Lecture 8

Implications for Fuels for Internal Combustion Engines

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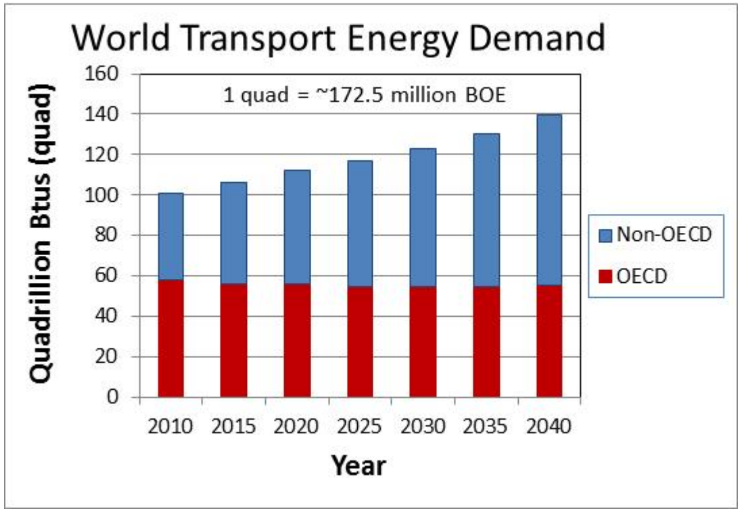
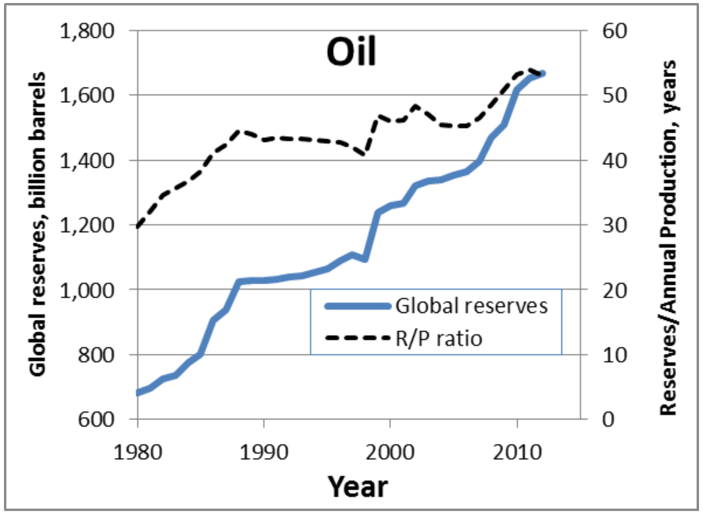
World Transport Energy

- Transport is essentially driven by liquid fuels – high energy density, ease of transport and storage, extensive infrastructure
- ~95% of transport energy supplied by petroleum
- Demand is increasing –because of growth in non-OECD countries



U.S. EIA (Energy Information Admin.)



Source: BP Statistical Review of World Energy 2013

Plenty of oil will be available

Even in 2040, ~90% of transport energy from petroleum – Alternatives cannot grow fast enough

Current IC Engines

- Spark Ignition (SI) – fuel/air are mixed and compressed, heat release via expanding flame.
    - Uses gasoline.
    - Light duty.
- Compression Ignition (CI) – air is compressed, heat release via autoignition of fuel as it mixes with air.
    - Uses diesel fuel.
    - Mostly heavy duty.
- CI engines more efficient but more expensive

Current Fuels for IC Engines

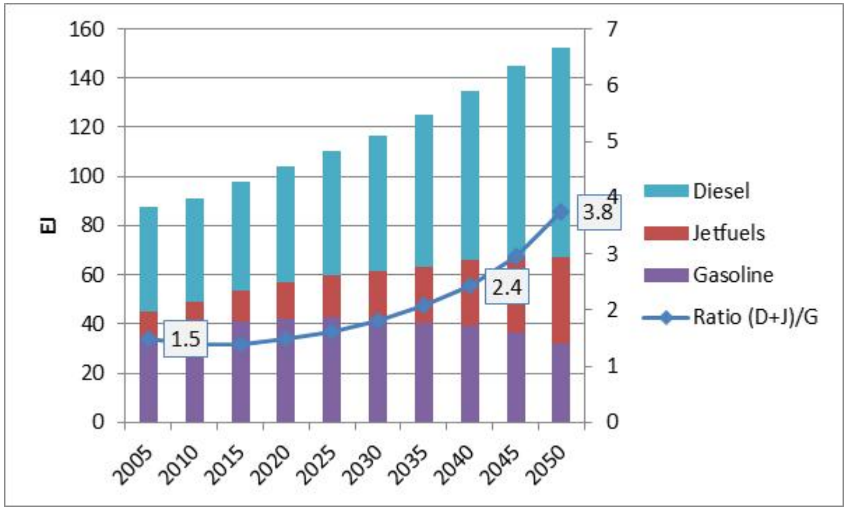
- Gasoline and diesel complex mixtures of hydrocarbons
- Primary fuel property is the autoignition quality –
- Gasolines are resistant to autoignition to avoid knock (measured by octane numbers, RON and MON) – used in SI engines
- Diesel fuels are prone to autoignition (measured by Cetane Number) – used in diesel engines
- Diesels are also less volatile, heavier. (Jet fuel is like a lighter diesel)

Jet fuel accounts for around 12% of transport energy and is like a light diesel

Naphtha is an example of “less processed” fuel. It is the product in the boiling range between 30ºC and 200ºC from different processes and is further processed to increase its octane number

Fuel Demand Structure Will Change

- Passenger Car Sector – a) future average car will be smaller/lighter and drive fewer miles compared to today b) larger scope for efficiency improvements e.g. hybridisation
- Future demand increase heavily skewed towards commercial transport



WEC, World Energy Council. Freeway Scenario.

- Very significant investments in refineries will be needed on current technology trajectory. Low octane gasoline (naphtha) will be abundant
- Octane of the gasoline pool needs to increase – also increases naphtha availability
- Efficient and clean engines using naphtha need to be developed. Otherwise refining efficiency and yield will go down.

What about alternatives?

- Annual global demand for transport fuels is very large – around 23 MBOED for gasoline, 26 MBOED for diesel (1.6 trillion litres each per year).
- Alternatives like biofuels are growing but cannot displace conventional fuels
- Biofuels – in 2012 supplied just under 4% of global transport energy
  - Food vs Fuel
  - Increasing environmental concerns
  - Costlier
  - No immediate prospect for 2nd generation biofuels or algal fuels
- Gas-to-liquids (GTL) – even by 2015, < 0.2% of total demand but cheap shale gas could have an impact
- Hydrogen – problems with production, transport and storage make its use for transport very unlikely
- CNG, LNG – renewed interest because of cheap shale gas but infrastructure limitations
- LPG – niche fuel

Global transport share of gas expected to increase to ~5% by 2040

Electric Vehicles

Different levels of electrification – hybridization to improve efficiency, full electric vehicles (FEV), plug-in EVs (PEV)

- Only FEVs get their energy from the grid rather than liquid fuels

Issues with FEVs –

- CO2 and overall energy impact depends on how electricity is generated
- Cost
- Driving range
- Charging time, convenience, infrastructure
- Scope limited to small vehicles working in urban cycles

Hybrid Electric Vehicles (FEVs) are expected to become wide-spread

Fuel demand from the personal transportation sector is expected to be significantly reduced by the spread of HEVs but not from FEVs or PEVs

Engine Development Trends

High efficiency, low emissions and affordable

SI Engines : Improve fuel economy – downsizing and turbocharging.

- Knock and fuel anti-knock quality become important
- Cost increase if high performance is to be maintained

CI Engines: Reduce soot and NOx.

- High engine/after-treatment cost with existing diesel fuel
- Efficiency might be compromised

Hybridization:

- Cost increase
- More benefit in low-duty urban cycles.
- Easier to implement on light-duty vehicles

SPARK IGNITION ENGINES

Fuel Anti-knock or Octane Quality

- Higher efficiency → knock and fuel anti-knock quality
- Traditionally measured by RON and MON – Research and Motor Octane Numbers
- Manufacture of transport fuels is dominated by the requirements to meet RON/MON specifications
- Both scales are based on primary reference fuels (PRF) – mixtures of isooctane and n-heptane
- Practical fuels become relatively more resistant to autoignition compared to PRF as pressure increases for a given temperature.
- Fuels of different chemistry are ranked differently depending on temperature and pressure development in the end gas.

In real engines anti-knock quality of practical fuels depends both on fuel chemistry and on engine design and operating conditions.

Dependence of K on T and P

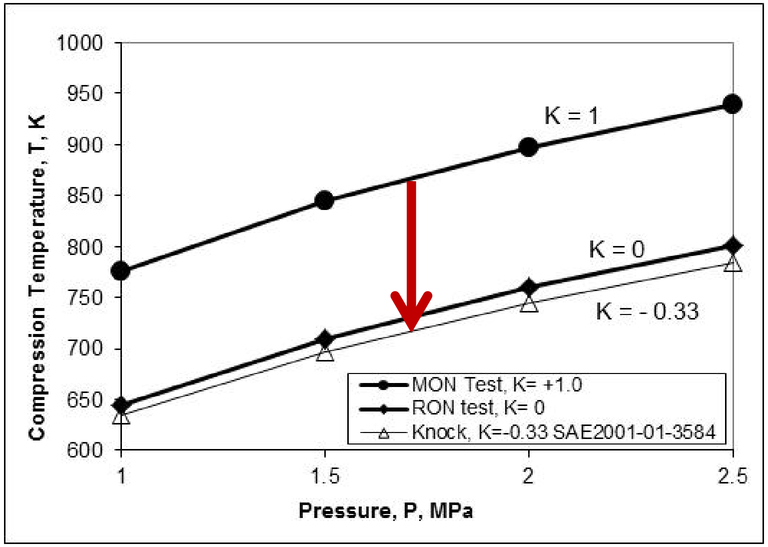
$$OI = (1-K)RON - KMON = RON - KS$$

$$S = RON - MON$$

Experimental results from both knocking SI engines and HCCI engines.

For a given pressure MON test (K=1) has higher temperature compared to RON (K=0) test.

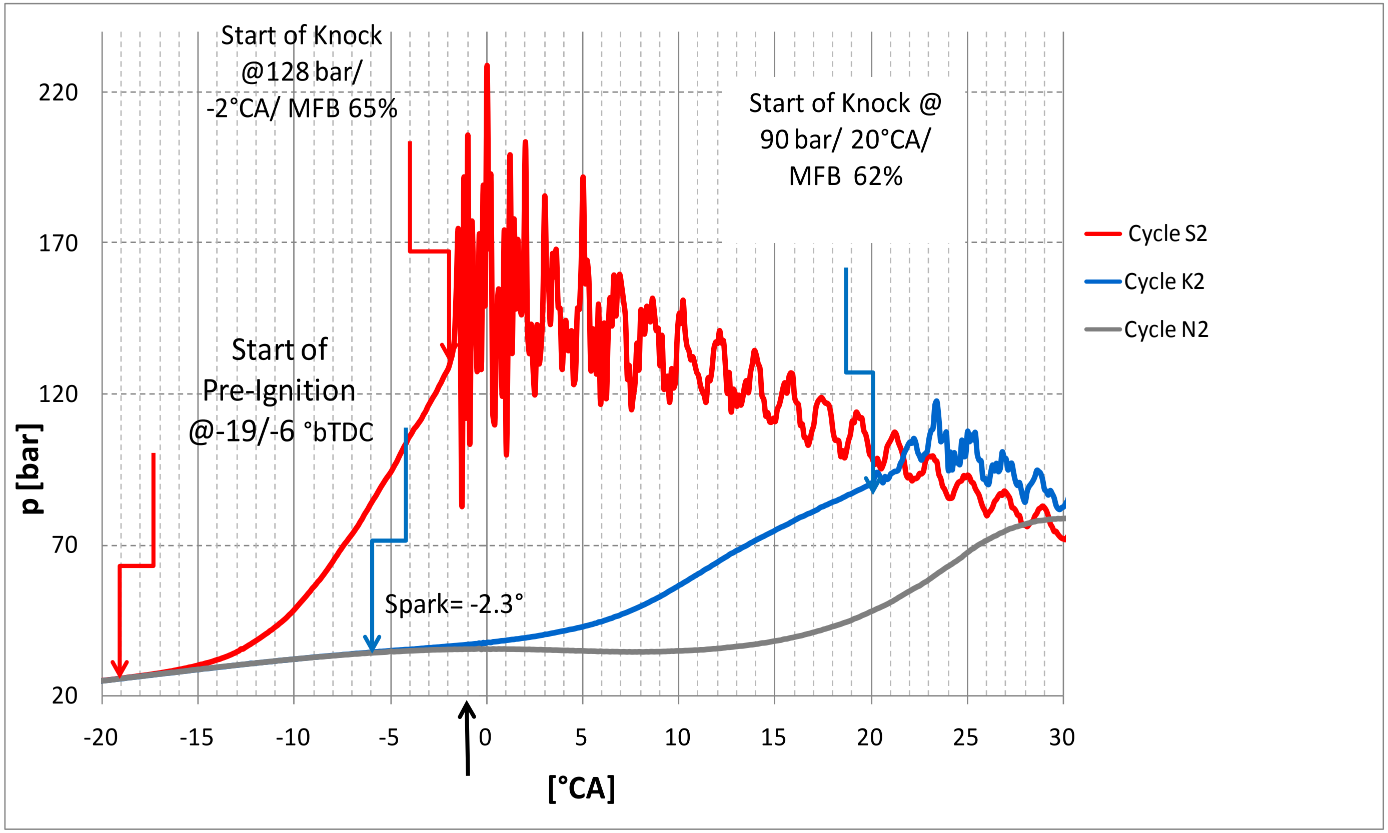
In SI engines, as efficiency increases, for a given pressure, temperature of the unburned mixture decreases (or for a given temperature, pressure increases)



Modern SI engines are "beyond" RON and have negative K values. This trend will continue as SI engines seek better efficiency.

For a given RON, *lower* MON is better

Pre-ignition and extremely violent knock (Superknock) events observed in prototype boosted test engines



Why different knock intensities in cycles K2 and S2?

Kalghatgi, G.T. and Bradley, D. 2012, *International Journal of Engine Research* 13(4): pp 399-414

Pre-ignition Background

Pre-ignition was a major concern in the 1950s and was considered more of a limiting factor for engine efficiency than knock

Pre-ignition and Superknock are different but related phenomena

- Pre-ignition occurs when an advancing flame front is initiated before the spark plug fires
- It starts at a hot spot or ignition centre
- The pressure and temperature in the end-gas are higher than in normal combustion
- **Superknock is caused by auto-ignition in the end gas at high pressure/temperature**

Kalghatgi, G.T. and Bradley, D., “Preignition and superknock in turbocharged spark ignition (SI) engines”, *Int. J. of Engine Res* 2012; 13: 399-414

Preignition leading to Superknock

Three links in the chain of probability leading to Superknock

- Initial ignition – in DISI engines from the ignition of oil droplets. NOT RELATED TO FUEL OCTANE QUALITY
- Flame initiation – More likely the higher the laminar burning velocity
- Developing Detonation – because of autoignition at high pressure and temperature. Leads to high knock intensity. Less likely if fuel anti-knock quality is high

Thus ethanol more likely to cause preignition but less likely to lead to superknock.

SI Fuel Implications

- Current specifications and other fuel initiatives are often not consistent with the requirement of modern engines (K < 0)

Minimum MON of 85 in Europe

Anti-knock quality specified by(RON+MON)/2 in the U.S.....

Result - harder-to-make and less suitable fuels for current and future engines.

- Rational specifications needed. Some are necessary e.g. low sulphur and benzene but others?

Introducing MON specifications where there are none is a retrogressive step

- Higher anti-knock quality helps mitigate superknock

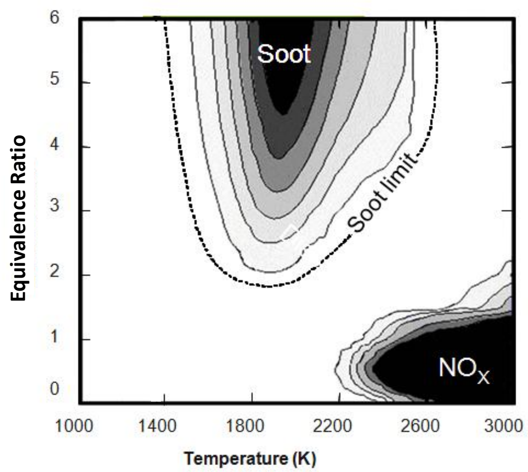
Pressure to increase anti-knock quality of gasoline. Big challenge for refining industry. Will increase the availability of naphtha

Making the best use of available fuel anti-knock quality – Octane on Demand (OOD)

- High anti-knock quality of the fuel is required only over a limited operating range
- Engines with dual fuel systems to supply octane on demand can be developed
- A market fuel can be separated on board into higher and lower octane components, engine redesigned (e.g. higher CR) to improve overall efficiency – Honda SAE 2014-01-2614, Toyota/ExxonMobil SAE 2014-01-1200
- A low octane fuel (naphtha) and a high octane fuel (e.g. methanol, MTBE) can be separately sourced and an engine can be run in OOD mode to improve efficiency. Further CO2 benefit from fuel manufacture. Also another path to use naphtha – Saudi Aramco 2015-01-1264, SAE 2015-01-1265, SAE 2016-01-0679, SAE 2016-01-0683, Fuel , Vol 207, pp 470-487, 2017, Applied Energy Vol 208, pp1538-1561, 2017.

COMPRESSION IGNITION ENGINES

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)

Gasoline Compression Ignition (GCI)

- Inject “gasoline” much earlier compared to diesel fuel
- High ignition delay makes pre-mixed, low NOx/low soot CI combustion very much easier
  - Unlike HCCI, fuel/air not fully premixed. In-cycle control over combustion phasing.
- Great scope for simplifying the future CI (diesel) engine by running it on gasoline-like fuels –

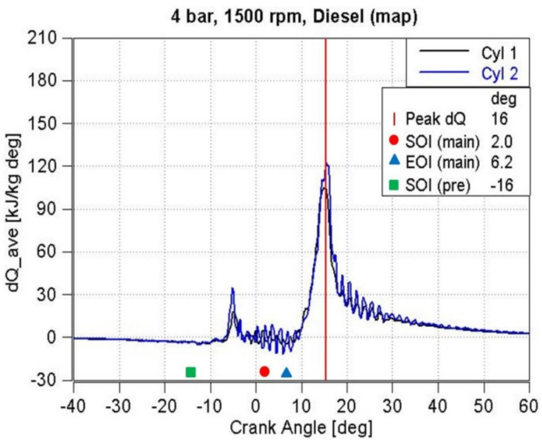
  •lower injection pressure
  • HC and CO rather than NOx after-treatment
  • very high efficiency, scope for “downsizing”, exploiting low noise at low load to improve efficiency…..
- Needs low octane gasoline - 70 to 85 RON but could be much less volatile than current gasolines. **Save energy / CO_2 also in the refinery**

Kalghatgi and co-workers, SAE 2006-01-3385, 2007-01-006, 2009-01-2648, 2010-01-0607, 2012-01-0677
Johansson and co-workers SAE 2009-01-0944, 2009-01-2668, 2012-01-0687, Int. J. Eng. Res. (2011) 12: 194-208
Reitz and co-workers, SAE 2009-01-1442, Int. J of Eng. Res. (2011), 4:394-411
Sellnau et al. SAE 2011-01-1386, SAE 2012-01-0384, Weall and Collings, SAE 2009-01-1791, 2007-01-4058

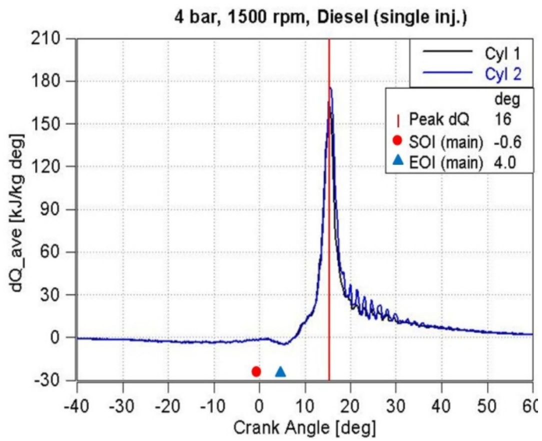
GCI – Efficiencies are at least as high as in the best diesel engines

- 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

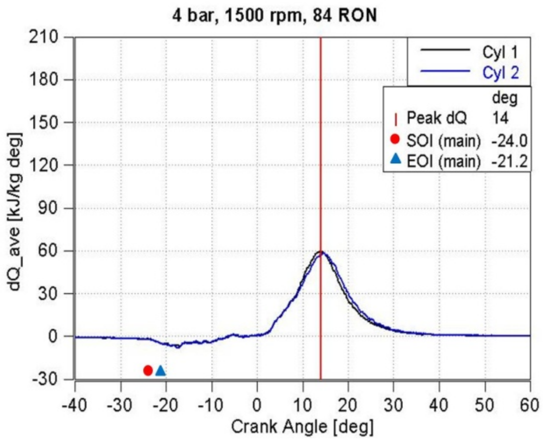
Heat Release Rate and Maximum Pressure Rise Rate in a Multi-cylinder (V6) Engine



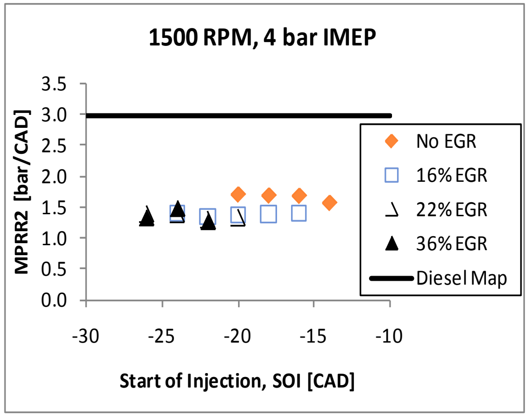
MAP cond., diesel fuel, 2 injections



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

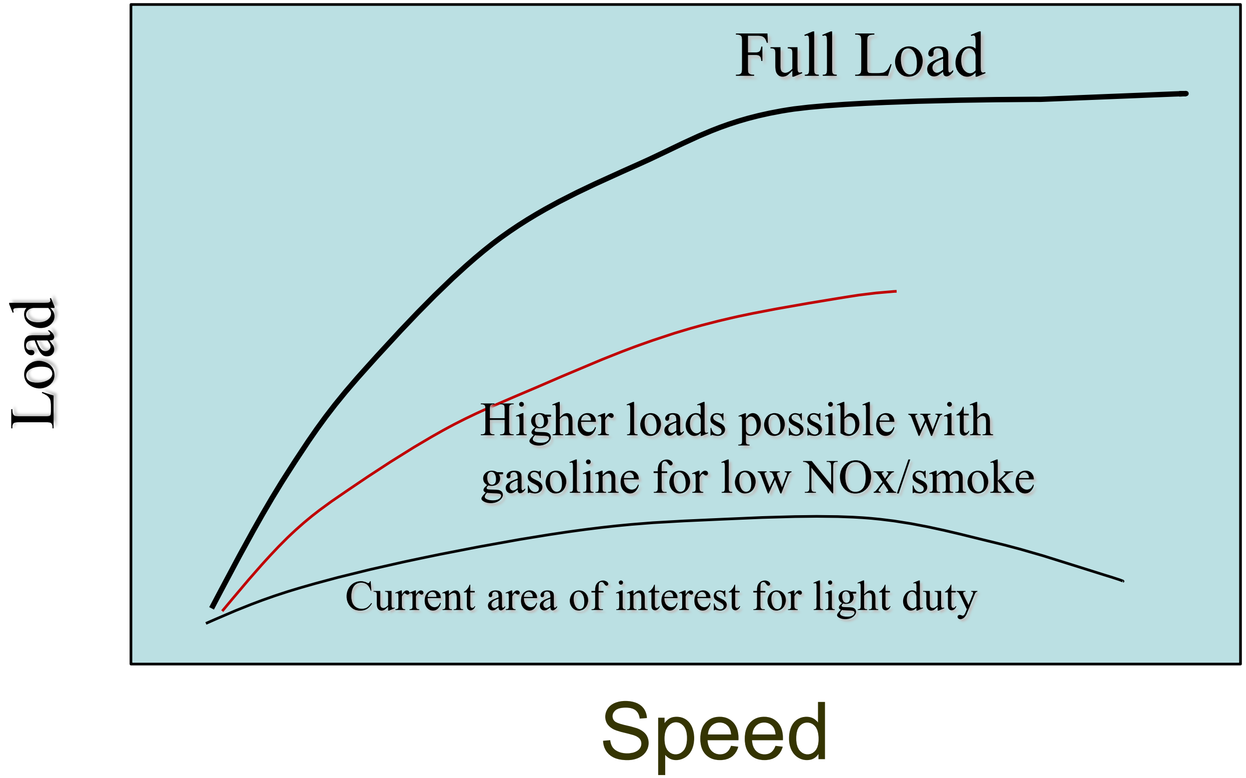


Single Inj., 84 RON gasoline, but with the same position for Max. Heat release



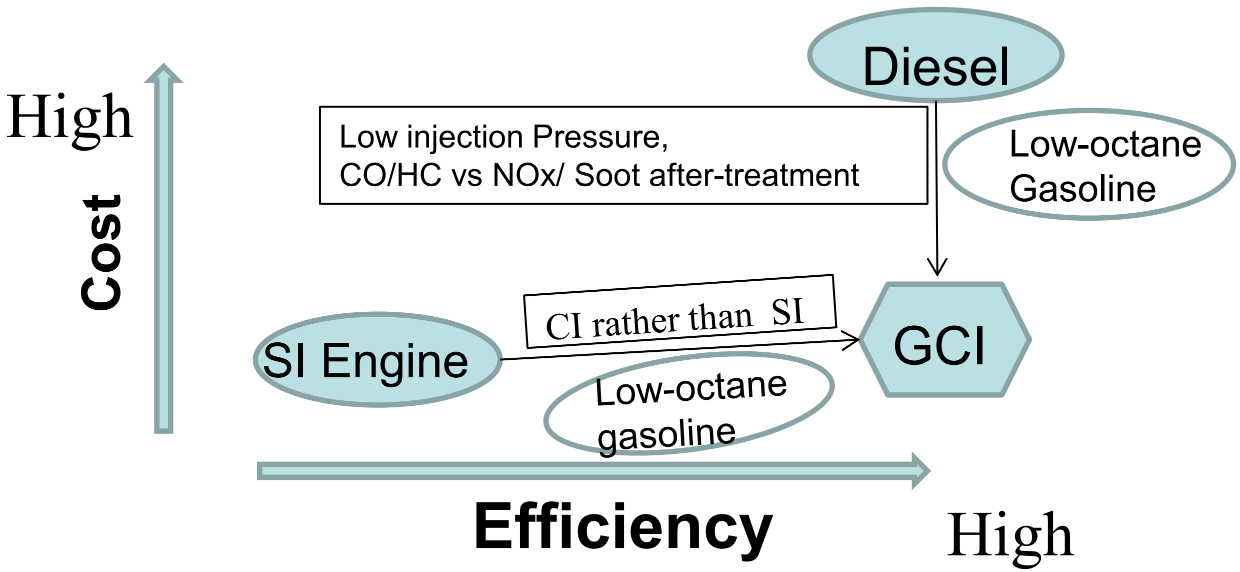
At low load, in real light-duty diesel engines, efficiency and smoke are sacrificed to reduce MPRR (i.e. noise) when using diesel fuel. This can be avoided if gasoline is used (Kalghatgi et al., Fuel 2013,)

Scope for optimising transmission systems



Mean transmission speed could be reduced.
Downsizing or downspeeding.

Develop Fuel/Engine Systems – e.g., run CI engines on gasoline-like fuels



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

- GCI enables high efficiency, low emissions, low cost engines using less processed fuels
- Opens up a path to mitigate expected demand imbalance between light and heavy fuels.

Development Challenges for GCI

1. Cold start
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

GCI – Developing fuel/engine systems

Use existing fuels and alter engines

- GDCI from Delphi - use market gasoline, re-design SI engine (CR, injection system, combustion chamber...) to run in CI mode. Significantly improved efficiency compared to SI operation.
- RCCI – Use market gasoline and diesel fuel, re-design injection strategy of diesel engine. Low NOx/ low soot and high efficiency
- Use gasoline/diesel fuel mixtures in GDCI?

Essential enabling/transition technologies. But would not be sustainable if we can get the benefits of GCI with less processed fuels.

Use existing technology with less processed/enabling fuels

- SAE 2013-01-0267, Chang.et al (Saudi Aramco/FEV). Use heavy naphtha with DCN of 38 (instead of 52+ DCN European diesel) in a vehicle to achieve Euro 6 emissions targets without compromising driveability and efficiency.

Also Lund

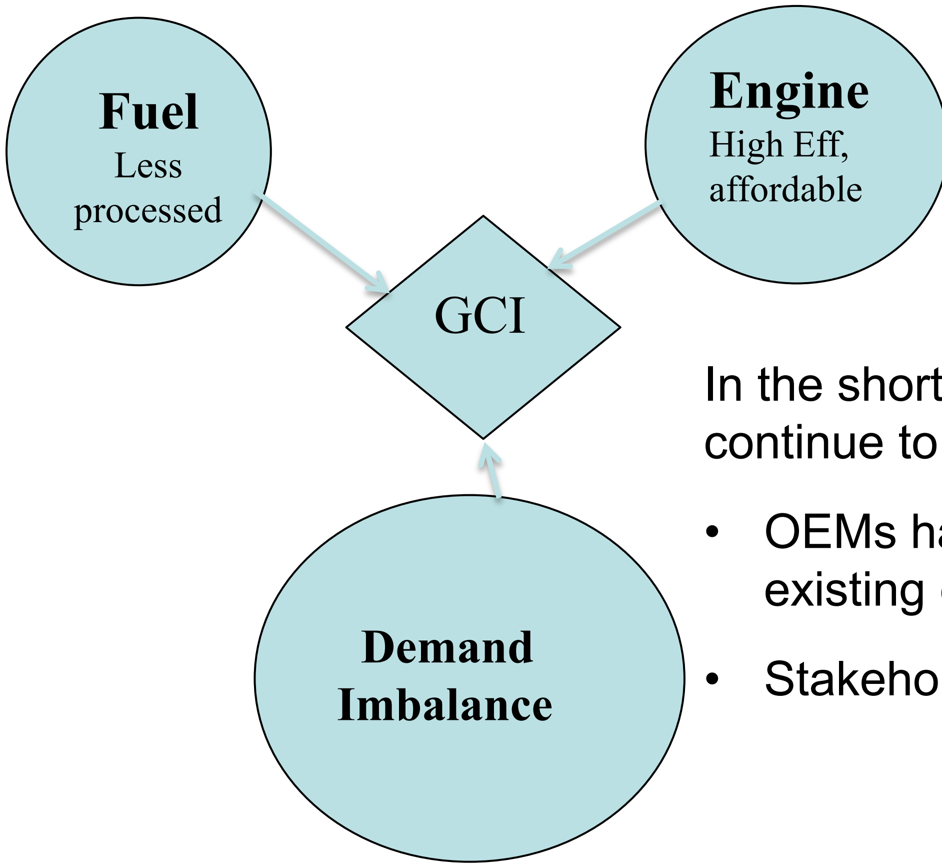
GCI – Improving the efficiency of a SI engine by running it in CI mode using naphtha

SAE 2014-01-1301, Viollet et al. (Saudi Aramco)

- Single – cylinder DISI research engine with CR of 14. Maximum fuel injection pressure of 150 bar
- Light naphtha (~66 RON/ 31 DCN) enabled the engine to be run in CI mode at idle + 5 other steady state conditions covering the FTP 75 cycle.
- 26% lower fuel consumption on FTP 75 cycle compared to running the engine in SI mode on 91 RON gasoline.
- At low loads, fuel efficiency improvement is much larger (e.g., 50% at idle)

Naphtha is an example of "less processed" fuel. It is the product in the boiling range between 30ºC and 200ºC from different processes. It is further processed to increase octane

Future CI engines should move away from using conventional diesel fuel



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

- OEMs have too much invested in existing diesel technology
- 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, Saudi Arabia?)
- The demand imbalance will start to bite

A Possible Long-term Fuels Scenario

~ 40% high efficiency SI engines – need high RON and low MON fuels. Gasoline specifications to be revised. Ethanol will play a role (May be methanol even?)

- ~ 60% GCI engines running on 70-85 RON, wide volatility range fuel. Heavier oil fractions need to be cracked to bring them in the diesel boiling range with much less upgrading required in terms of octane.
- Common fuel components for both SI and CI engines – fuel blending becomes more flexible
- Current bio-diesels with cetane in the 50s will have little relevance
- Very high cetane of gas-to-liquids (GTL) diesel has no advantage
- During the transition, GCI will have to run with existing gasoline and diesel fuels e.g. 10% diesel blends or RCCI. Both will use 90% gasoline and help mitigate the demand mismatch that is expected otherwise.

THANK YOU

Details in

Fuel / Engine Interactions

SAE International, 2014

[***http://books.sae.org/r-409/***](http://books.sae.org/r-409/)