Fuel Anti-Knock Quality and Knock in SI Engines

Gautam Kalghatgi

• Ch.4. Fuel/Engine Interactions
Knock and Fuel Anti-Knock Quality

- Caused by autoignition of the end-gas ahead of the advancing flame front
- Depends on the pressure and temperature history of the end gas

.....and on the anti-knock or autoignition quality of the fuel which is the most important fuel property for SI engines

Auto-ignition process is the same in HCCI engines
• Knock intensity is measured in engine experiments from filtered (between 5 kHz and 10 kHz) pressure signals.
• Knock Intensity (KI) is often defined as peak to peak amplitude of the filtered signal
• Audible knock can be detected when KI is around 0.2 bar
• Mild knock is a noise problem - largely cosmetic.
• Knock is also detected by measuring engine vibrations
• Sustained knock at high intensities could damage the engine
Knock and Engine Performance

As ignition timing is advanced, Knock intensity increases. Also torque and efficiency increase, up to a point – MBT, Maximum Brake Torque, timing. Knock Limited Spark Advance (KLSA) is the spark timing when the knock intensity reaches its threshold value. Knock Limited Torque (KLT) is the torque at KLSA.
Knock and Engine Performance

• As ignition timing is advanced, Knock intensity increases. Also torque and efficiency increase, up to a point – MBT, Maximum Brake Torque, timing.

• KLSA – Knock Limited Spark Advance. The ignition timing when knock reaches a pre-set level

• KLSA increases with anti-knock quality, OI

When the engine cannot be run at MBT timing because of knock, the engine is said to be “Knock limited”

OR – Octane Requirement – OI of fuel which gives KLSA = MBT. In this case it is 110.
Knock Damage to Piston

Damage starts at edge of piston furthest from sparkplug, i.e. in the “endgas) causes erosion and pitting of piston.

High heat transfer to the piston can cause local melting and burning leading to catastrophic engine failure.
Autoignition Quality Of Fuels

(see SAE 2005-01-0239)

• Knock occurs because of autoignition in the end gas
• Model the autoignition chemistry of a fuel with changing pressure and temperature in the engine?

• Chemistry cannot be properly modeled for real fuels

Ignition delay, $\tau$
Livengood-Wu integral - $\int \frac{dt}{\tau} = 1$
Data on $\tau$ as a function of temperature and pressure is not available for different fuels

Empirical approach essential
Fuel Anti-knock or Octane Quality

- Traditionally measured by RON and MON; both scales are based on primary reference fuels (PRF)
- Chemistry of practical fuels is different from PRF
- RON and MON of the fuel describe knock behaviour only at RON and MON test conditions
- 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.
How should the anti-knock quality of a practical fuel be defined?

- Experiments in single cylinder engines based on measurements of knock intensity using different fuels and different operating conditions.
- Tests based on measurements of power and acceleration performance in 52 cars equipped with knock sensors.
- Tests in HCCI engines – allows access to pressure/temperature regimes not possible with SI engine knock.

RON, MON, Octane Index and K

Octane Index, OI = (1-K)RON + K MON = RON -KS

- K depends only on the pressure/temperature history of the end-gas
- For PRF, by definition, RON = MON = OI
- The chemistry of real fuels is very different from that of PRF and OI depends on K

OI is the octane number of an equivalent PRF

- For the MON test, K = 1, for the cooler RON test, K = 0
- K can be negative if the unburned gas temperature is lower than in the RON test

K has no fundamental significance. It only helps to explain the changing behaviour of a sensitive fuel at different conditions.
Dependence of K on T and P

OI = (1-K)RON – KMON = RON -KS

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
Experimental Detail

52 European and Japanese cars tested – different technologies, PFI, DISI, turbo…SAE 2001-01-3585, SAE 2005-01-0244…

- Set of fuels of different chemistries. RON range from 86 to 101, MON range from 81 to 98
- Each car tested on eight to ten fuels
- Little correlation between sensitivity and RON
- Three accelerations, power at three constant speeds measured
- Each acceleration measured three times
- EMS system conditioned at each fuel change

Fuels used in Road tests in SAE 2005-01-0244
### Examples of Fuel Sets Used in Experiments

<table>
<thead>
<tr>
<th>Fuel Code</th>
<th>Fuel Composition</th>
<th>C/H</th>
<th>Stoich</th>
<th>RON</th>
<th>MON</th>
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<tbody>
<tr>
<td>AIS1</td>
<td>75% Alky+25% iso-Oct</td>
<td>0.463</td>
<td>14.95</td>
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<td>30% Alky+70% iso-Oct</td>
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<td>0.469</td>
<td>14.92</td>
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<td>0.467</td>
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### Volume Percent

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<th>n-hept</th>
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*SAE 2001-01-3584*
Octane Index (OI) – Knocking Engine

**KLSA – Knock Limited Spark Advance. The ignition timing when knock reaches a preset level**

\[
y = 0.0493x^2 - 8.505x + 364.47
\]

\[R^2 = 0.9347\]

\[
\begin{align*}
85 & \quad 90 & \quad 95 & \quad 100 & \quad 105 & \quad 110 \\
-5 & \quad 5 & \quad 10 & \quad 15 & \quad 20 & \quad
\end{align*}
\]

**DISI, CR = 12.5**

2000 RPM

K = -0.4

SAE 2005-01-0244

SAE 2005-01-0239

\[
\text{KLSA} = 0.0327(OI)^2 - 5.5845(OI) + 235.55
\]

\[R^2 = 0.9941\]

\[
\begin{align*}
80 & \quad 85 & \quad 90 & \quad 95 & \quad 100 & \quad 105 & \quad 110 \\
85.0 & \quad 90.0 & \quad 95.0 & \quad 100.0 & \quad 105.0 & \quad 110.0 & \quad
\end{align*}
\]

\[
\text{OI} = 1.4\text{RON} - 0.4\text{MON}
\]
Effect of Engine speed on K and OR

SAE 2005-01-0244

K increases but OR decreases with engine speed. Ideally, we must have OI = OR.

CR = 11. Three fuels. RON = 100 and S = 4, 8, 12; OI = RON - KS
Sensitive fuels better at low speed

Ideally OI should be equal to or greater than OR. There is a general trend that, as OR increases, K decreases. Hence the OI of sensitive fuels increases as the OR increases ie, for the same RON, a sensitive fuel follows the requirement of the engine better.

A CURIOSITY -
Suppose K = A –B[OR]
OI = [1-K]RON + KMON = RON – KS
OI = OR. Hence RON – AS =[OR][1-BS] and this identity is satisfied if S=1/B and RON = A/B
For the data shown above, RON = 98.7, S =31
OI. Power at 2500 RPM – Mercedes A160

\[ OI = RON + 0.54S \]
OI. Acceleration time – Toyota Avensis DISI

Mean Accel Time
DISI engine
K = -0.74
SAE 2005-01-0244
Octane Index (OI) – HCCI, negative K

900 RPM, $\lambda = 4$, 2 bar abs. inlet pr., 40°C intake temperature. K = -1.5

SAE 2003-01-1816
Octane Index (OI) – HCCI, positive K

1200 RPM, 3.5 Lambda
250°C Inlet Temp
2 PRFs, 1 TRF (50/50)
and 4 Wide Boiling Range Fuels. K = +2.5 OI₀ = 77
SAE 2004-01-1969

CA50 = \( \alpha[OI - OI₀] \)
OI = (1-K)RON+KMON
Dependence of $K$ on $T$ and $P$

$T_{\text{comp}} = T_0 \left[ \frac{P}{P_0} \right]^{(n-1)/n}$

$PV^n = \text{constant}$

$PV = mR_0 T$

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

- $T_{\text{comp15}}$, temperature at 15 bar chosen as the generic thermodynamic parameter

Modern SI engines are “beyond” RON and have negative $K$ values
Dependence of $K$ on $T_{comp15}$

- $OI = (1-K)RON + KMON = RON - KS$
- $T_{comp15}$ is the compression temperature when the pressure is 15 bar
- Non-PRF fuels become comparatively more resistant to autoignition as pressure is raised for a given temperature.

Modern SI engines have negative $K$ values
Some fuels don’t behave as expected from their $OI$ – particularly at high $T_{comp15}$
Qualitative explanation for change in K

- Octane scale based on paraffinic fuels
- In the MON test conditions, paraffinic fuels are more dominated by NTC (Negative Temperature Coefficient) chemistry. Hence their MON is high.
- Temperature - pressure variations different in different rating conditions. Hence fuels of different chemistry will be ranked differently in different tests.
Octane Requirement in Cars

- Minimum Octane Index (Octane number of PRF) to get best performance
- Depends on model used
- Engineering judgement required (Whelan et al, SAE 982721)

Model for polynomial:

\[ y = -0.000233(OI)^2 + 0.0553(OI) - 2.2264 \]

\[ R^2 = 0.9293 \]
Octane Requirement in Cars

- Depends on calibration strategy
- May not correspond to the best performance the engine is capable of. A fuel of 91 RON and 81 MON has $\text{OI}=97$ in this car. Why no improvement for $\text{OI}>95$? Calibration on PRF?!
- Room for more aggressive calibration to take advantage of available fuels (SAE 982721)
Conclusions

- Anti-knock quality of the fuel should be defined by the Octane Index, $OI = (1-K)\text{RON} + K\text{MON}$. As $OI$ increases, performance improves.
- $K$ depends on engine conditions and can be negative.
- $K$ decreases as Octane Requirement (on PRF) increases or as temperature of the end-gas decreases for a given pressure.

Measurements on European and Japanese cars equipped with knock sensors show that $K$ is negative in most cases.
Requirements of Future Engines

- Future SI engines require higher anti-knock quality fuels.
- Moreover for a given RON, lower MON has higher OI – sensitivity is better. This is because they will run at lower temperatures for a given pressure. (HCCI engines also prefer sensitive fuels)
- The source of sensitivity in fuels are aromatics, olefins and oxygenates. These components are also the main source of high RON

Will such fuels be easily available?
Gasoline Fuel Specifications

• Each area has specifications that the fuel has to meet
• In Europe gasoline octane numbers, volatility, sulphur and benzene levels, aromatic, olefin levels have to meet specifications
• World Wide Fuels Charter – drawn up by all the auto companies also recommends fuel quality measures
• Aromatic levels to be limited to 35% vol and olefins to 18% vol. In some countries MTBE cannot be used.

This will push sensitivity down and make it difficult to get high RON. Fuels are being forced in a direction opposite to that required by future engines.
Change fuel specifications?

Relax European aromatics spec which is 35%v maximum?

- Controlling emissions – still relevant with modern engines and catalysts especially with other specifications on volatility and low sulphur and benzene in place?
- Deposits in engines – combustion chamber deposits are likely to be less of a problem because of higher temperatures. Also better addressed through additives.
- CO2 emissions – increasing aromatics increases engine-out CO2 but balanced by possible increase in efficiency. Savings in CO2 possible in the refinery. Possible overall CO2 benefit
  - Better energy security through better refinery yield?
  - Higher energy content per litre – better fuel economy.