Lecture 7

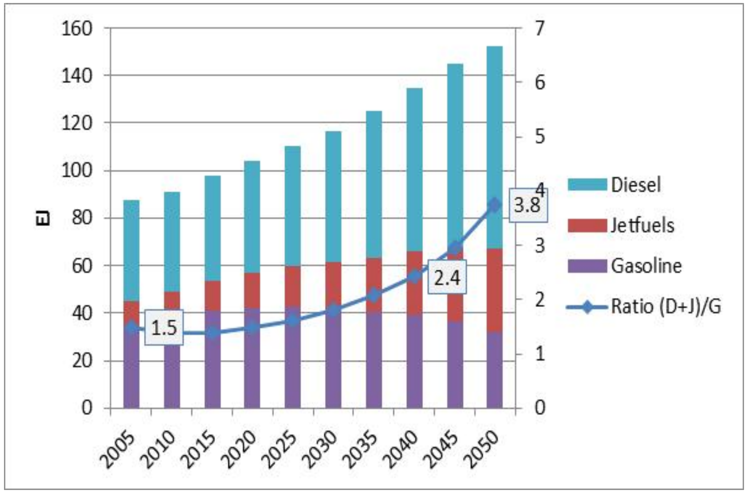
Gasoline Compression Ignition GCI – Opportunities and Challenges

Gautam Kalghatgi

- Fuel/Engine Interactions, Ch.6
- Kalghatgi, G., Johansson, B. 2018 "Gasoline compression ignition (GCI) approach to efficient, clean, affordable future engines" Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol 232 (1), pp118-138. 2018
- Kalghatgi, G.T., Risberg, P. and Ångström, H-E, "Advantages of a fuel with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion", SAE Paper No. 2006-01-3385, Journal of Fuels and Lubricants-V115-4
- Kalghatgi, G.T., Risberg, P. and Ångström, H-E, " Partially pre-mixed auto-ignition of gasoline to attain low smoke and low NOx at high load in a compression ignition engine and comparison with a diesel fuel", SAE 2007-01-006
- Kalghatgi, G.T., Hildingsson, L. Johansson, B. and Harrison, A.J., "Low- NOx, low-smoke operation of a diesel engine using "premixed enough" compression ignition – Effects of fuel autoignition quality, volatility and aromatic content", THIESEL 2010, Thermo and fluid dynamic processes in diesel engines, September 14-17, Valencia,2010
- Kalghatgi, G.T., Hildingsson,L., Harrison, A.J., L. and Johansson, B. "Surrogate fuels for premixed combustion in compression ignition engines", International Journal of Engine Research, October 2011; vol. 12, 5: pp. 452-465

Demand increase heavily skewed towards commercial transport - middle distillates

•Greater Efficiency Improvements in Passenger Car Sector (mostly uses gasoline) – a) future global average car will be smaller/lighter and drive fewer miles compared to today b) electrification
•Passenger car numbers might increase to 1.6-1.9 billion by 2040 but gasoline demand will not change much. Diesel and Jet fuel demand will increase by around 70%.



WEC Freeway Scenario - http://www.worldenergy.org/wp-content/uploads/2012/09/wec_transport_scenarios_2050.pdf

- Increasing pressure on gasoline anti-knock quality
- Marine transport moves to diesel
- 100s of billions $ investments will be needed in refineries
- “Homeless Hydrocarbons” – low octane light components like naphtha will be in abundance
- High efficiency engines which can use such components need to be developed

CI Engine Development Trends

High efficiency, low emissions and affordable

Compression Ignition (CI) engines currently are diesel engines

High efficiency - no throttling, high compression ratio, reduced compression losses

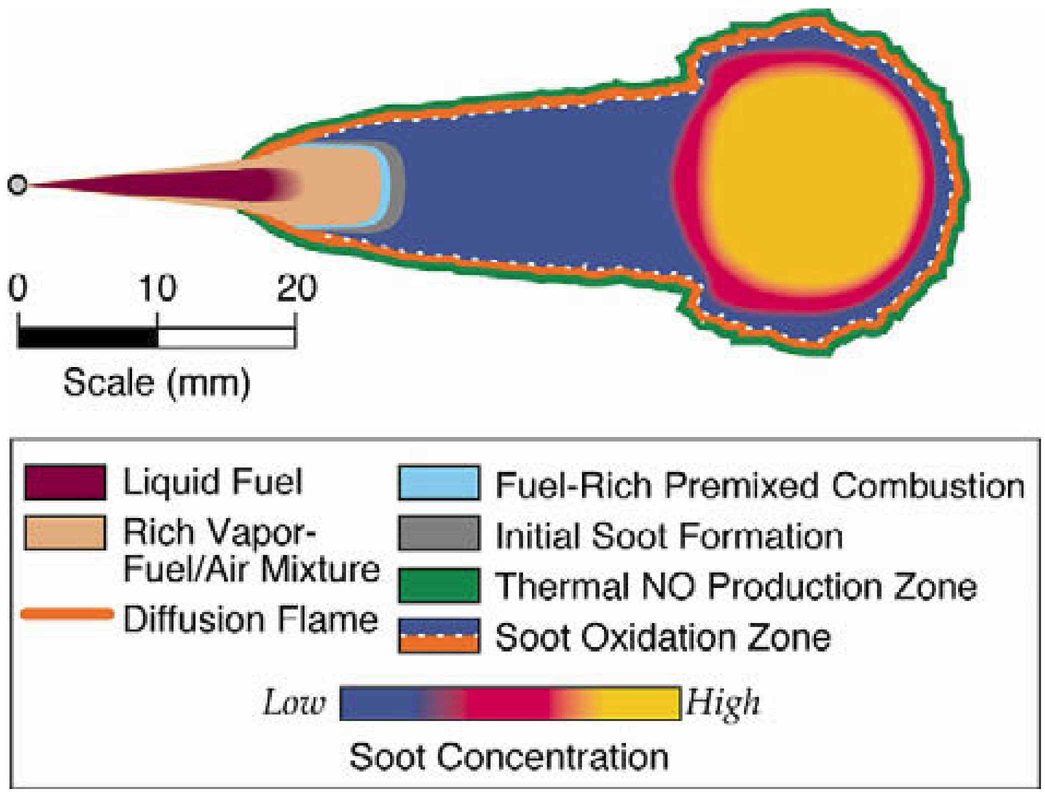
High Emissions: Soot and NOx. Difficult to control through exhaust after-treatment unlike in SI engines

High Cost : With conventional diesel fuel,

- High injection pressures (to reduce soot)
- High engine/after-treatment cost with existing diesel fuel

Model of Conventional Diesel Combustion

John Dec, Proceedings Combust. Inst., 32 (2009) pp 2727-2742



- At very low loads, fuel injection is over before combustion starts
- At all other loads combustion starts while fuel is still being injected

Gasoline Compression Ignition (GCI) Engines

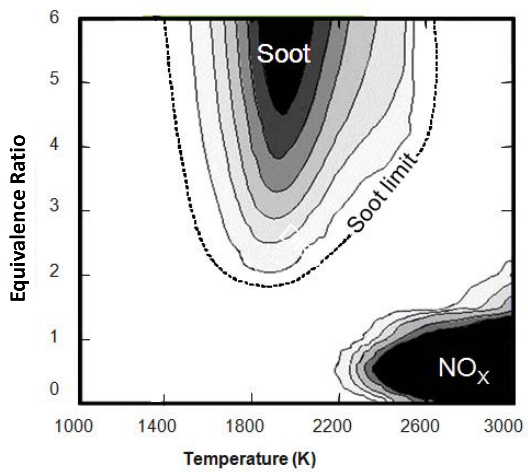
Low NOx, Low Particulates for Compression Ignition

- Particulates and NOx emissions causing more concern and standards are getting more stringent
- Conventional diesel fuel ignites easily, before it has a chance to mix with oxygen in the cylinder giving high particulates and NOx
- Advanced diesel engines are expensive and complicated because they are trying to control particulates and NOx while using conventional diesel fuel
- Control of particulates and NOx much easier with fuels with high ignition delay - "Gasoline-like" Fuels

Gasoline Compression Ignition (GCI) – Inject "gasoline" in a "diesel" engine much earlier in the cycle compared to diesel fuel

- Higher ignition delay allows more time for mixing before combustion
- In –cycle control of combustion phasing by injection timing as in a diesel engine

Premixed Compression Ignition (PCI)



Dec (2009) Proc. CI, 32:2727-2742

- Regulations to control NOx and soot getting tighter
- NOx can be controlled by EGR which brings down combustion temperature
- Increasing EGR reduces soot oxidation and increases engine-out soot
- Soot formation should be avoided

- Final fuel injection must be completed sufficiently before combustion starts to avoid soot-forming equivalence ratios – $\Phi < 2$. Premixed Compression Ignition, PCI
- Advanced diesel engines are expensive and complicated because they are trying to achieve PCI while using conventional diesel fuel (DCN > 40)

PCI much easier with fuels with high ignition delay i.e. "Gasoline" CI (GCI)

“Premixed-enough” CI

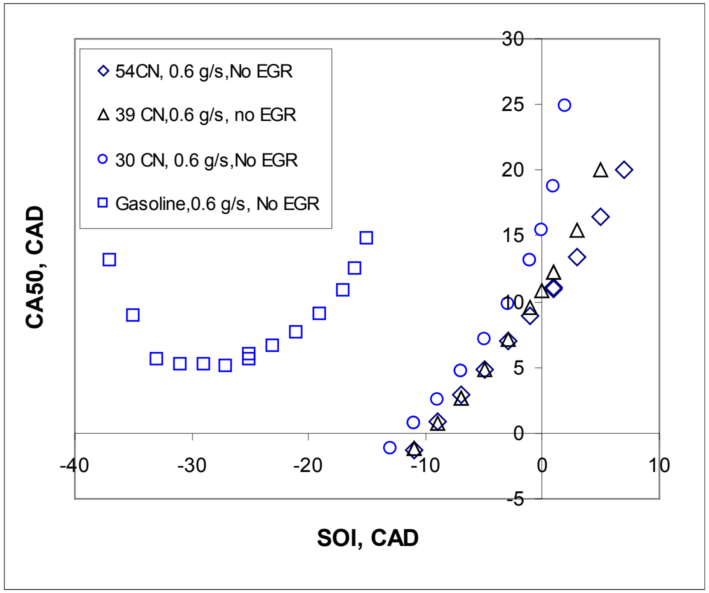
- Fuel/air must not be fully pre-mixed unlike in HCCI
- Allows in-cycle control over combustion phasing
- At low loads, with high ignition delay fuels, combustion occurs by auto-ignition in lean packets – zero smoke, low NOx and low noise but high HC and CO
- Low injection pressures help . Perhaps larger hole size.
- At high loads, multiple injection strategies help alleviate high pressure-rise rates and noise

Ideal fuel is “low-quality” gasoline – Gasoline Compression Ignition (GCI)

With GCI, efficiency at least as good as with diesel, much lower injection pressures needed and after-treatment focus shifts to HC and CO control rather than NOx and soot control

Results from 2 L single-cylinder, 14 CR

Reported in SAE 2006-01-3385 and SAE 2007-01-006



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

Expected results –

- CA50 decreases with CN

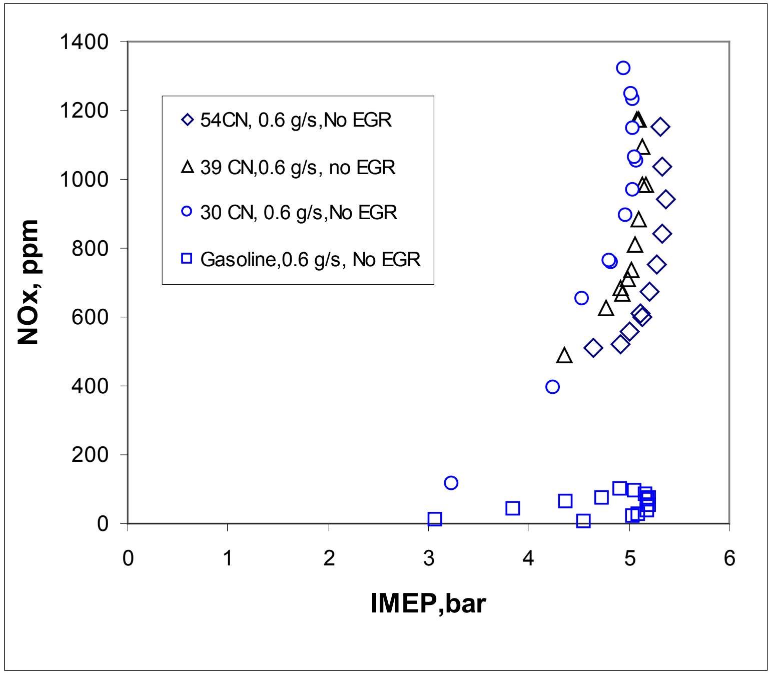
0.6 g/s, No EGR, Pin =1.5 bar abs, Tin = 40 C, 1200 RPM λ= 3.8

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

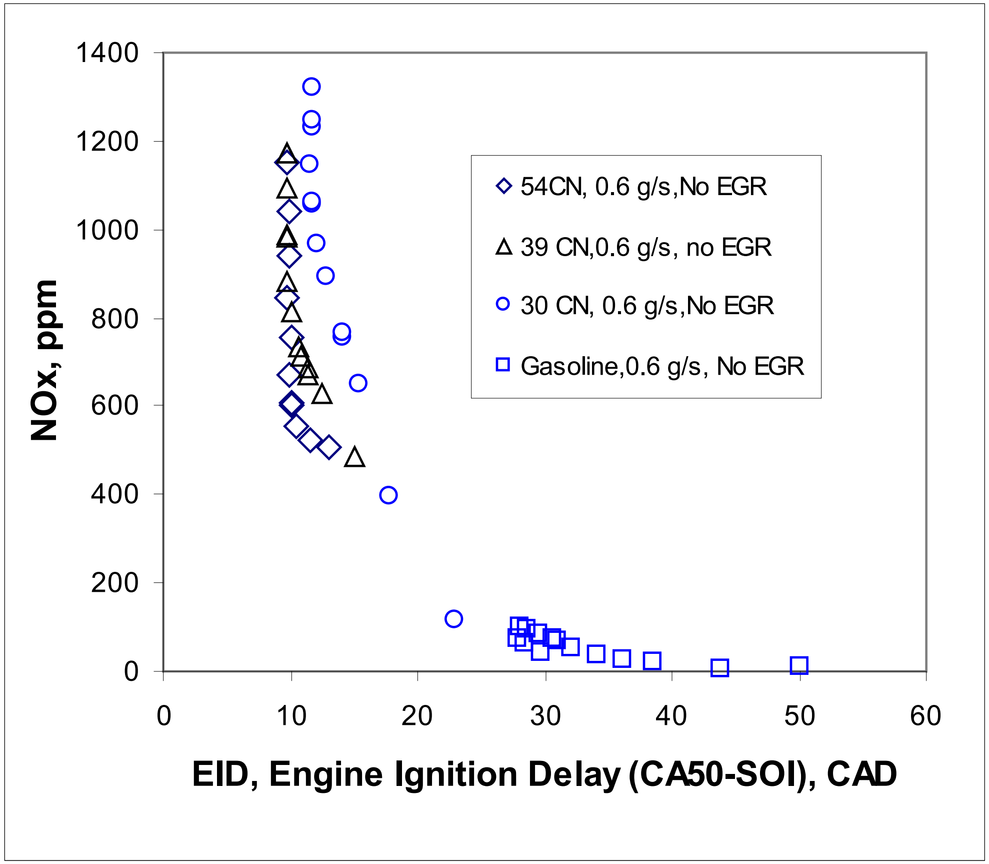
Results from 2 L single-cylinder, 14 CR



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

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

Results from 2 L single-cylinder, 14 CR



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

NOx decreases with Combustion delay

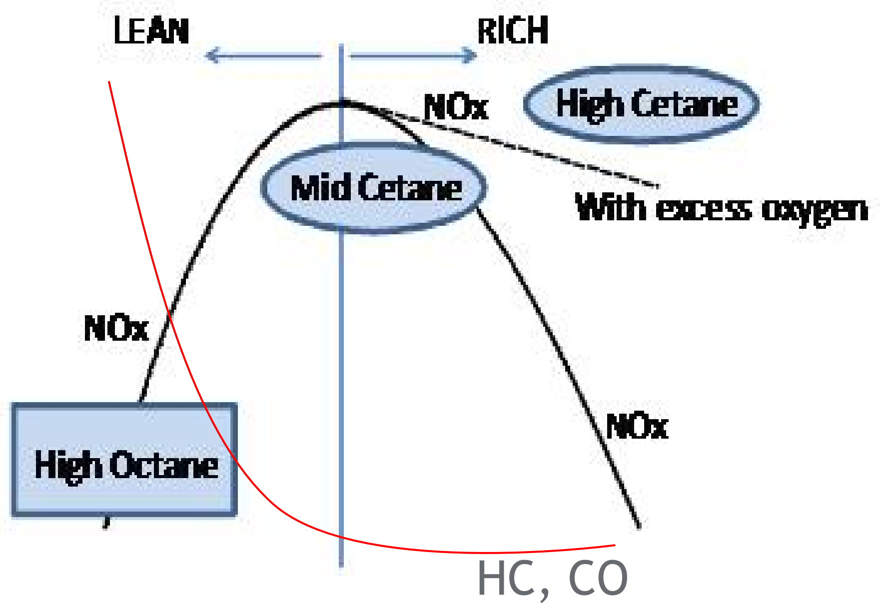
Ignition/combustion delay and mixing

At low loads

- For all fuels, injection is over before combustion starts
- Smoke is very low FSN < 0.08 for D1
- Packets of different mixture strength at the start of combustion
- The longer the ignition delay, the leaner these packets because the global mixture strength is lean

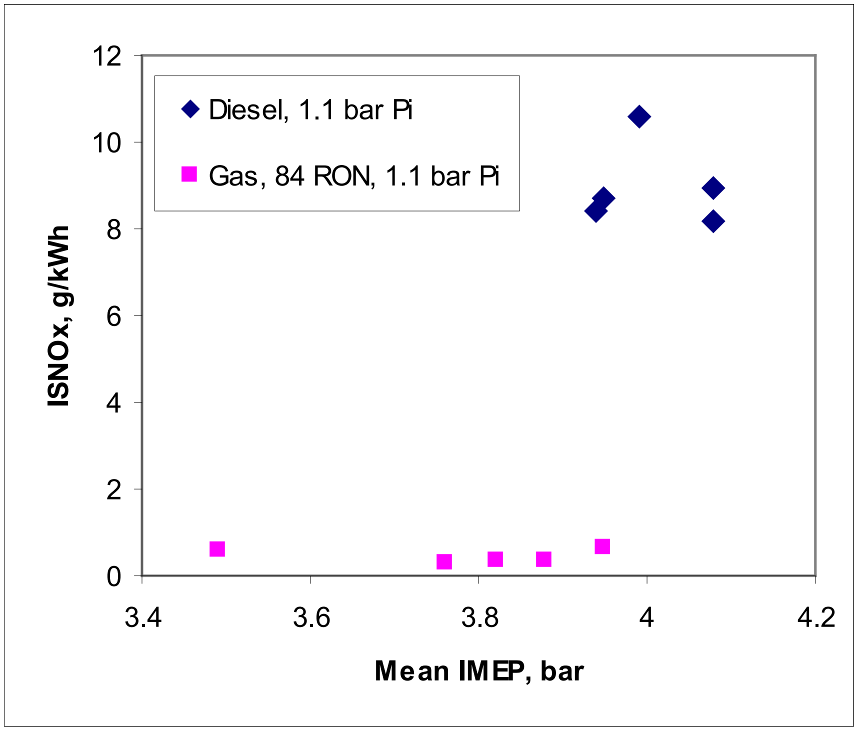
HC and CO are inverse of NOx

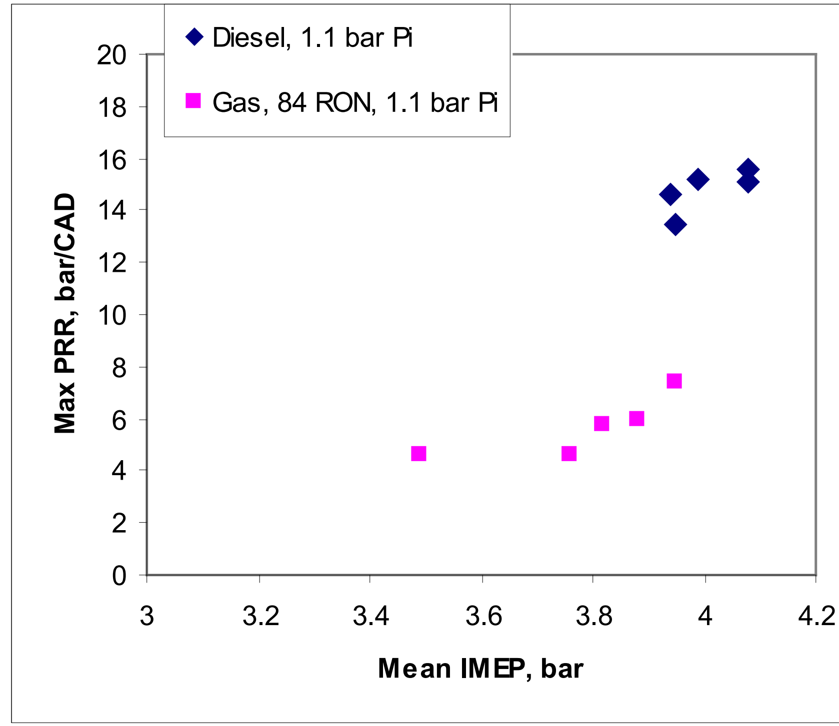
High cetane diesel will burn in richer packets while gasoline (high octane) will burn in lean packets.



Results from 0.537 L, 15.9 CR eng. at 1200 RPM. No EGR. 4 bar IMEP. Diesel (56 CN) vs 84 RON gasoline

At low loads both NOx and Max Pressure Rise Rate are lower for gasoline i.e. with long ignition delay but high HC and CO

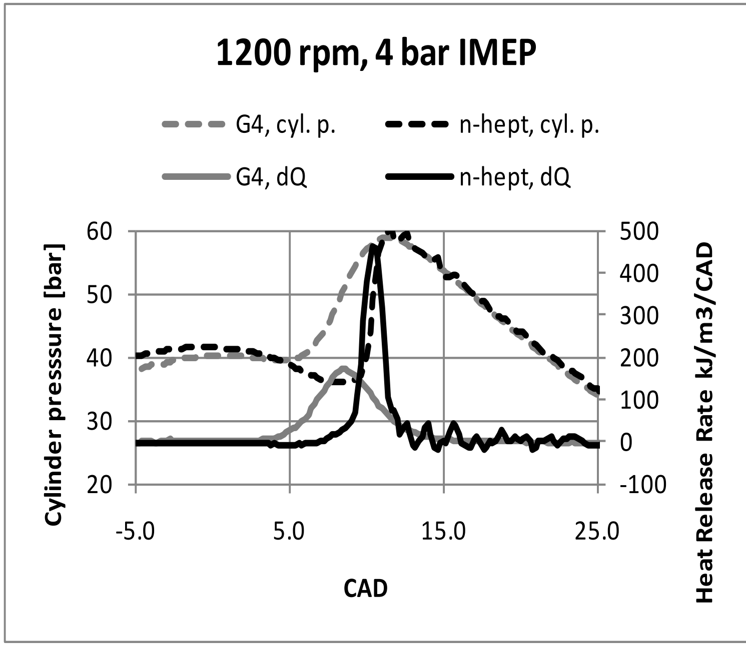


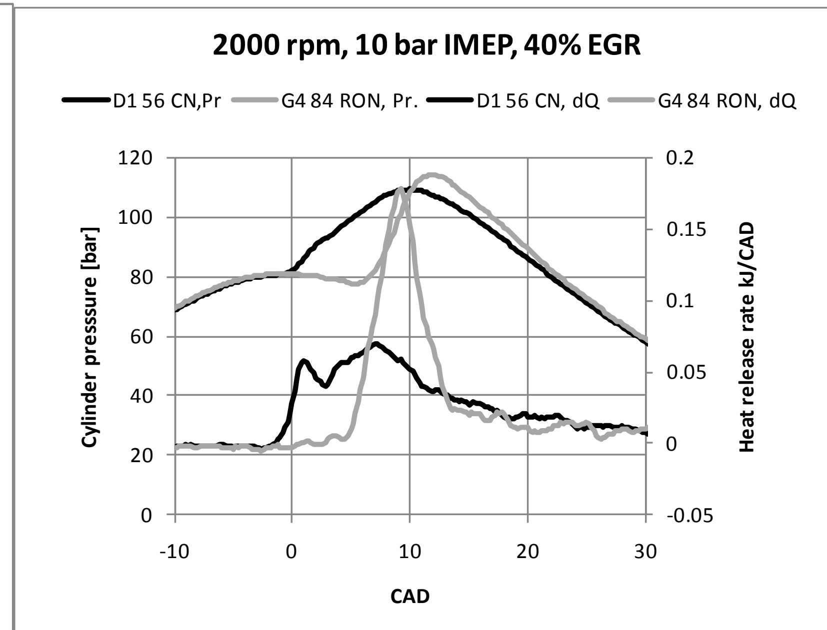


ASME, ICES2009-76034, J. Eng. For Gas Turbines Power, vol 152

SOI sweep at fixed fuel rate

Heat Release Rate and MPRR 0.537 L engine



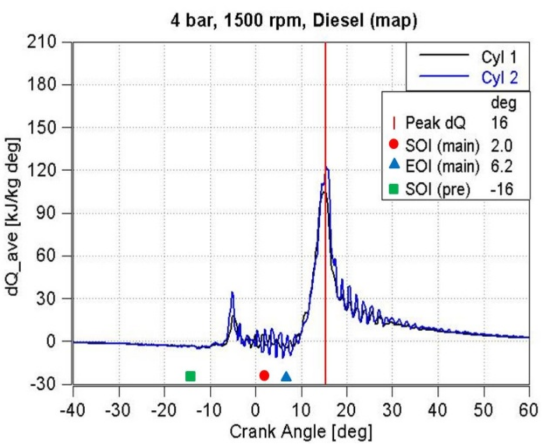


Average pressure and heat release rate for G4 (SOI = -12 CAD) and n-heptane (SOI = +0.7 CAD)., CA50 = 10.5 CAD

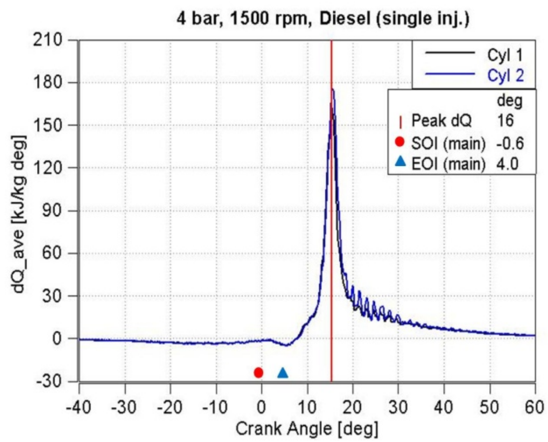
Average pressure and heat release rate at high load, 40% EGR for G4 (SOI = -9.5 CAD) and D1 (SOI = -3.6 CAD)., CA50 = 11 CAD

At low loads, gasoline will have lower MPRR compared to diesel. At high loads, the reverse is true

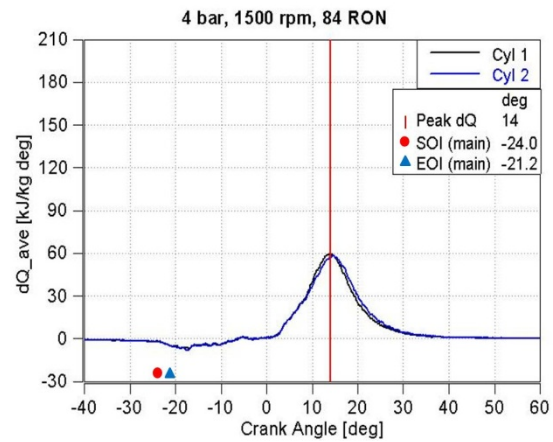
Heat Release Rate and Maximum Pressure Rise Rate in a Multi-cylinder (V6) Engine



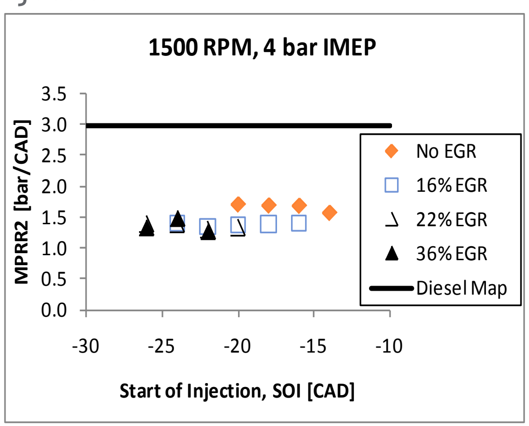
MAP cond., diesel fuel, 2 injections



Single Inj., diesel fuel, but with the same
Position for Max. Heat release



Single Inj., 84 RON gasoline, but with the same position for Max. Heat release



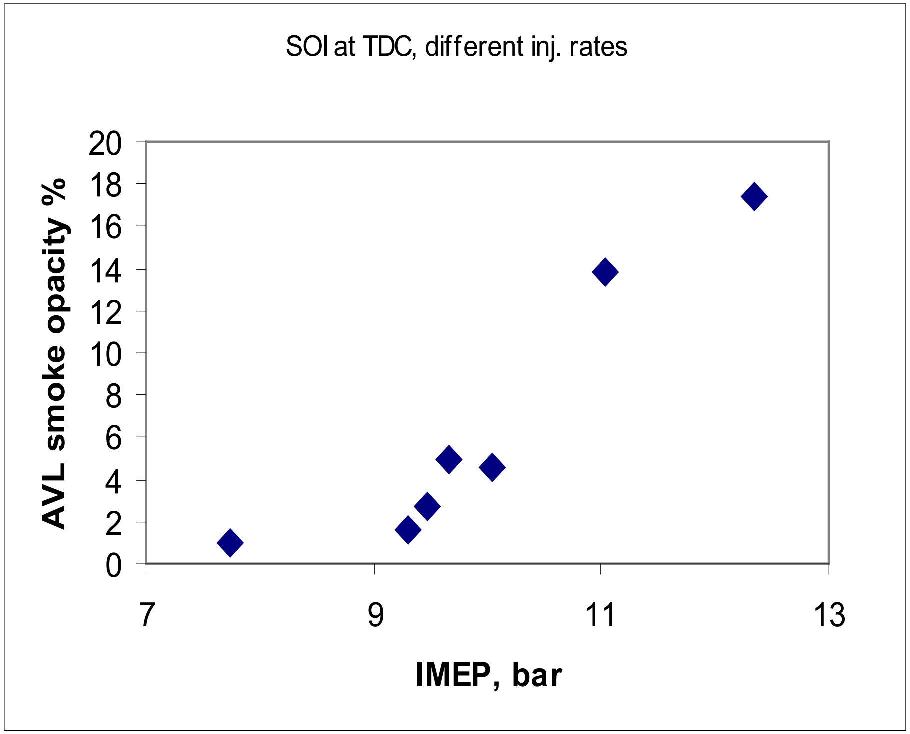
In real, light-duty engines, efficiency and smoke are sacrificed to reduce MPRR (i.e. noise) when using diesel fuel. This can be avoided if gasoline is used

Kalghatgi, G.T., Gurubaran, K., Davenport, A., Harrison, A.J., Taylor, A.K.M.F. and Hardalupas, Y., “ Some advantages and challenges of running a EuroIV, V6 diesel engine on a gasoline fuel”, Fuel 108: pp 197-207, 2013

SAE 2007-01-06.Smoke increases with injection quantity

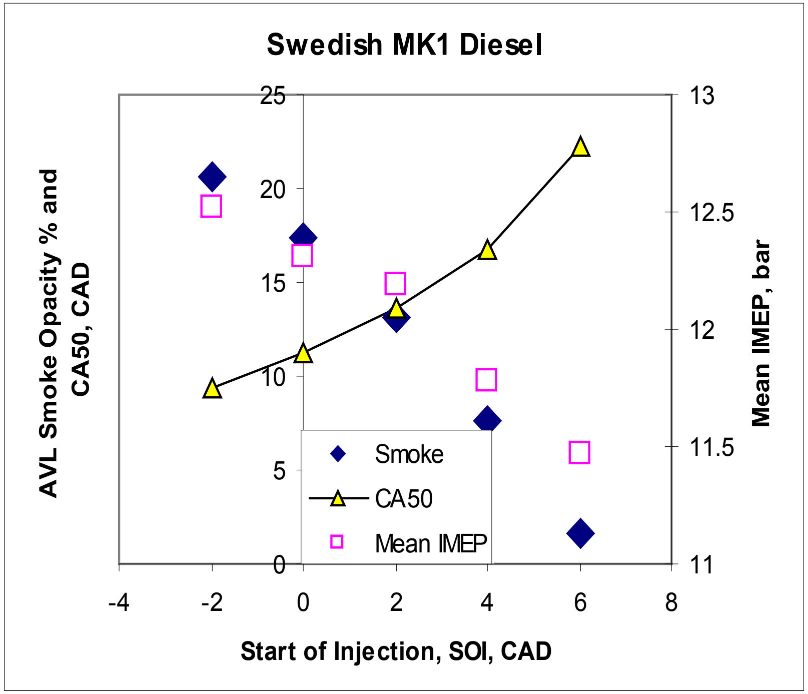
Pin = 2 bar abs, EGR ~ 38%

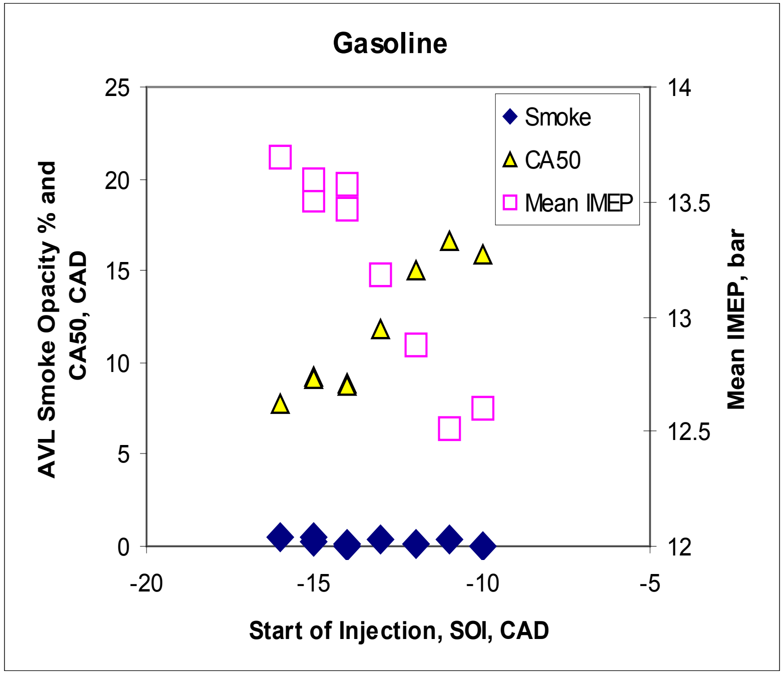
Swedish MK1 diesel fuel, Single Injection starting at TDC



Smoke vs IMEP, SOI at TDC

SAE 2007-01-06.Injection timing and smoke

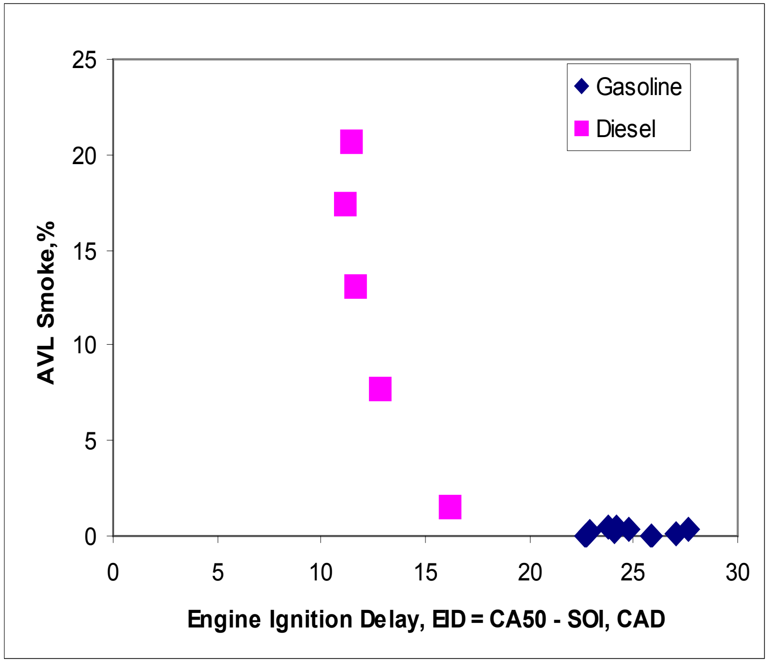




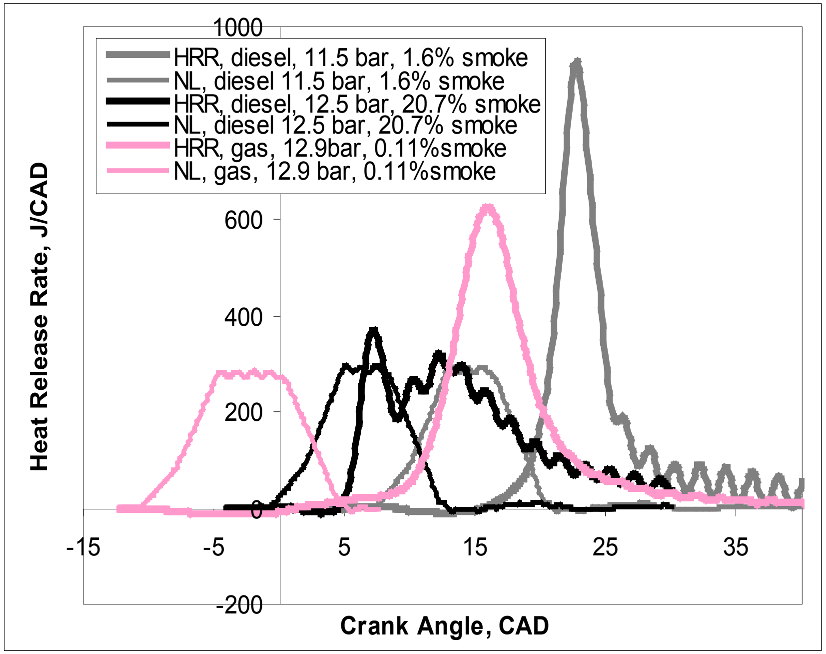
Smoke decreases as injection is retarded for diesel but very low for gasolin

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

SAE 2007-01-06.Low smoke for gasoline because of higher EID



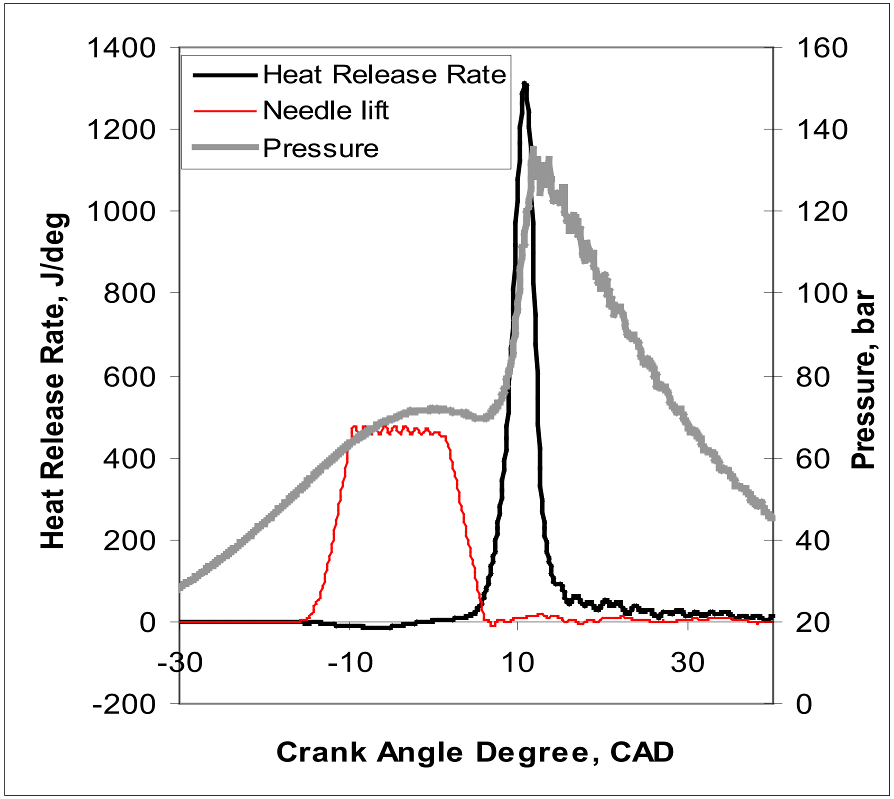
Smoke vs ignition delay



HRR and needle lift for three cases

Pin = 2 bar abs, 1.2 g/s fuel, EGR ~ 38%

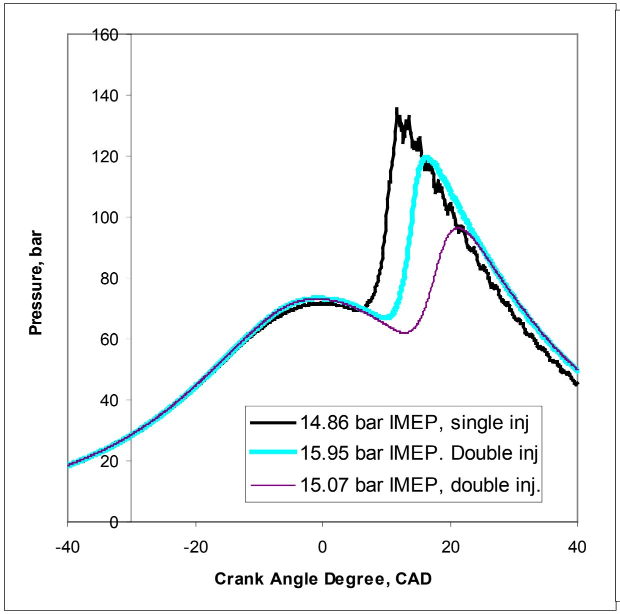
High IMEP point with gasoline, single injection

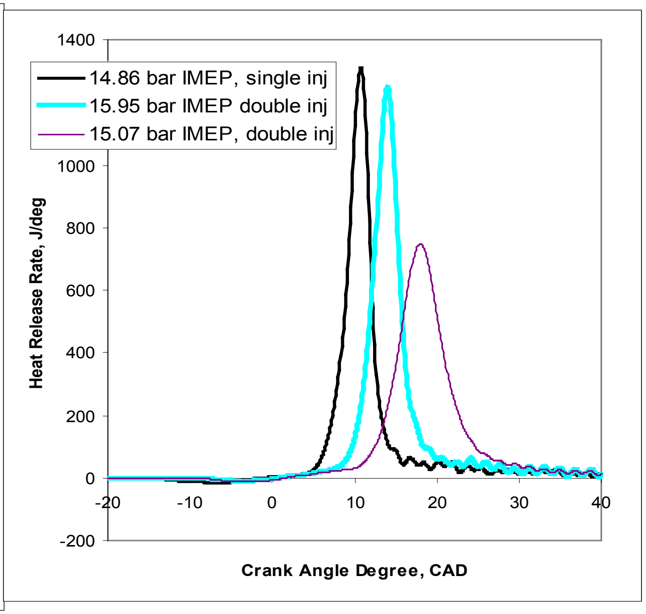


Pressure, heat release rate and needle lift curves for gasoline with 14.86 bar IMEP (0.115 bar std), 1.8% smoke and ISNOx , ISFC, ISCO and ISHC of 1.21 g/kWh, 178 g/kWh, 3.4 g/ kWh and 3.6 g/kWh respectively. Needle lift, arbitrary scale.

High Heat Release Rate. Can it be alleviated by using multiple injections?

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.

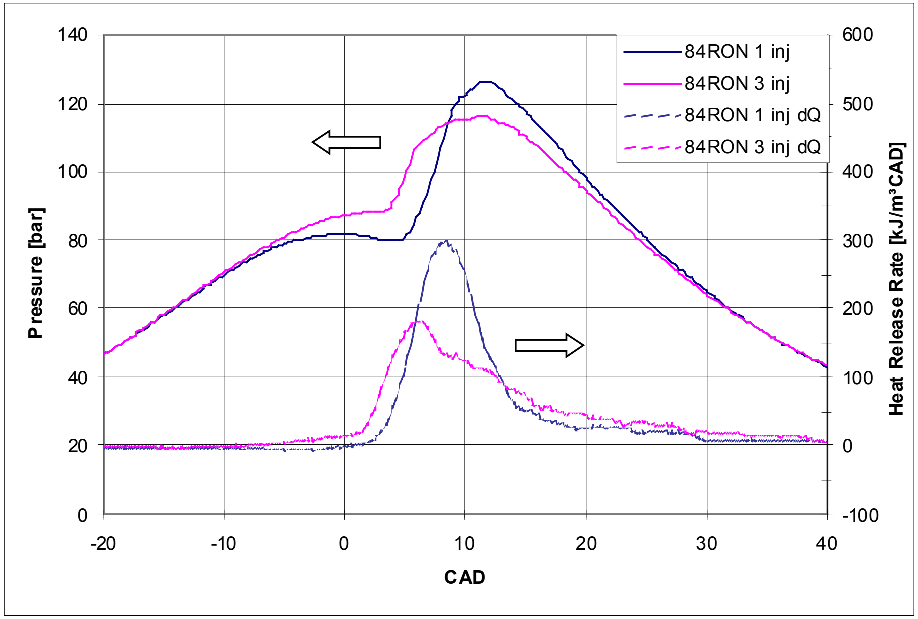
Injection	Fuel Rate Mean g/s	CO2 Intake %	IMEP* Mean bar	IMEP* std bar	AVL smoke % opacity	ISNOx g/kWh	ISFC g/kWh	ISHC g/kWh	ISCO g/kWh	MHRR* J/deg	Angle of MHRR* CAD
Single**	1.436	4.05	14.86	0.115	1.81	1.21	178	3.6	3.4	1446	10.8
Double***	1.46	4.14	15.07	0.138	0.28	0.59	179	3.0	5.8	817	18.2
Double*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

0.537 litre engine, 15.9 CR. Max pressure rise rate control with multiple injections

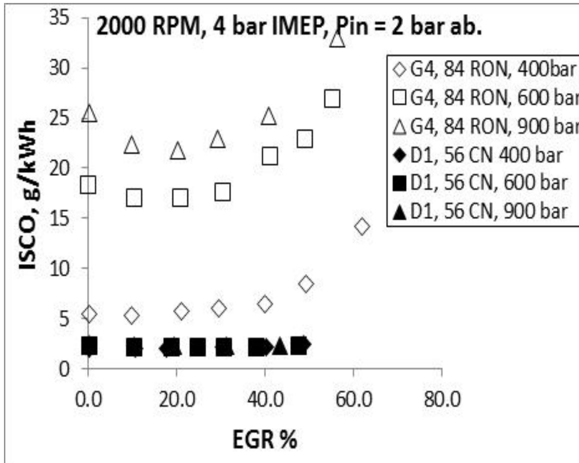


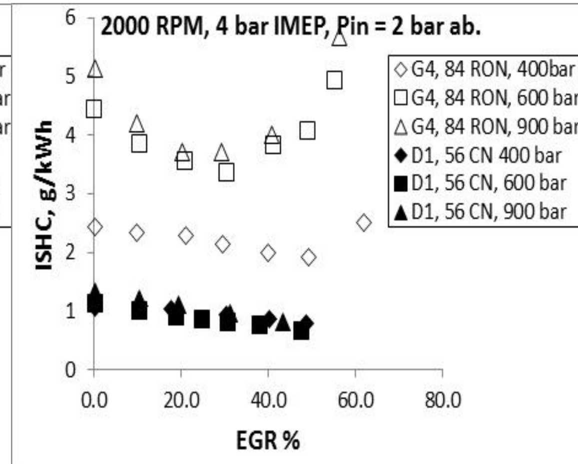
Pressure and heat release rate for single injection and triple injection (some increase in smoke). 84 RON gasoline, 2000 RPM, ~35% EGR, 900 bar injection pressure. IMEP of 12.3 bar in each case.

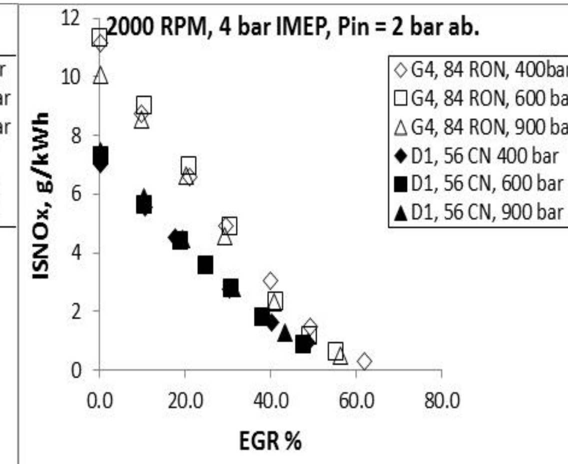
A lot of gasoline can be injected early in the cycle without causing heat release during the compression stroke. **Not possible with diesel.** An injection near TDC initiates combustion.

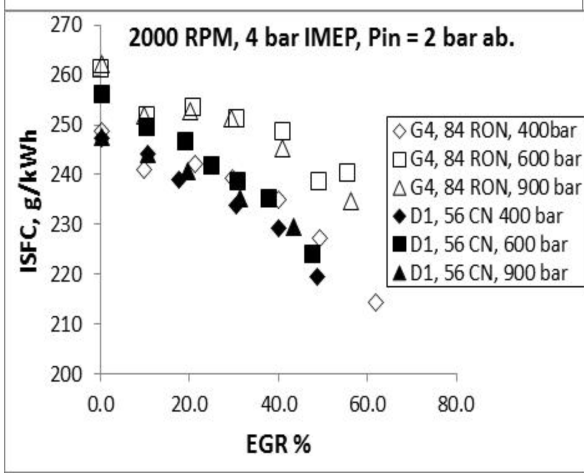
Kalghatgi, G.T., L. Hildingsson, B. Johansson, "Low NOx and low smoke operation of a diesel engine using gasoline-like fuels", ASME Paper # ICES2009-76034, Journal of Engineering for Gas Turbines and Power (Vol.132, Iss.9), 2010

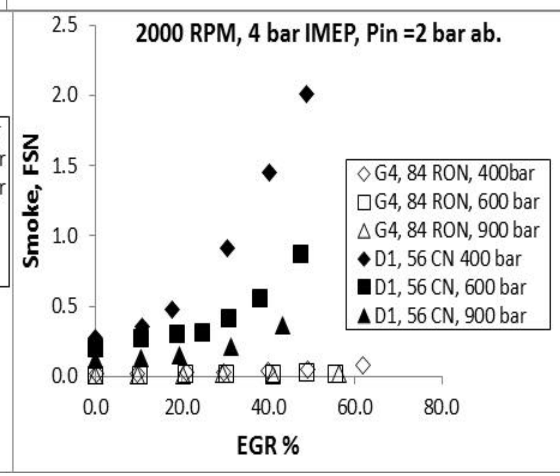
Avoid Overmixing - Injection pressure effects









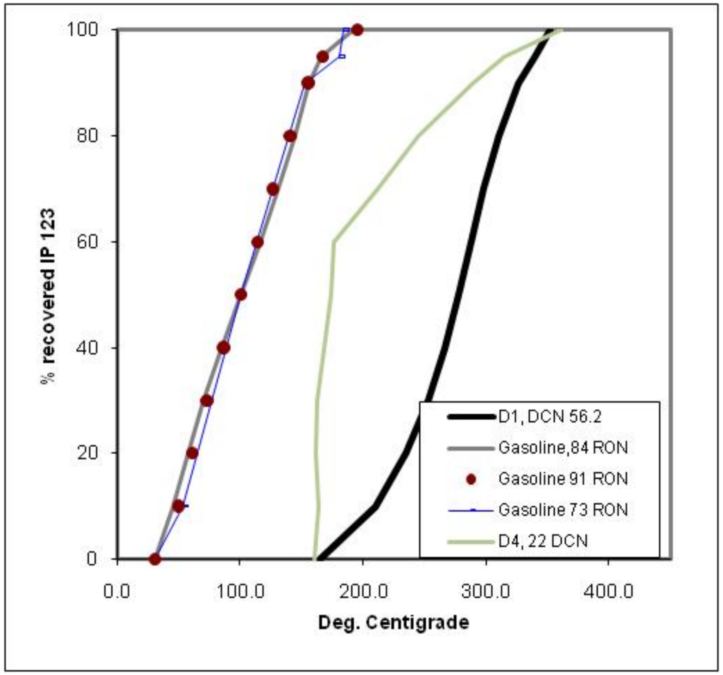


Should avoid over-mixing and over-leaning. Lower injection pressures better for fuels with long ignition delays. At higher loads, multiple injections.

Bigger injector holes might be better – more stratification

Fuel Effects on GCI – I. Volatility, Composition, Ignition delay

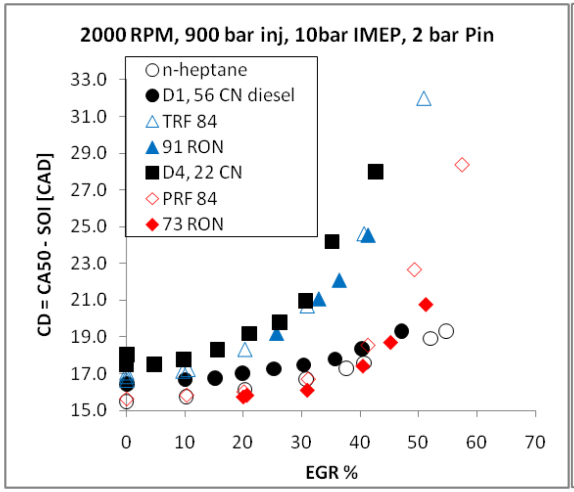
Fuel	RON	MON	DCN	Aromatic % vol	Isooct vol%	n-hep vol%	tolu vol%	density g/cc
PRF 84	84	84		0	84	16		0.682
TRF 84	84.5	74.5		65	0	35	65	0.785
TRF 82	82.1	78.1		26	50	24	26	0.723
n-Hept	0	0	55	0	0	100	0	0.632
ULG 72	72.9	68.4		19				0.715
ULG 78	78.5	73		23				0.726
ULG 84	84.1	78		26.5				0.736
ULG 91	90.7	81.8		29.8				0.731
D4			**22.5**	**75.3**				**0.865**
D1			**56**	**25.2**				**0.833**

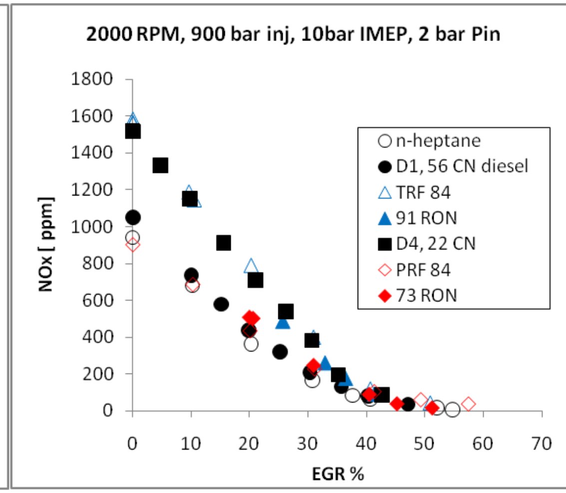


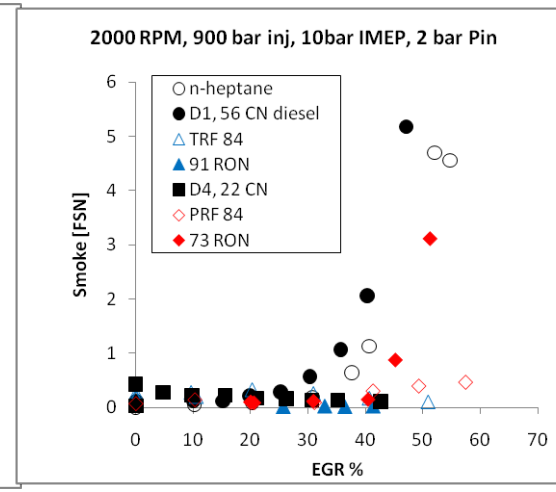
B.P.s of n-hept, isooctane, toluene – 98 C, 99 C 110 C

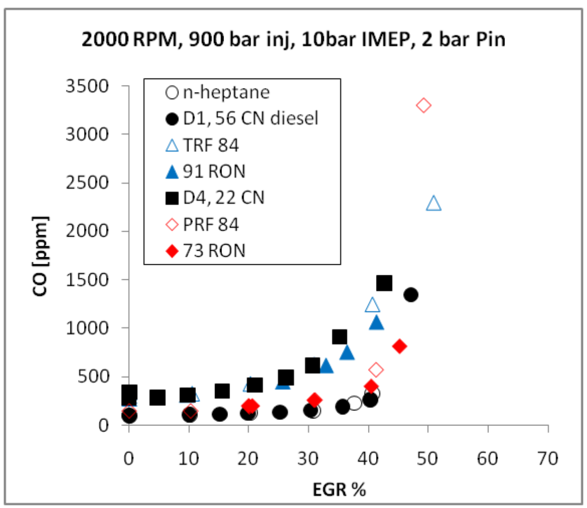
SAE 2009-01-1964, SAE 2010-01-0607, THIESEL 2010, International Combustion Symposium 2010

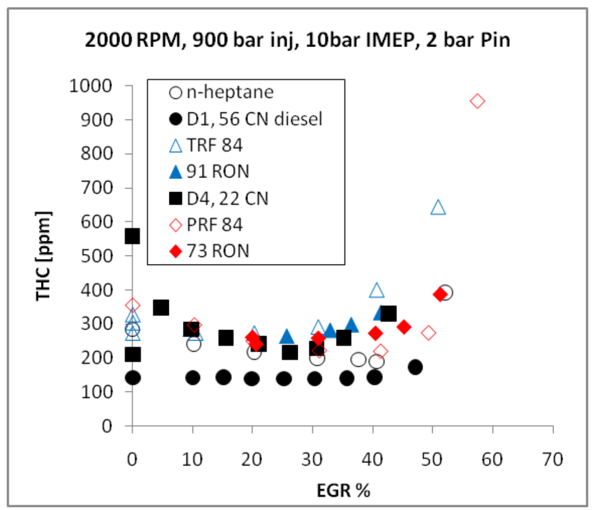
Fuel Effects on GCI - II







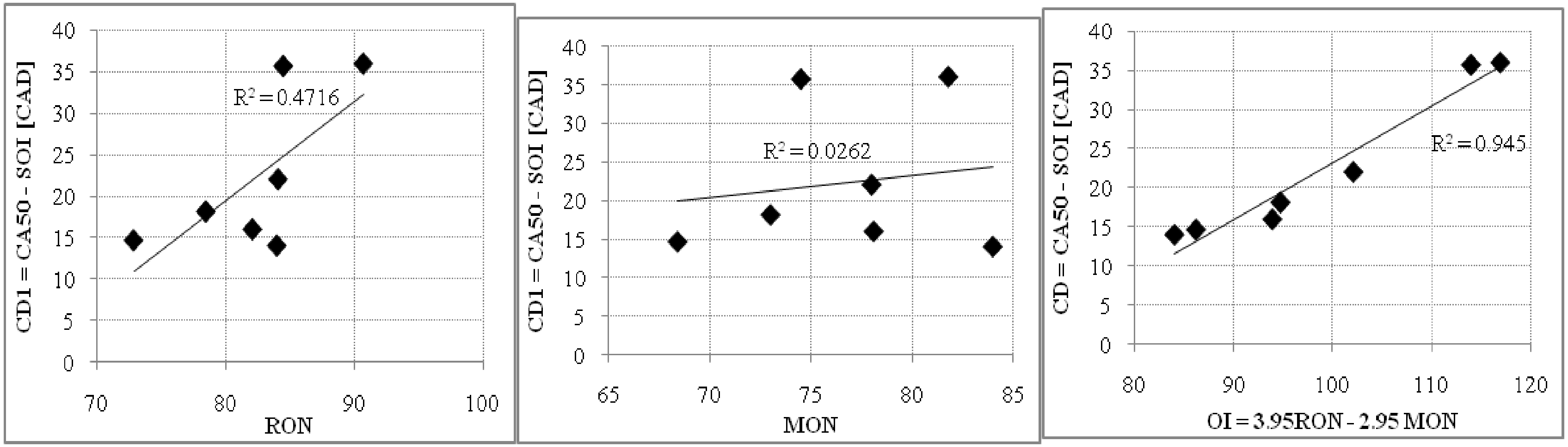




If two fuels match for combustion delay, they have similar NOx, CO, smoke and to some extent HC emissions for PCI

Fuel effects - III. Combustion delay and Octane Index

1200 RPM, 4 bar IMEP, 650 bar inj, 1.1 bar intake, no EGR, CA50 = 11 CAD



For gasolines and model fuels we can measure RON and MON

OI = (1- K) RON + KMON

If two fuels have the same RON and MON, they will have the same OI and hence the same combustion phasing.

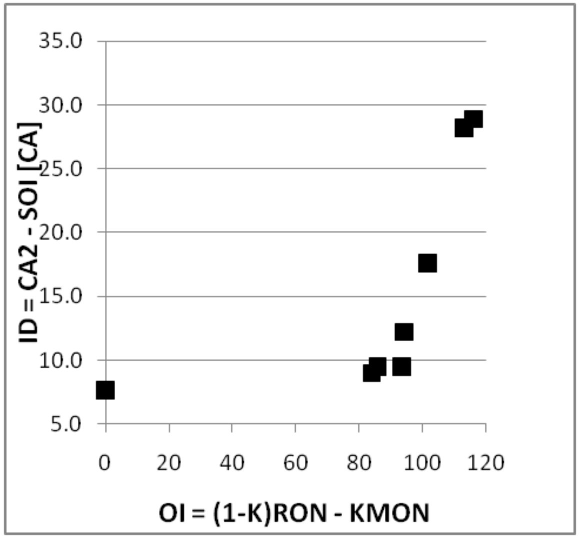
Then in PCI combustion, they will have comparable emissions

Hence a good surrogate for PCI is a toluene reference fuel with the same RON and MON as the target fuel

Kalghatgi et al" Autoignition quality of gasolines in partially premixed combustion in diesel engines", Proceedings of the Combustion Institute 33 (2011) 3015-3021.

Kalghatgi et al "Surrogate fuels for premixed combustion in compression ignition engines", *International Journal of Engine Research, October 2011; vol. 12, 5: pp. 452-465*

Ignition Delay Changes Non-linearly with OI



ID at 1200 RPM, 4 bar IMEP, No EGR

Little change in ignition delay in diesel autoignition range i.e CN > 40 or OI < 40. Optimum RON between 70 and 85. CN < 25 to see real benefits. **Low volatility not required if ignition delay is high enough.**

•Volatility will still play a role in mixing – wider volatility range might be beneficial by enabling more stratification.
Won et al. (J Auto 2011, 2012) – [10% diesel + 90% gasoline] allowed PCI operation over a wider speed/load range than a gasoline of the same RON and MON

- Initially GCI will have to use available fuels either in RCCI or as mixture of diesel and gasoline.

Fuel requirements of GCI engines

- Varying requirements on ignition delay (ID) at different operating conditions -
  - ID (octane) too high – start difficult, low load stability
  - ID too low – reduced benefits on soot and NOx
- Challenge of introducing a new fuel – use market fuels
- Use two fuels – RCCI. Mostly run on gasoline (high ID) use diesel (low ID) when needed. Relevant for heavy-duty engines today
- Compromise and find "optimum" ignition quality – ~70 RON. "Homeless hydrocarbons" can be used with little further processing ! Deal with challenges via engine management.
- No strict requirements on volatility – increases refinery flexibility. Wider volatility range seems to be beneficial (by increasing stratification?)
  - "Dieseline" – e.g. 10%-20% vol diesel in gasoline. Existing market fuels could be used
- RCCI and Dieseline interim enabling technologies.

GCI Efficiencies at least as high as the best diesel engines

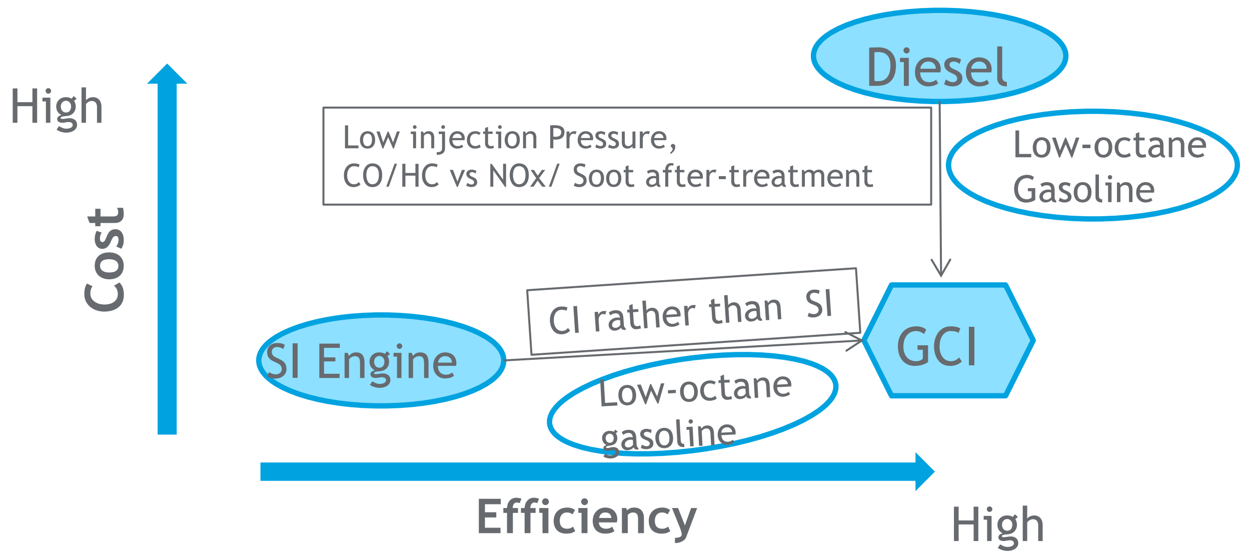
- Indicated efficiencies of around 56% demonstrated in heavy duty (large) engine tests (Lund, Wisconsin)
- Additional efficiency improvements in light duty engines possible –
  - Avoiding pilot injection at low loads
  - Down-sizing / down-speeding to reduce transmission losses
  - Avoid or minimize (if one is used) DPF regeneration
  - Reduced parasitic losses because of low injection pressure
- Scope for hybridization – like a diesel hybrid at lower cost. Hybridization both enabling and enhancing technology

Development Challenges for GCI

1. Cold start and idle
2. Stability at low load
3. Noise/pressure rise rate at medium and high loads
4. Emissions, particularly CO and HC – low temperature oxidation and DPF
5. Hardware optimization –
   Injectors, injection system, injection strategy
   Cooled EGR
   Turbocharger+ supercharger to get high boost at high EGR
6. Fuel quality – lubricity, detergency

- Could be done with mostly existing technology
- Different compromises for different applications
- Enabling technologies – hybridization, in-cylinder pressure based control, low temperature oxidation/DPF

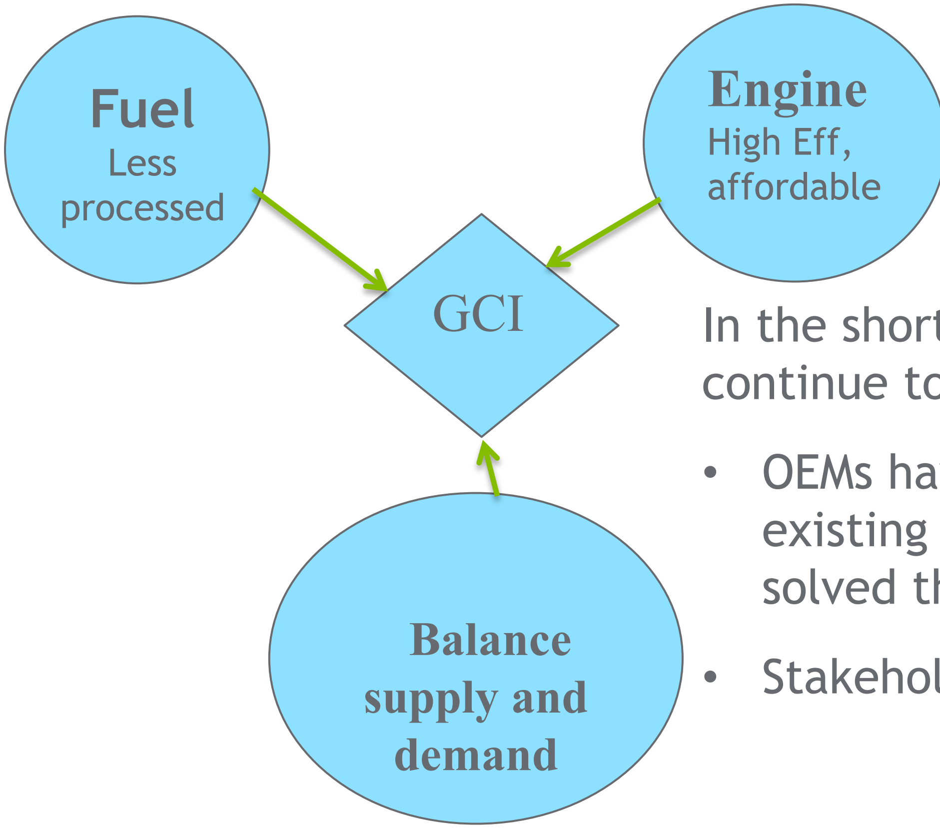
GCI -High efficiency, affordable, clean engines using less processed fuels



"Low-octane" Gasoline - RON between 70 and 85, no strict volatility requirement

- GCI enables high efficiency, low emissions, low cost engines using less processed fuels. Lower overall GHG impact – around 30% better compared to SI and 4-5% better compared to diesel
- Opens up a path to mitigate expected demand imbalance between light and heavy fuels.

Prospects for GCI



In the short term diesel engines will continue to use diesel fuels –

- OEMs have too much invested in existing diesel technology and solved the problems
- Stakeholders need to be aligned

Required development will take place when and where

- Commitment to existing diesel technology is weak and alignment of different stakeholders is easier (China?)
- The demand imbalance will start to bite
- Mazda SkyAktiv is a spark assisted GCI engine

Summary

- Global transport energy demand increasing – by 30%- 40% between now and 2040. All in non-OECD countries
- Even by 2040, most (~ 90%) of it will come from petroleum
- Demand growth heavily skewed towards commercial transport - More diesel and jet fuel needed compared to gasoline.
- Pressure to increase gasoline anti-knock quality. (Revision of gasoline anti-knock specifications needed)
- Great challenge to the refining industry – huge investments (100s of billions of $) AND "homeless hydrocarbons" - low-octane gasoline (More EVs means greater demand imbalance)
- Highly efficient engines running on such fuels need to be developed
- Gasoline Compression Ignition (GCI) engines offer such a prospect
- GCI have advantages from the engine side (low injection pressures etc) and the fuel side (less processed fuel)
- All stakeholders need to work together to bring such optimized fuel/engine systems to the market rather than only developing engines for existing market fuels