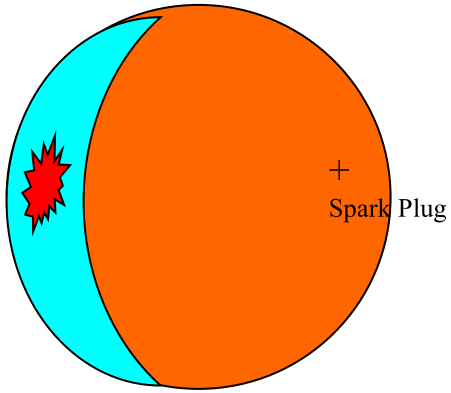
Fuel Anti-Knock Quality and Knock in SI Engines

Gautam Kalghatgi

- Ch.4. Fuel/Engine Interactions
- Kalghatgi, G.T. 2005 " Auto-ignition quality of practical fuels and implications for fuel requirements of future SI and HCCI engines", SAE Paper # 2005-01-0239
- Kalghatgi, G.T., Babiker, H. and Badra, J.,2015 "A simple method to predict knock using toluene, iso-octane, n-heptane blends (TPRF) as gasoline surrogates", SAE 2015-01-0757, SAE Int. J. Engines 8(2):505-519,

Knock and Fuel Anti-Knock Quality

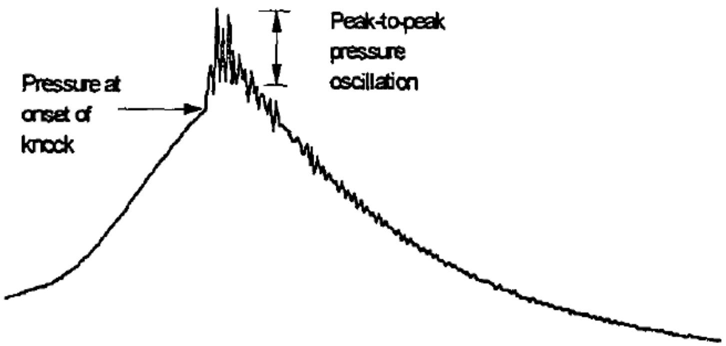


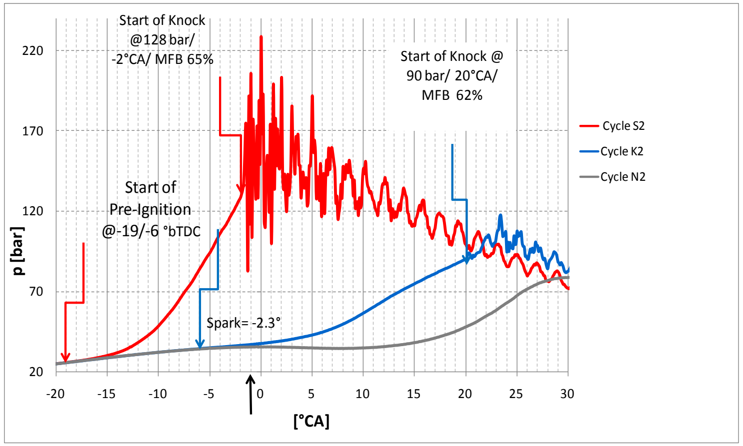
- Caused by autoignition of the end-gas ahead of the advancing flame front
- Depends on the pressure and temperature history of the end gas

…..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

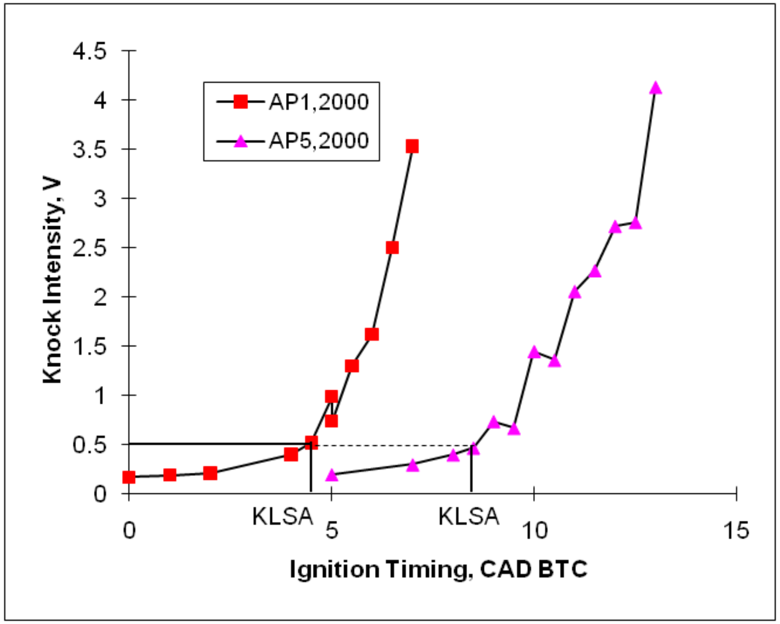
Knock noise

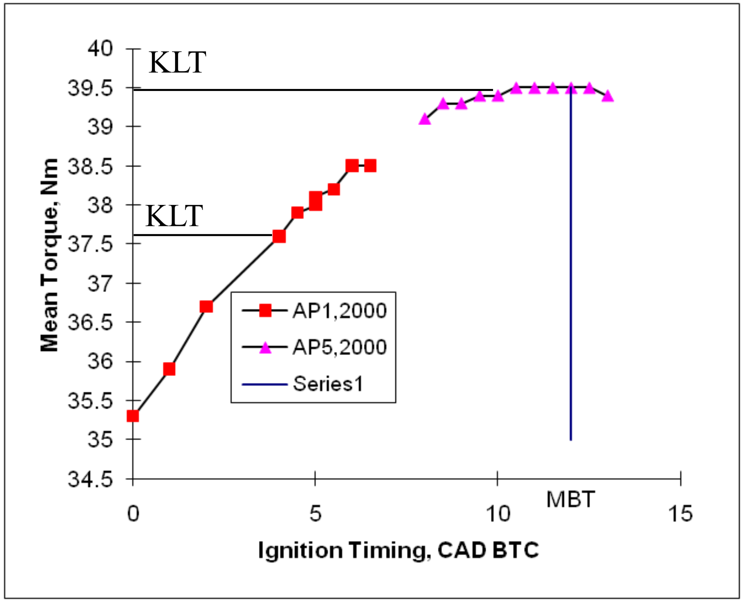




- Knock intensity is measured in engine experiments from filtered (between 5 kHz and 10 kHz) pressure signals.
- Knock Intensity (KI) is often defined as peak to peak amplitude of the filtered signal
- Audible knock can be detected when KI is around 0.2 bar
- Mild knock is a noise problem - largely cosmetic.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

Knock and Engine Performance





AP1 - 94 RON/ 91 MON, AP5 – 98 RON/91 MON (SAE 2001-01-3584)

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

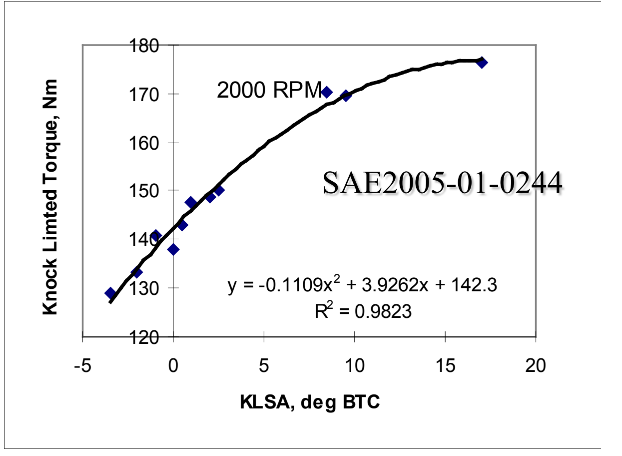
Knock Limited Torque (KLT) is the torque at KLSA

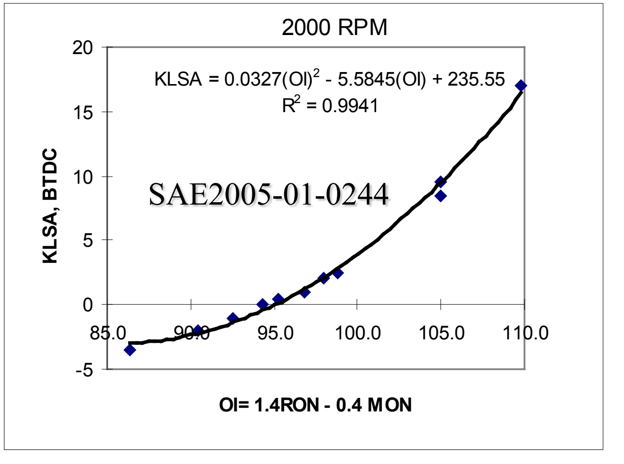
Knock and Engine Performance

- 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"

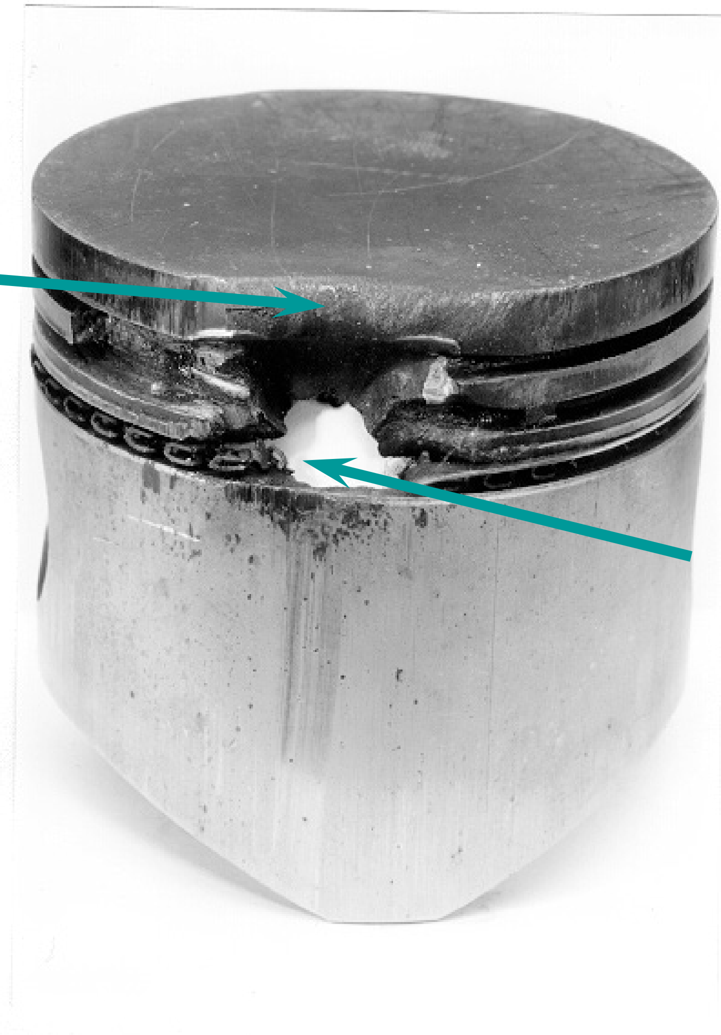
OR – Octane Requirement – OI of fuel which gives KLSA = MBT. In this case it is 110.





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, τ

Livengood-Wu integral - $\int (dt/\tau) = 1$

Data on τ 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

SAE Paper #s 2001-01-3584, 2001-01-3585, 2003-01-1816, 2003-01-3215, 2004-01-1969, 2004-01-1952, 2005-01-0239, 2005-01-0244

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

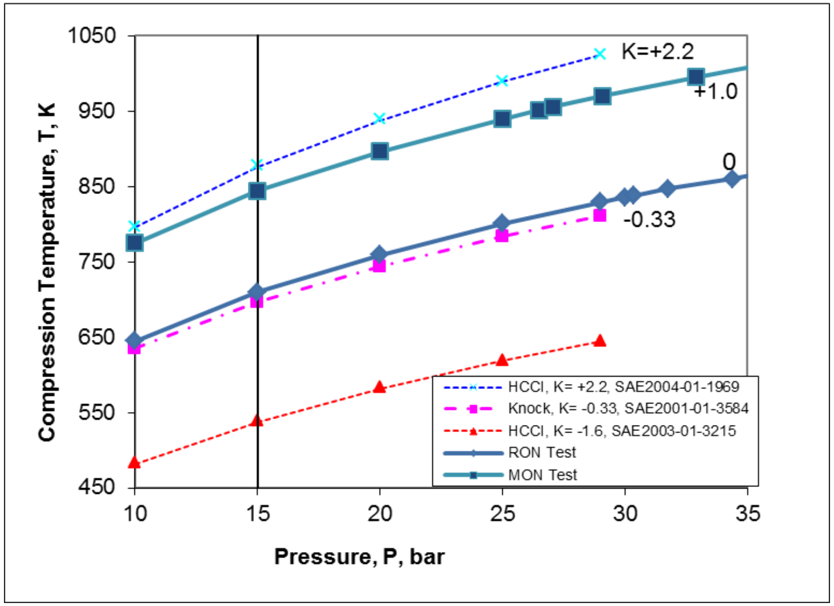
Dependence of K on T and P

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)



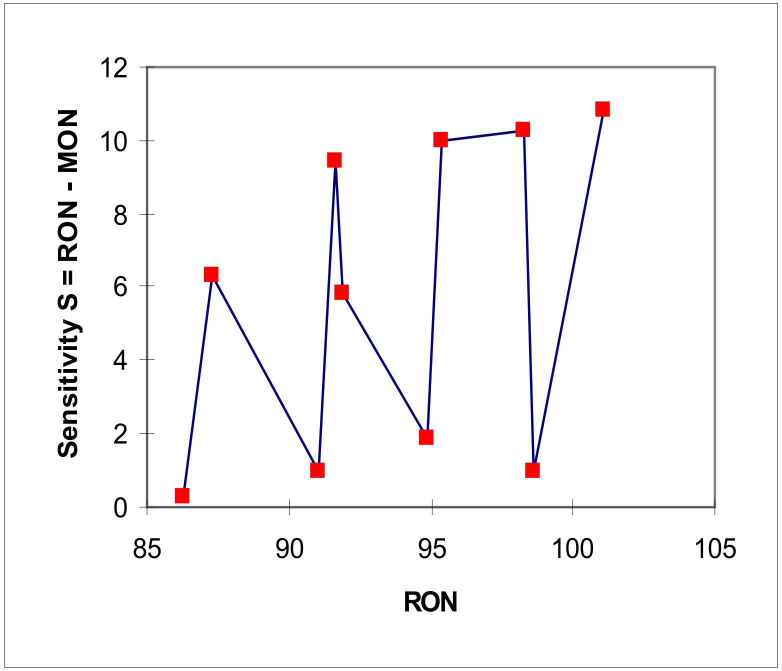
Modern SI engines are “beyond” RON and have negative K values. This trend will continue as SI engines seek better efficiency.

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

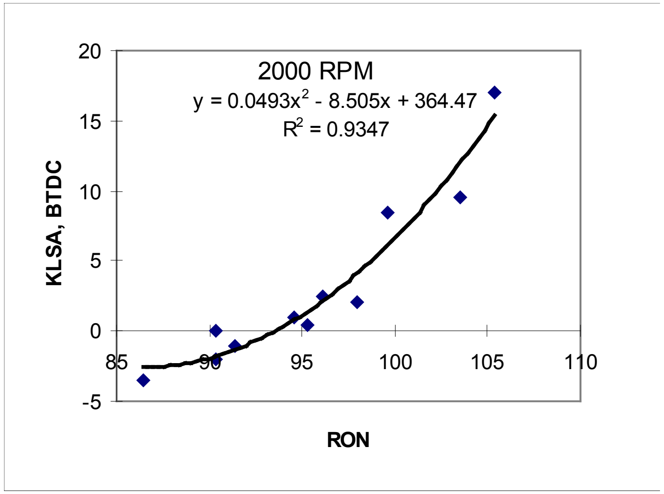
SAE 2001-01-3584

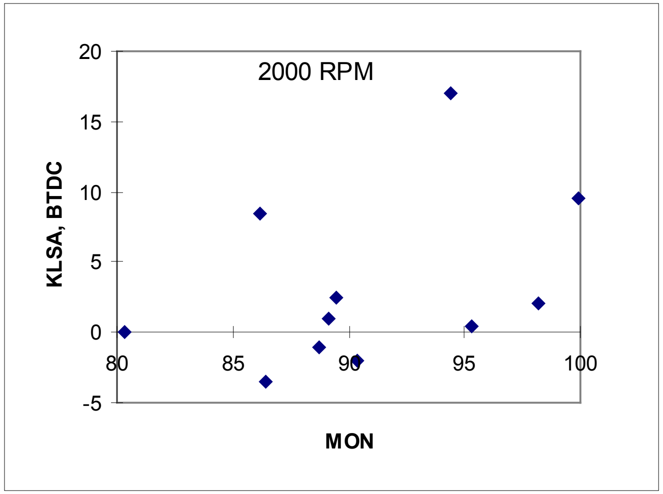
Fuel Code	Fuel Composition	C/H	Stoich AFR	RON	MON
AIS1	75%Alky+25%iso-Oct	0.463	14.95	95.5	93.9
AIS2	30%Aky+70%iso-Oct	0.451	15.03	98.2	97.5
ALK	100% Alkylate (TBR 5381/97)	0.47	14.91	94	91.8
AN1	95%Alky+5%n-hept	0.469	14.92	89.2	89.1
AN2	91%Alky+9%nhept	0.467	14.93	86.3	86.2
AP1	95% ALKY+5% PLAT	0.478	14.86	94.2	91.4
AP2	90% ALKY +10% PLAT	0.487	14.81	94.8	91
AP3	85% ALKY +15% PLAT	0.495	14.76	95.6	91.2
AP5	60% ALKY+40% PLAT	0.543	14.51	98.3	91.2
AP6	40% ALKY+60% PLAT	0.587	14.31	100.1	91.2
Iso-Oct	100% iso-Octane	0.444	15.08	100	100
LCC	Light Cat-Cracked (SPL6175)	0.484	14.82	95.6	85.7
LNH1	98.3% LCC + 1.7% n-Hept	0.483	14.83	95.5	85
PLAT	100% Platformate (TBR 5284/96)	0.695	13.91	102	90.5
PNH2	92.2%PLAT+7.8%n-Hept	0.666	14.01	98.2	87.4
PNH3	85% PLAT+ 15% n-Heptane	0.636	14.11	93	83
PNH4	80% PLAT+ 20% n-hept	0.625	14.15	89.5	80.8
PNH5	88.2%PLAT+11.8%n-Heptane	0.652	14.05	95.5	84.6
PNH6	95% PLAT+5%n-Heptane	0.677	13.97	99.6	88.7
PNH7	75% PLAT + 25% n-hept	0.609	14.21	85.4	78
PRF85	85% Isooctane+ 15% n-hept	0.444	14.92	85	85

SAE 2005-01-0244

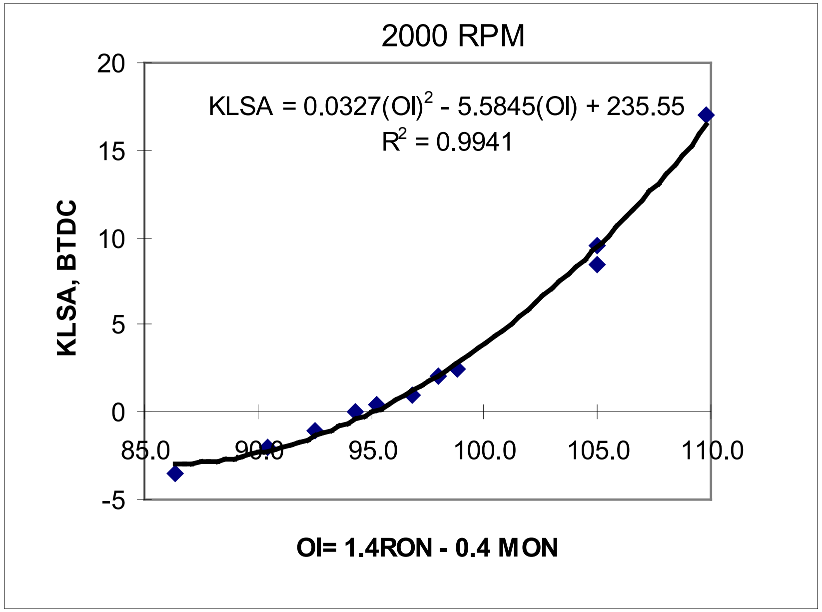
				Volume Percent				
Code		RON	MON	Isooct	n-hep	Tol	DIB	MTBE
A	PRF 86	86.4	86.4	86	14			
B	PRF 90	90.4	90.4	90	10			
C	PRF 95	95.3	95.3	95	5			
D	PRF 98	98.2	98.2	98	2			
E	TOLHEP 91	91.5	79.0		28	72		
F	TOLHEP 95	95.1	82.7		24	76		
G	TOLHEP 98	98.5	84.0		20	80		
H	TOLHEP102	102	90.7		15	85		
I	TOLHEP105	105	94.4		12	88		
J	PRFDIB 91	91.4	88.7	77	13		10	
K	PRFDIB 94	94.6	89.1	72	13		15	
L	PRFDIB 96	96.1	89.5	68	12		20	
M	ISMTBE102	104	99.9	92				8
N	RG	90.3	80.3					
O	PG	99.6	86.2					

Octane Index (OI) – Knocking Engine



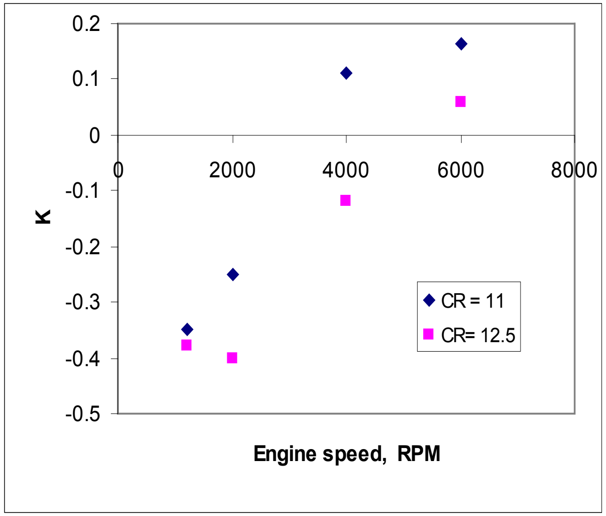


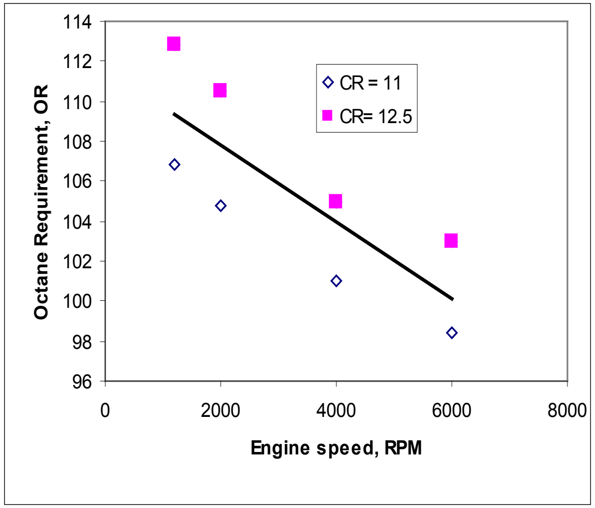
KLSA – Knock Limited Spark Advance. The ignition timing when knock reaches a pre-set level



DISI, CR = 12.5
2000 RPM
K = -0.4
SAE 2005-01-0244
SAE 2005-01-0239

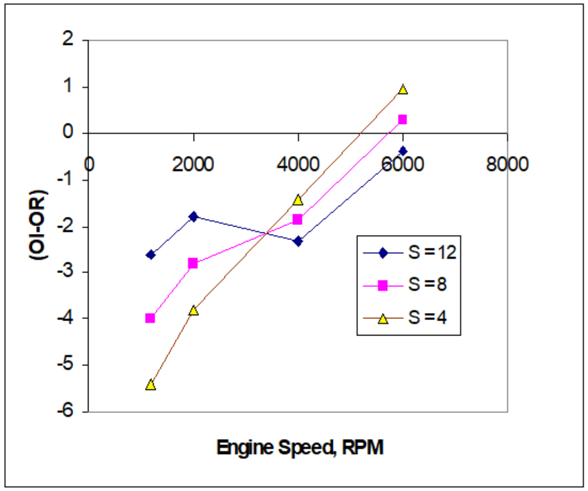
Effect of Engine speed on K and OR
SAE 2005-01-0244

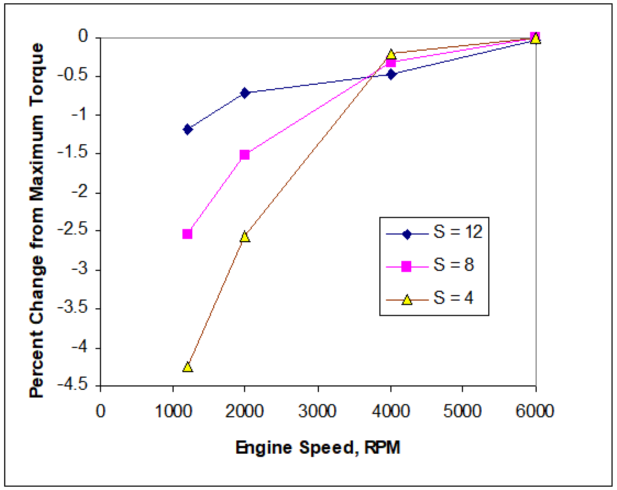




K increases but OR decreases with engine speed. Ideally, we must have OI = OR.

CR =11. Three fuels. RON = 100 and S = 4, 8, 12; OI = RON - KS





Sensitive fuels better at low speed

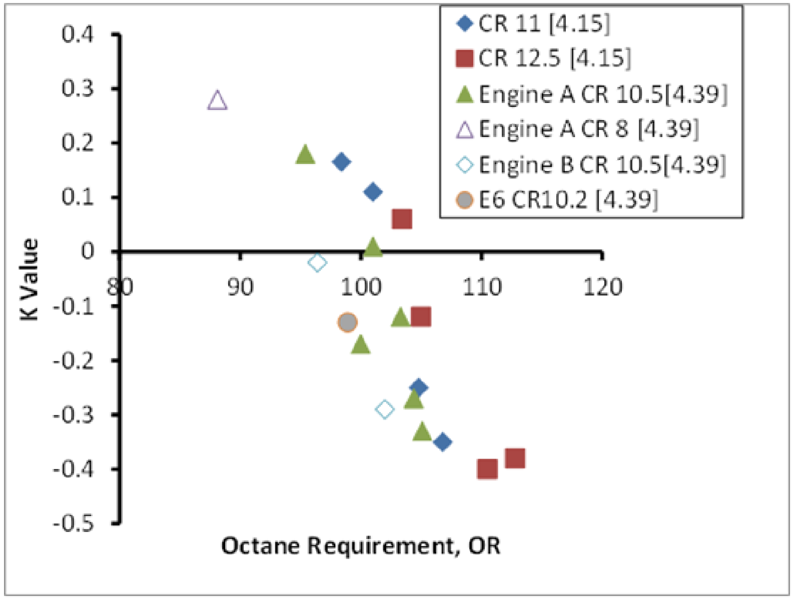


Fig. 4.13 Fuel/Engine Interactions

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 -

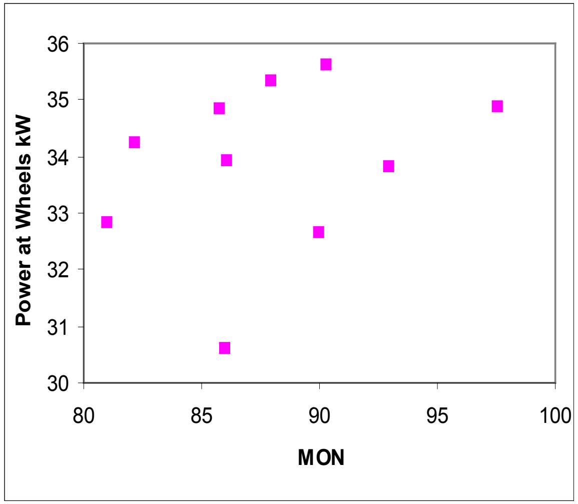
Suppose K = A –B[OR]

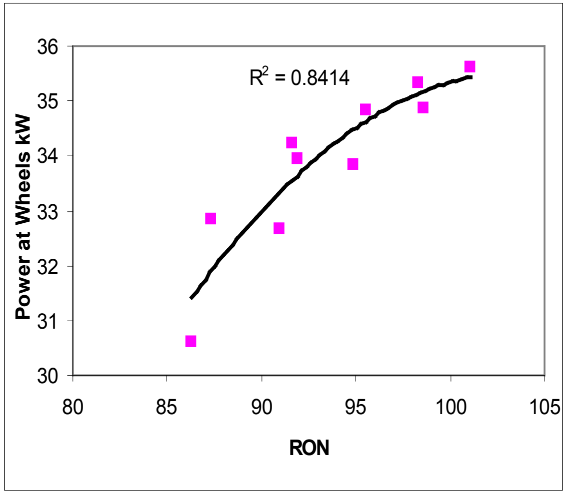
OI = [1-K]RON + KMON = RON – KS

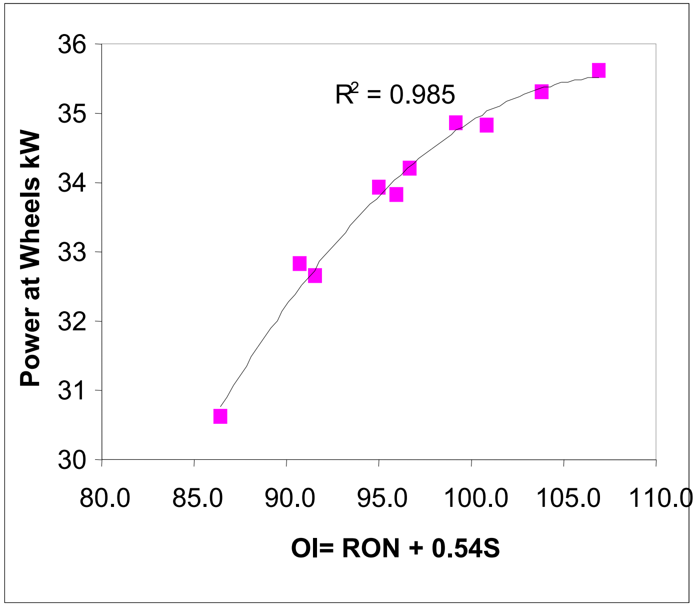
OI = OR. Hence RON – AS =[OR][1-BS] and this identity is satisfied if S=1/B and RON = A/B

For the data shown above, RON = 98.7, S =31

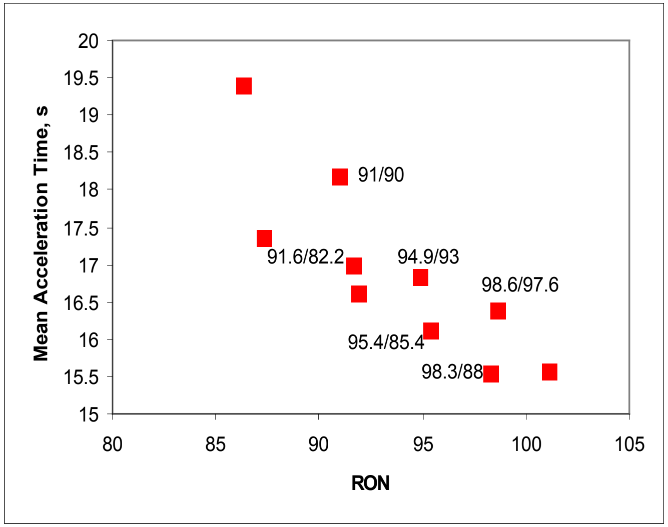
OI. Power at 2500 RPM – Mercedes A160

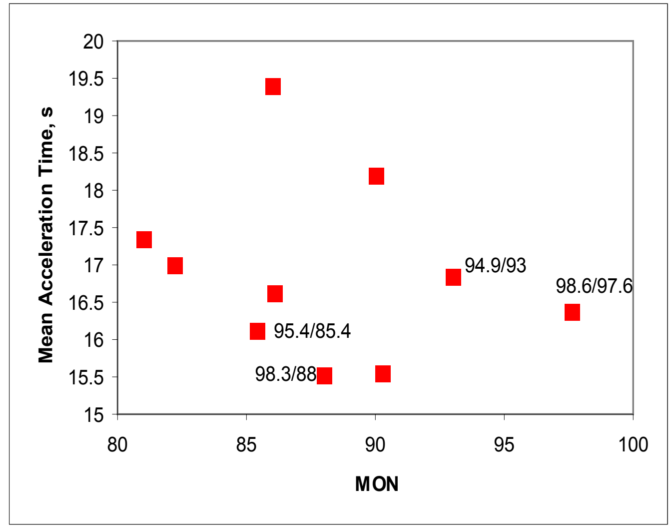


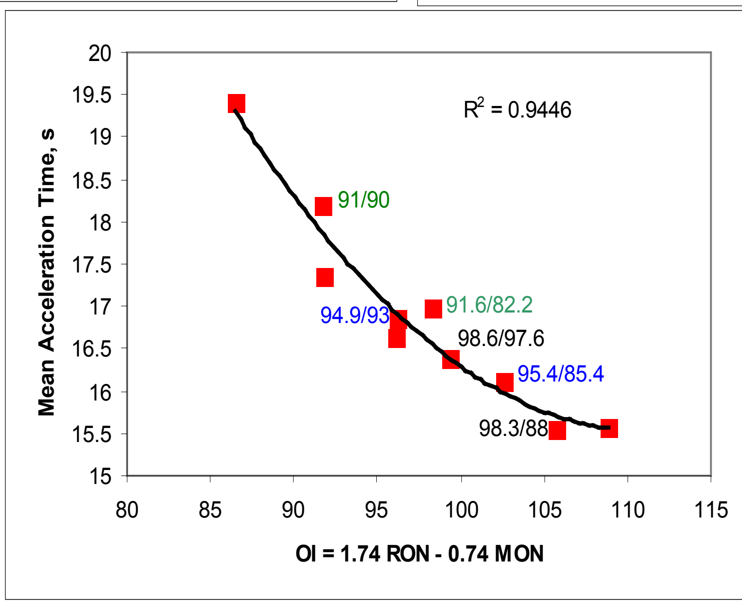




OI. Acceleration time – Toyota Avensis DISI

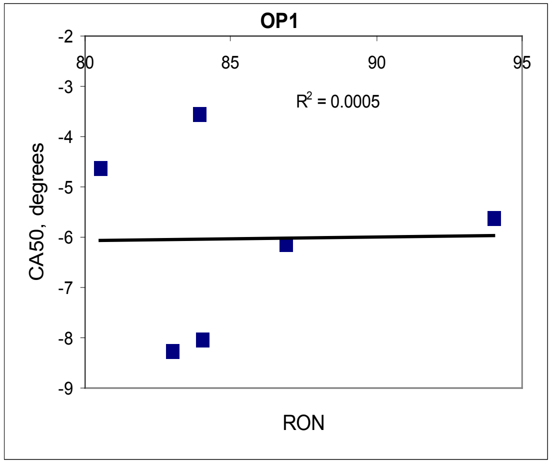


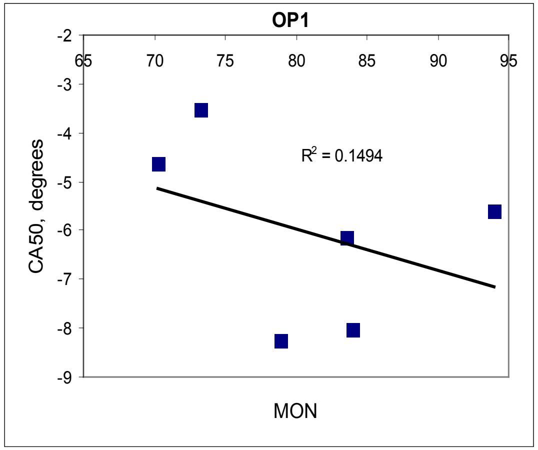


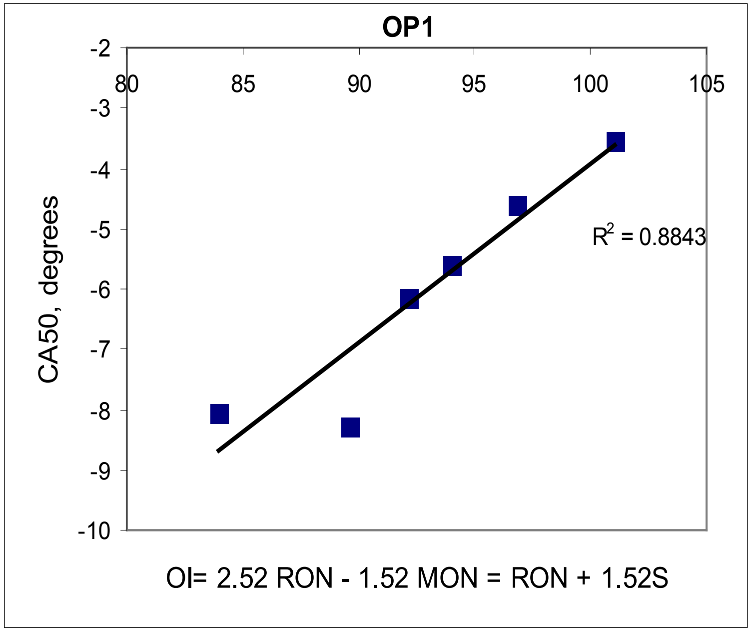


Mean Accel Time
DISI engine
K = -0.74
SAE 2005-01-0244

Octane Index (OI) – HCCI, negative K

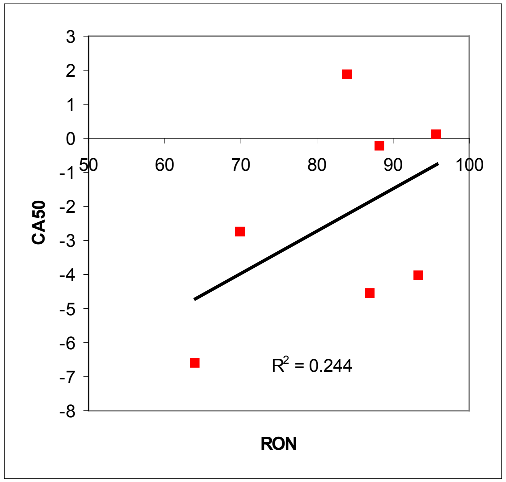


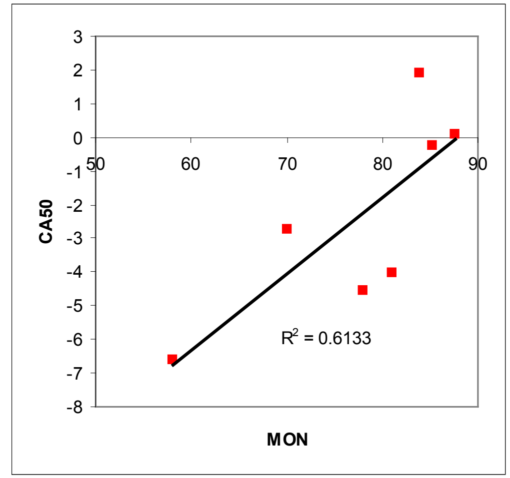


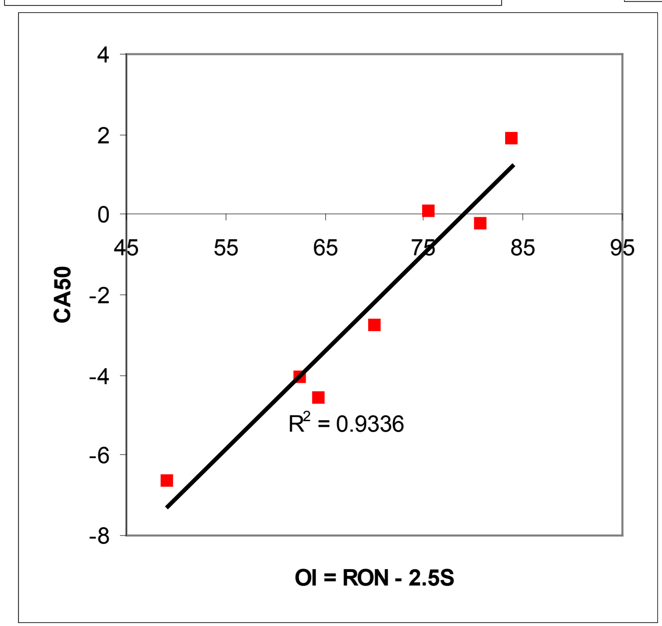


900 RPM, λ =4, 2 bar abs. inlet pr., 40°C intake temperature. K = -1.5
SAE 2003-01-1816

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 $OI_0 = 77$
SAE 2004-01-1969

$CA50 = \alpha[OI - OI_0]$

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

Dependence of K on T and P

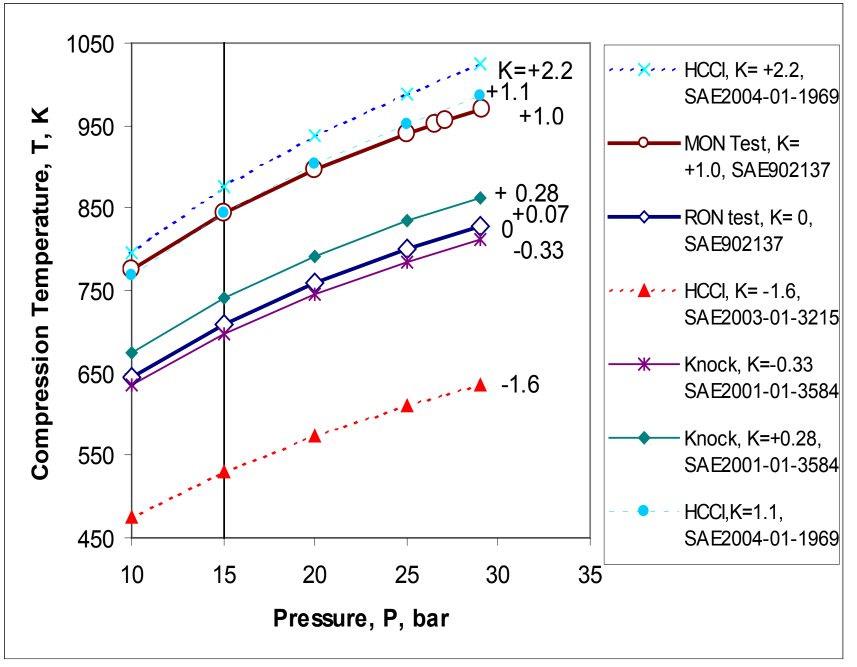
$T_{comp} = T_0[P/P_0]^{((n-1)/n)}$

PV^n = constant

$PV = mR_0T$

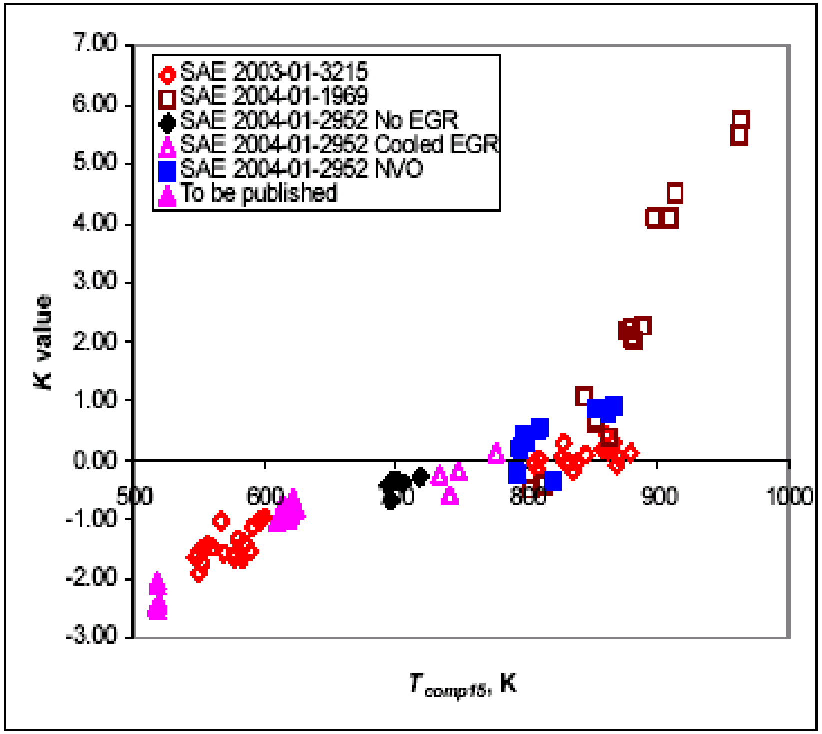
For a given pressure MON test (K=1) has higher temperature compared to RON (K=0) test

- T_{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.

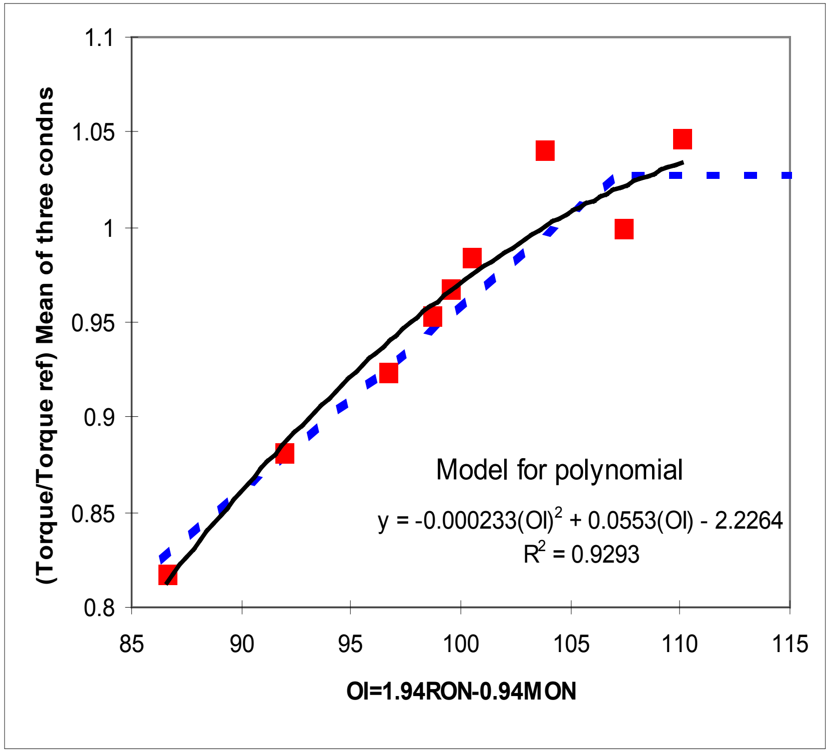
Modern SI engines have negative K values
Some fuels don't behave as expected from their OI – particularly at high T_{comp15}

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.

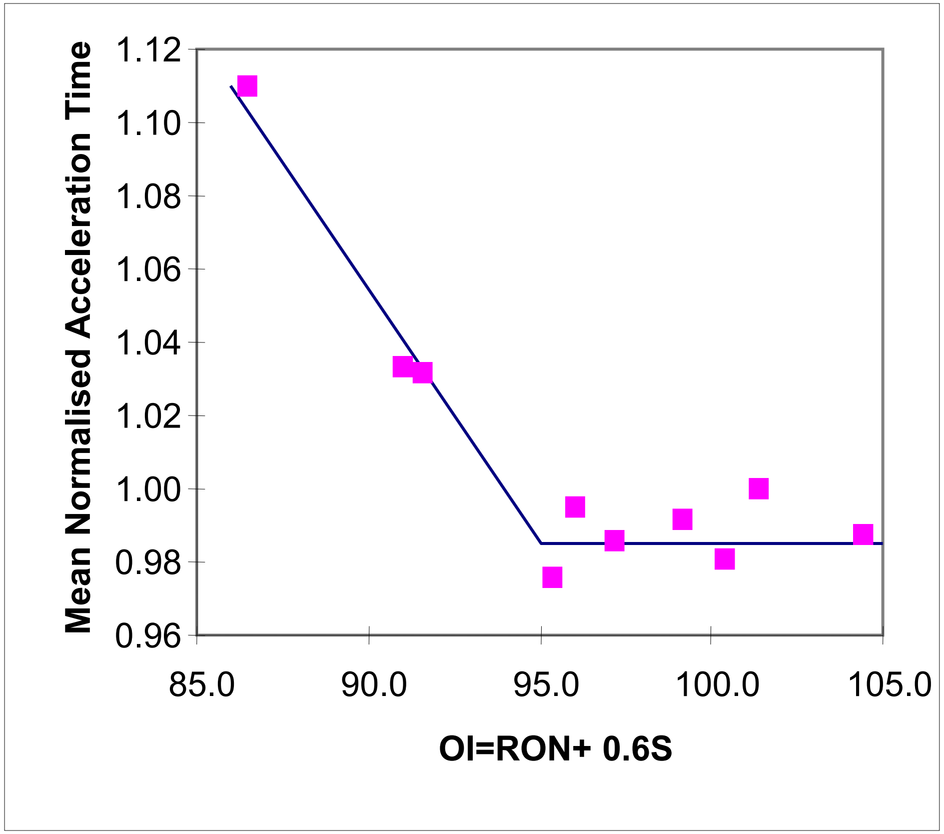
Octane Requirement in Cars

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



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 OI=97 in this car. Why no improvement for OI>95? Calibration on PRF?!
- Room for more agressive 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)RON + KMON. 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.
- CO_2 emissions – increasing aromatics increases engine-out CO_2 but balanced by possible increase in efficiency. Savings in CO_2 possible in the refinery. Possible overall CO_2 benefit
- Better energy security through better refinery yield?
- Higher energy content per litre – better fuel economy.