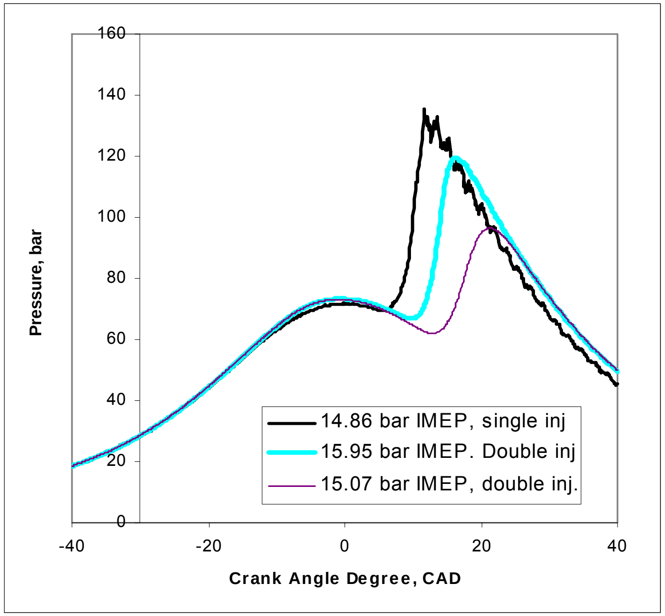
- **With diesel fuel, double injection increases ISFC compared to single injection**
- **With gasoline, double injection does not increase ISFC**
- **ISFC decreases as IMEP increases**

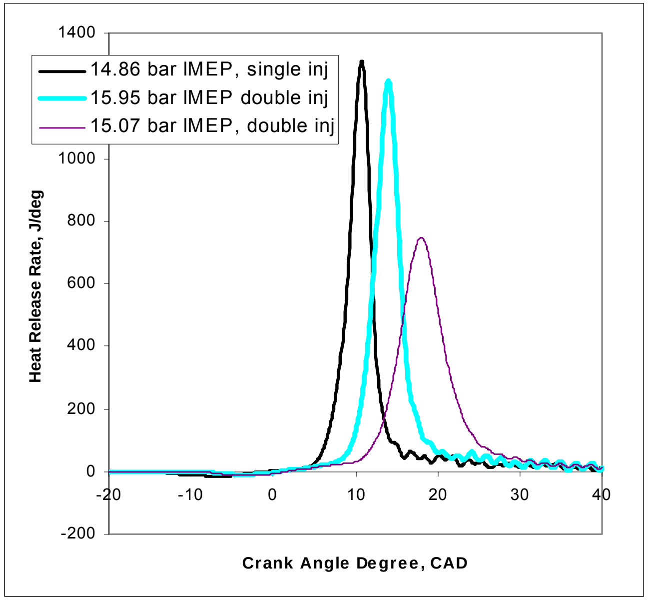
Smoke at high IMEP with gasoline



- 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.

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 from SAE 2006-01-3385

*** 1.19 g/s @ -11 CAD and rest at -150 CAD

Conclusions (1)

- 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 – this option not possible with diesel fuel.
- 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….)

Conclusions (2)

- Further work is needed to understand the effect of higher speeds and the lowest loads that can be run in partially premixed mode on gasoline
- In general, if smoke and NOx are to be reduced by promoting premixed combustion, the fuel needs to be as much like gasoline as possible
- In practice, the extent to which this is possible depends on other critical requirements – low noise, cold starting, low load operation … - being met
- What currently matters is the diesel fuel quality required by future diesel engines.
- If the strategy to reduce smoke and NOx in such engines is to promote premixed combustion, increasing fuel cetane number will not help – it might actually make control of smoke more difficult. Higher volatility for the fuel might be beneficial.

CI engines - latest trends & vehicle / fuel issues

- Current CI design trends around "high" cetane (e.g. 53)
- "Pre-mixed enough" combustion requires "low cetane fuels" – a future path ?
- At an extreme, gasoline fuel can be run in a "pre-mixed enough" CI engine
- Using appropriate fuel properties might allow engine simplification (with ultra low emissions):
  - Reduced injections pressures, EGR
  - & therefore reduced boost pressure ?
  - Vehicle efficiency gains & TTW CO2 ?
- Can refinery efficiency be increased too ?

Lower cost CI engines ?
Increased efficiency ?

Lower WTT CO2 ?

Next steps ?

- **Vehicle understanding:**
  - Practically possible i.e. Vehicle optimisations possible over current exploratory work
  - Can TTW CO2 be lowered, within practical design limitations (e.g. noise, low load)
  - More cost effective way to deliver CI (i.e. low injection pressures)
  - Possibility of light duty / heavy duty divergence
- **Fuels understanding**
  - Could future CI fuel properties change & shift in demand for & types of fuels
  - Benefits for WWT CO2

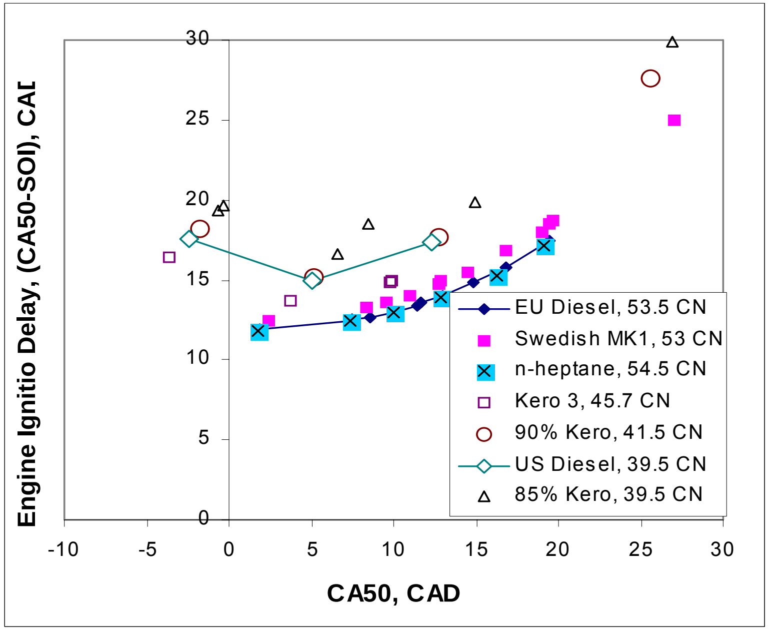
Previous work with diesel fuels of different auto-ignition quality

•Different diesel fuels tested with different Injection strategies in SAE 2005-01-2127

•At fixed operating conditions in Nissan MK combustion, injection timing sweeps

• Higher EID and lower NOx for lower Cetane (more resistant to auto-ignition) fuels at the same CA50

• But these tests were done at low Comp. Ratio (CR) of 11.4 and low loads 3.1-4.2 bar IMEP.



Pin = 1.5 bar abs, 1200 RPM,

25% EGR, λ = 4, Tin = 40 C

Rest of the results from SAE 2006-01-3385 and 2007-01-006