Lecture 7

Further insights into knock onset, knock intensity, preignition and superknock in SI engines

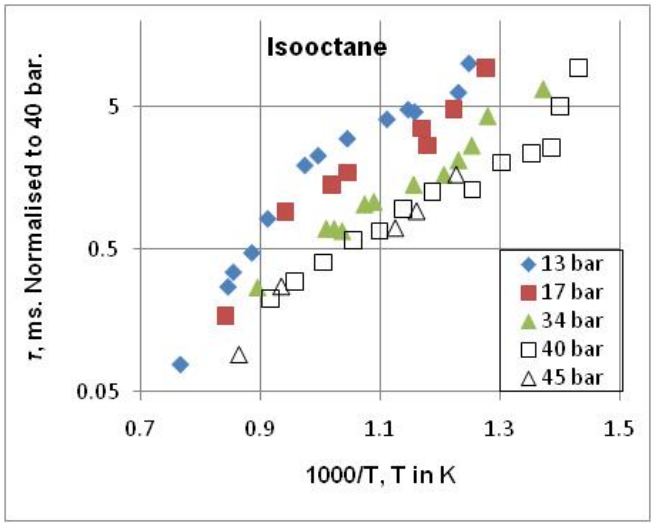
Gautam Kalghatgi

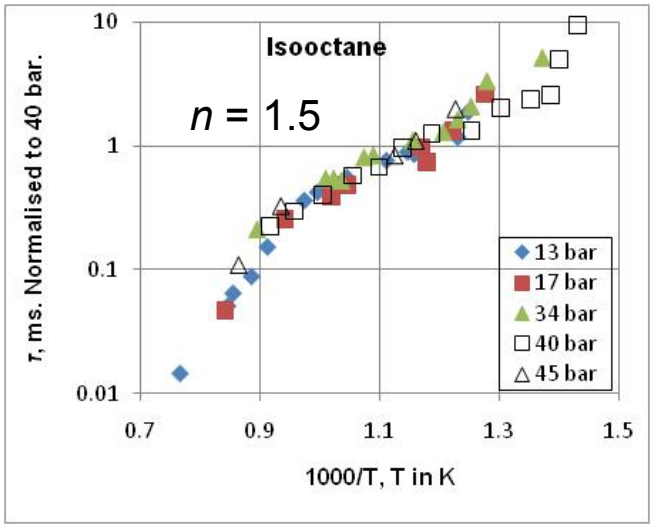
- Gautam Kalghatgi, 2018 “Knock onset, knock intensity, superknock and preignition in SI engines” International J of Engine Research, Vol. 19(1): 7–20)
- Kalghatgi, G.T., Babiker, H. and Badra, J.,2015 “A simple method to predict knock using toluene, iso-octane, n-heptane blends (TPRF) as gasoline surrogates”, SAE 2015-01-0757, SAE Int. J. Engines 8(2):505-519
- Kalghatgi, G.T. and Bradley, D., “Pre-ignition and super-knock in turbo-charged spark ignition (SI) engines”, International Journal of Engine Research 2012 13: 399
- Kalghatgi, G.T., Algunaibet, I. and Morganti, K. “ On knock Intensity and Superknock in SI Engines”, SAE Int. J. Engines; 10(3):SAE 2017-01-0689
- Gautam Kalghatgi, Kai Morganti and Ibrahim Algunaibet. “Some insights on the stochastic nature of knock and the evolution of hot spots in the end-gas during the engine cycle from experimental measurements of knock onset and knock intensity”, SAE 2017-01-2233

Knock is a stochastic phenomenon

- Though fuel/air are fully premixed, end-gas is not homogeneous because of turbulent mixing of hot gases with cold charge
- Autoignition occurs in hot spots
- Combustion and knock are marked by cycle-to-cycle variations and are stochastic phenomena
- Most knock studies focus on onset of knock which is triggered by autoignition in a hot spot
- Knock intensity is determined by the evolution of the pressure wave set off by knock onset
- Primary operating principle in SI engines is to avoid knock
- Even then, very high intensity knock – superknock – can occur occasionally in boosted engines.
- Another stochastic phenomenon – preignition – is necessary
- Superknock has to be described in probabilistic terms
- Many measures used to describe knock, e.g. knock intensity are not truly objective

Ignition delay and autoignition depend on pressure as well as temperature





Ignition delay, measured in shock tubes, RCMs fundamental property

Fieweger et al., C&F, vol 109, pp 599-619, 1997

$\tau = \tau_0 f(T)(p/p_0)^{-n}$

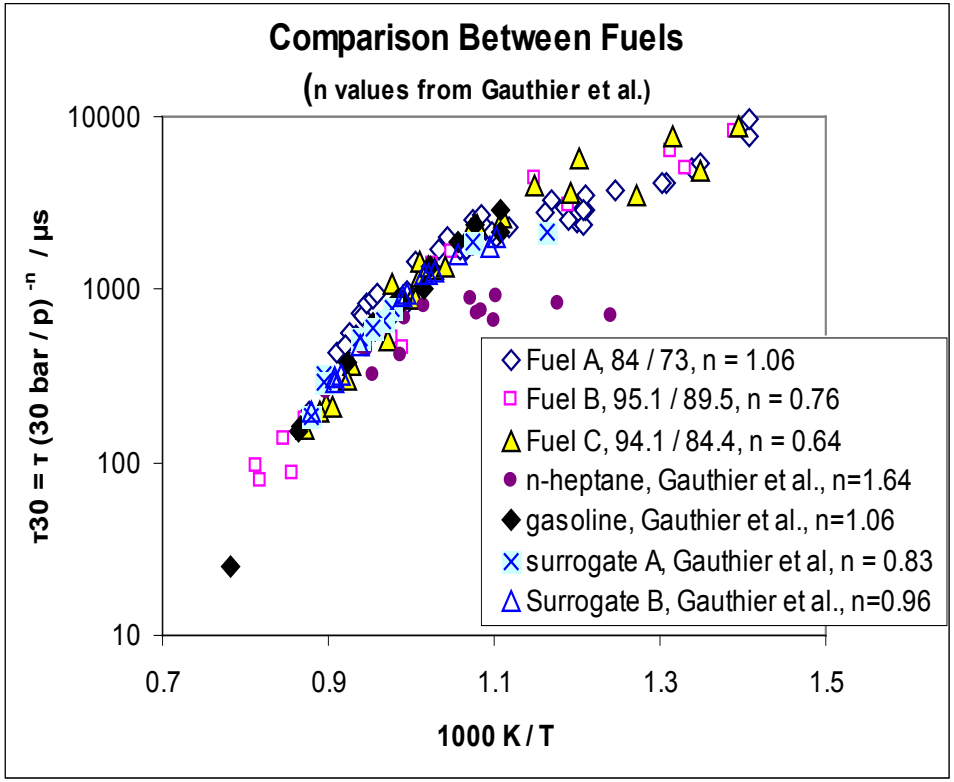
τ_0 is the ignition delay at T and p_0

n is ~1.5 for PRF but around 1 or less for non-paraffins from experiments in shock tubes

Differences in observed behaviour between PRF and non-paraffins in HCCI tests and knock can only be explained by assuming such difference in *n* using the Livengood-Wu integral.

$$I = \int (1/\tau).dt = 1$$

Pressure Effects on Auto-ignition



The difference between different fuels at a fixed pressure is very small, especially at high temperatures. The main difference is in the pressure exponent.

(Fikri et al. CNF 152, pp 276-281, 2008)

- At 1500 RPM, 15 ms is 135 crank angle degrees (CAD)
- 1 CAD step contributes little to *I*

As pressure is increased for a given temperature, non-paraffinic fuels become more resistant to Knock i.e K value decreases in OI = RON - KS

Measured values of n for different fuels

			i-octane	n-hept	toluene	ethanol	DIB**		
	RON	MON	vol%	vol%	vol%	vol%	vol%	n	Ref.
TRF 84***	84	73		35	65			**1.06**	2
Fuel B	95.1	89.5	62	18		20		**0.76**	3
Fuel C	94.6	85	25	20	45		10	**0.65**	3
Gasoline*	92	82						**1.05**	1
Surrogate A	88	85	63	17	20			**0.83**	1
Surrogate B	87	85	69	17	14			**0.96**	1
n-heptane	0	0		100				**1.64**	1
iso-octane	100	100	100					**1.5**	

*(RON+MON)/2 for Gasoline was 87, assumed sensitivity of 10. RON and MON for Surrogate A and Surrogate B were estimated from blending rules
**DIB is di-isobutylene, 2-4-4 trimethyl-1-pentene
***Fuel A in [4.19], TOLHEP 1 in [4.27]

$$\text{Ignition delay, } \tau = f(T)p^{-n}$$

Ref.1. Gauthier, B.M., Davidson, D.F. and Hanson, R.K. 2004. " Shock tube determination of ignition delay times in full-blend and surrogate fuel mixtures." *Combustion and Flame* 139: pp 300-311.
Ref. 2. Herzler, J., Fikri, M, Hitzbleck, K, Starke, R., Schulz, C., Roth, P. and Kalghatgi, G.T. 2007. "Shock-tube study of the ignition of n-heptane/toluene/air mixtures at intermediate temperatures and high pressures." *Combustion and Flame* 149: pp 25-31.
Ref.3. Fikri, M., Herzler, J., Starke, R., Schulz, C., Roth, P. and Kalghatgi,G.T.2008. "Autoignition of Gasoline Surrogate Mixtures at Intermediate Temperatures and High Pressures." *Combustion and Flame* 152: pp 276-281.

Toluene, n-heptane, iso-octane (TPRF) blends as gasoline surrogates

SAE 2015-01-0757. OI = RON -KS

- Established a method to identify the correct TPRF composition that matches the RON and S of the target gasoline
- Used the method to specify the TPRF surrogate for a Saudi gasoline used in knock tests at different engine conditions
- Found the ignition delays (ID) for this TPRF surrogate at different pressures/temperatures using a kinetic model
- Fit a simple Arrhenius type equation with a pressure correction for ID < 15 ms
- Used this equation along with measured pressure, estimated temperature in the Livengood-Wu integral to predict knock phasing which agreed with the observed phasing for gasoline
- Presented simple equations for ID for a range of RON and MON
- Further Simplification – Ignition Delay equation as a function of, P, T, RON and MON - SAE 2016-01-0702

Ignition Delay Equation - I

Ignition delay(τ_i) for TPRFs of different RON and MON were calculated at different pressure (P) and temperature (T) in SAE 2015-01-0757

For a given RON and MON an equation of the form $\tau_i = Aexp(\frac{B}{T})P^{-n}$ was fitted to these data for τ_i< 15 ms.

RON	MON	S	(R+M)/2	TN	Isooct	n-hep	toluene	A	B	n
				From eq.s 8 &11 in [17]	% (v/v)	% (v/v)	% (v/v)	ms	K	(P in bar)
88	78	10	83	69.6	8.0	28.5	63.5	0.03146	7023	1.125
88	79	9	83.5	69.6	18.8	26.1	55.1	0.03147	7035	1.137
88	80	8	84	69.6	28.9	23.9	47.3	0.03428	6990	1.150
90	80	10	85	71.6	10.8	25.9	63.3	0.02663	7209	1.123
90	81	9	85.5	71.6	21.5	23.5	54.9	0.02735	7201	1.135
90	82	8	86	71.6	31.5	21.4	47.1	0.03065	7134	1.149
92	81	11	86.5	73.6	2.1	25.9	72.0	0.02516	7298	1.107
92	82	10	87	73.6	13.6	23.3	63.1	0.02236	7403	1.121
92	84	8	88	73.6	34.1	18.9	47.0	0.02704	7292	1.147
95	84	11	89.5	76.7	6.6	21.8	71.7	0.01719	7694	1.103
95	85	10	90	76.7	18.0	19.3	62.7	0.01689	7719	1.116
95.1	86	9.1	90.55	76.8	27.6	17.1	55.3	0.02168	7485	1.125
95	87	8	91	76.7	38.1	15.1	46.8	0.02198	7554	1.145
98	87	11	92.5	79.9	11.1	17.6	71.3	0.01173	8103	1.098
98	88	10	93	79.9	22.4	15.2	62.4	0.01216	8085	1.110
98	89	9	93.5	79.9	32.7	13.1	54.2	0.01403	7992	1.124
100	88	12	94	82.0	1.7	17.6	80.6	0.01050	8243	1.077
100	89	11	94.5	82.0	14.2	14.7	71.0	0.00883	8402	1.091
100	90	10	95	82.0	25.3	12.5	62.2	0.00958	8352	1.105
100	91	9	95.5	82.0	35.5	10.5	54.0	0.01136	8236	1.121

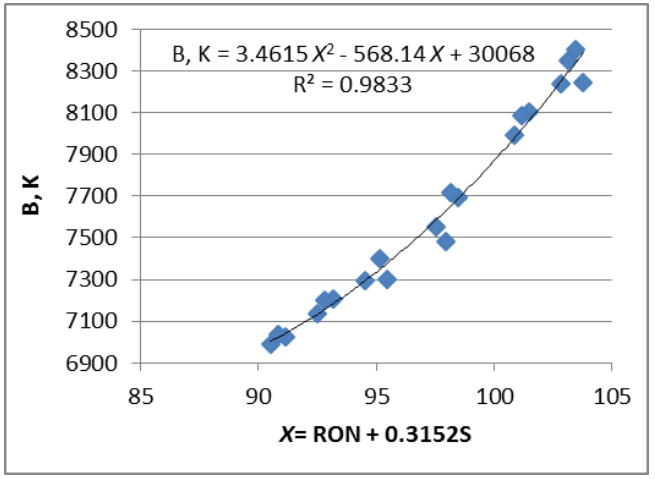
Ignition Delay Equation - II

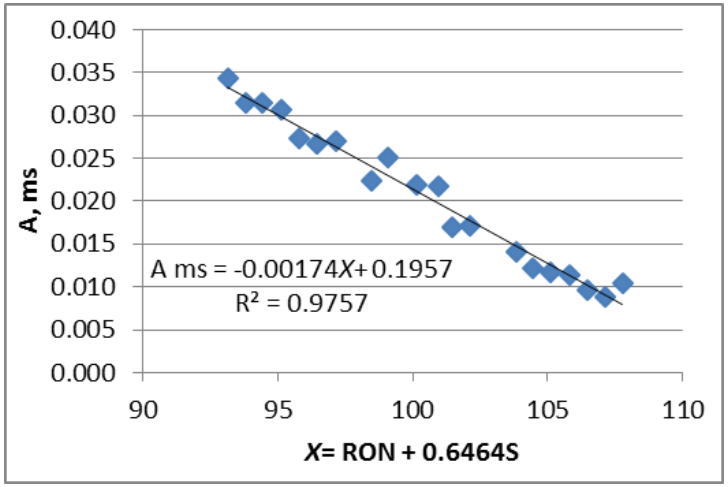
SAE 2016-01-0702

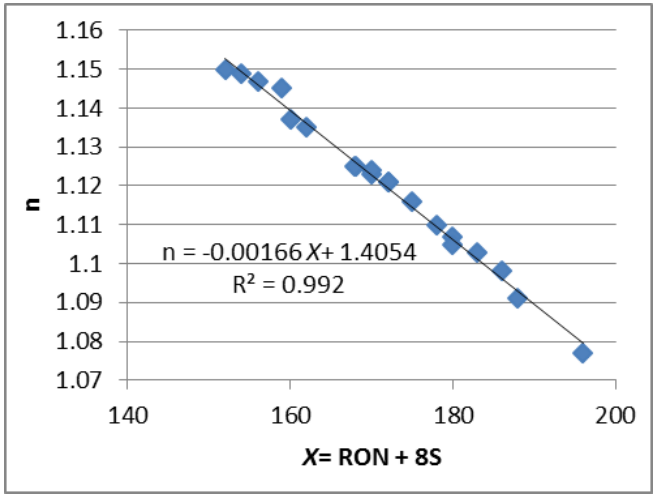
A generic equation of the form $Z = \alpha X^2 + \beta X + \gamma$ is used to model the constants in $\tau_i = Aexp(\frac{B}{T})P^{-n}$ where Z is A, B or n and $X = RON + \delta S$

Best fit values for α, β, γ and δ

Z	δ	α	β	γ	R^2
A, ms	0.6464	0	-0.00174	0.1957	0.9757
B, K	0.3125	3.4615	-568.140	30068	0.9833
n	8.0000	0	-0.00166	1.4056	0.9920





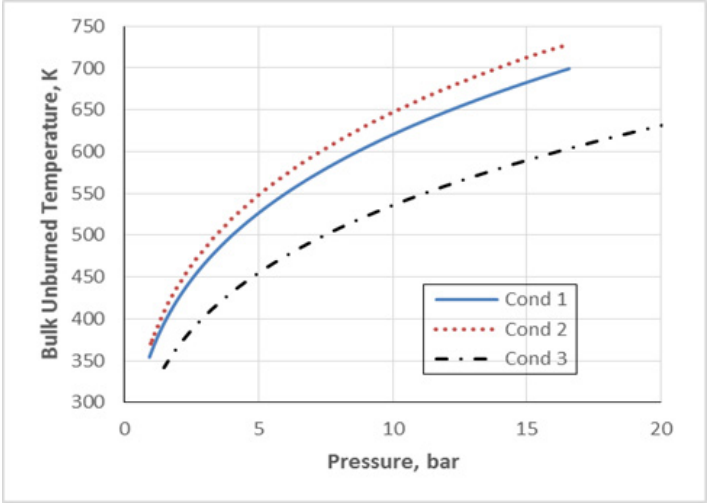


Engine Experiments and Predictions of Knock onset Using the Ignition Delay Equation (SAE 2016-01-0702)

Engine Experiments – Operating Conditions

- Knock tests were conducted in a single cylinder (10.5 CR) DISI engine at three different operating conditions

Cond.	Speed, RPM	Intake Temp. °C (Tin)	Intake Pr. KPa abs. (Pin)	Mean bulk T_{comp15} K	ΔT K. temp increment in hot spot at 15 bar*
1	1500	30	102.0	685	10
2	1500	65	102.0	713	10
3	1500	30	165.0	590	30



- **Spark timing sweep at each operating condition for each fuel**
- **Pressure data for 300 cycles collected at each spark timing**
- **Sampling interval of 0.1 crank angle degree (CAD) between -30 CAD and +90 CAD**

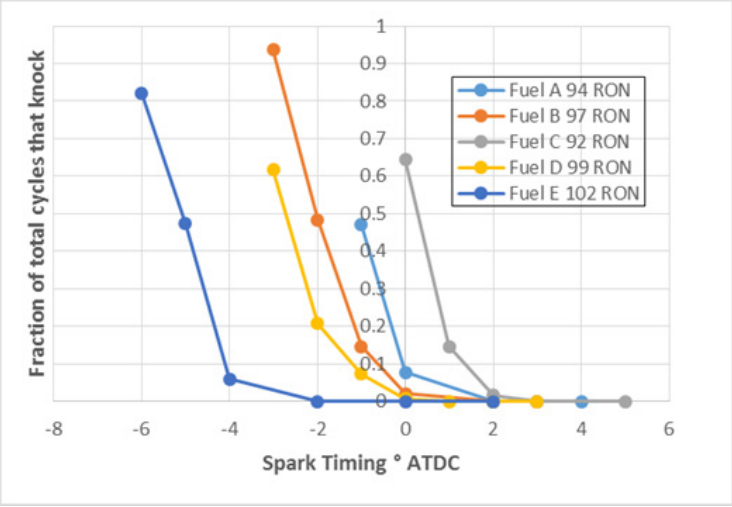
Engine Experiments - Fuels Used

- Five different fuels were used

Fuel	Description	RON	MON	A, ms	B, K	n
A	Face Fuel F	94.1	87.5	0.02454	7444	1.1617
B	Face Fuel G	96.7	86	0.01541	7874	1.103
C	Face Fuel G + 7% vol n-hep	91.9	83.8	0.0267	7285	1.1455
D	Face Fuel G + 10% vol ethanol	99.1	87.0	0.0097	8256	1.0804
E*	PRF 87 + 20% vol ethanol	101.8	93.7	0.00946	8472	1.1290

* 69.6% v iso-octane+ 10.4%v n-heptane + 20% v ethanol

For Fuel E (RON > 100), A, B and n calculated using ignition delay model as a function of toluene number of toluene/heptane blend of the same RON (Appendix B)

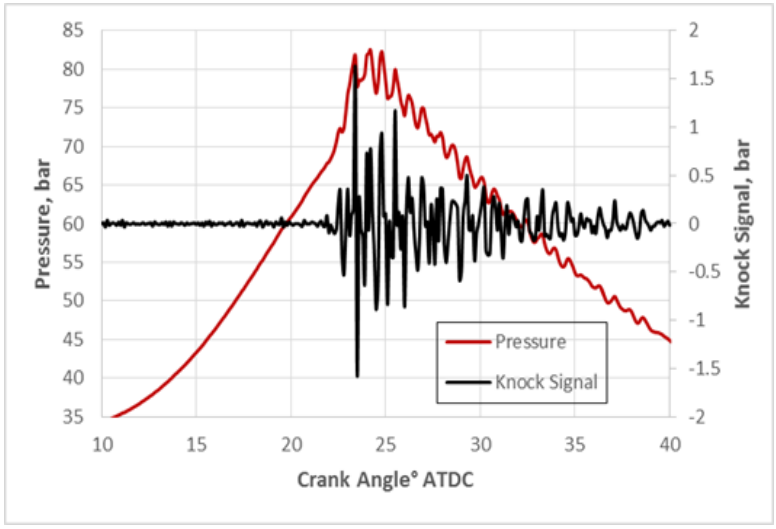


The most advanced spark timing considered for each fuel/condition

Fuel	Cond 1	Cond 2	Cond 3
A	-15	-10	-1
B	-11	-8	-3
C	-14	-8	0
D	-14	-13	-3
E	-27	-21	-6

Knock Metrics- Experimental determination

- For each knocking cycle



To get the knock signal from the pressure trace –

- Find smoothed pressure, Ps(i), at a crank angle position i, given by:

$$Ps(i) = \frac{P(i-1) + P(i) + P(i+1)}{3}$$

(Running average of three adjacent points)

- The knock signal, Pk(i), at a crank angle position, i, is given by:

$$Pk(i) = P(i) - Ps(i)$$

Knock Intensity, KI – (Max – Min) of knock signal. Not truly objective measure

- The crank angle at knock onset, CAk, is defined as the crank angle position when the knock signal, Pk, first deviates from zero by 0.05 bar
- Cycles with KI > 0.5 bar considered ‘ knocking’

Knock Onset Point – Prediction Using Livengood-Wu Integral

- **Knock is assumed to occur when the Livengood-Wu integral with time, $I = \int_0^{te} \frac{dt}{\tau_i(P,T)}$ reaches unity.**
- **$\tau_i = Aexp(\frac{B}{T})P^{-n}$ with A, B and n for the TPRF surrogate of the same RON and MON as the test fuel**
- **We use measured pressure**
- **Temperature Estimation**

Knock is initiated by autoignition in a hot spot.

Bulk temperature of unburned gas –

We know the volume when P is 15 bar. We know the number of moles of air and fuel and estimate the moles of residual

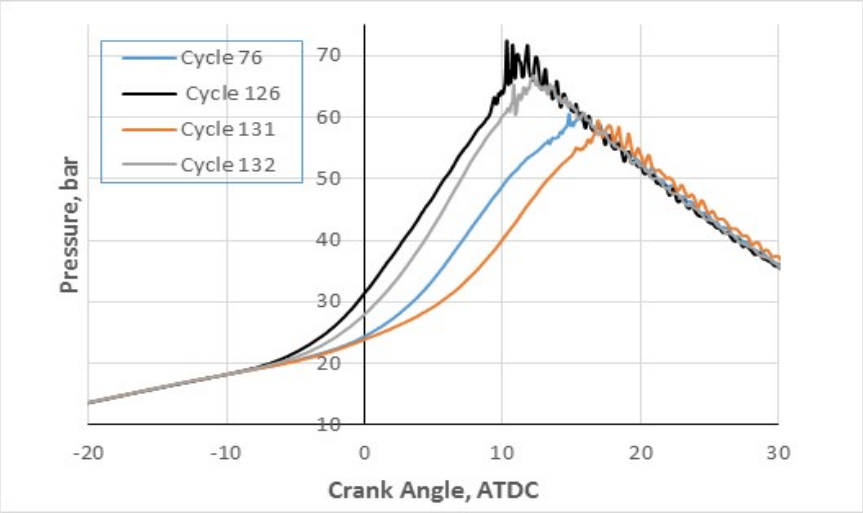
Find T at this pressure from PV = mRT to get T_{comp15}

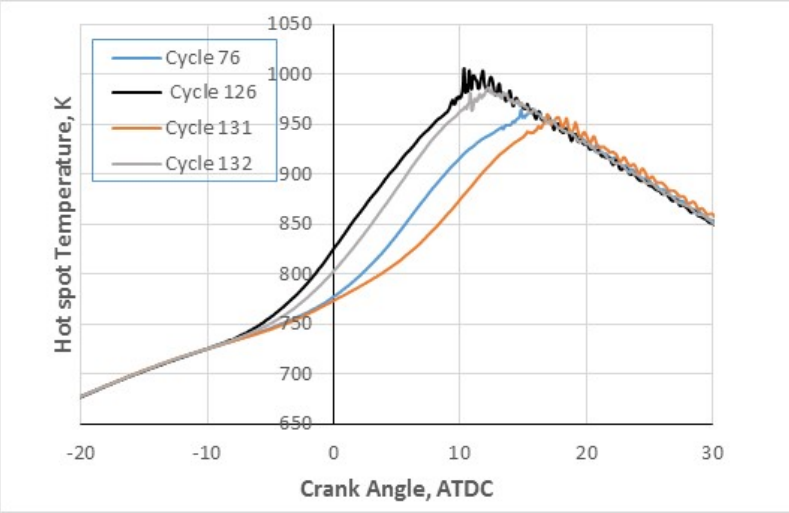
Hot Spot Temperature – We assume that the temperature in the hot spot is greater than Tcomp15 by ΔT i.e T15 = Tcomp15 + ΔT. ΔT = 10 K for Cond.s 1 and 2, 30 K for boosted Cond. 3

Find T at other pressures from

$(T/T_{15}) = (P/15)^{(1-\frac{1}{x})}$. x was determined to be 1.31 in these tests from ln (P) vs ln (V) near TDC before ignition

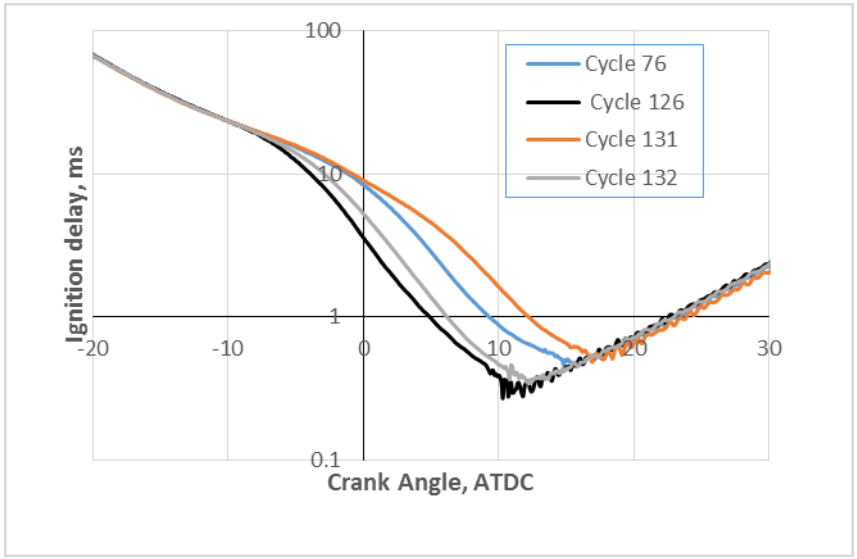
Knock Onset Point – Prediction vs Comparison - I

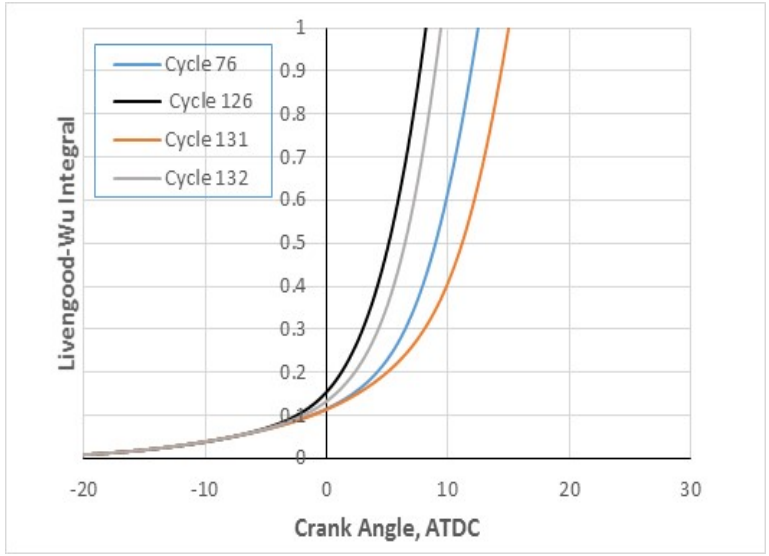




- Pressure signals from four knocking cycles using Fuel A at Condition 1. Spark timing – 15 CAD before TDC.
- Temperature in the hot spot for the cycles shown : it was calculated assuming ΔT = 10 K and x = 1.31. Fuel A, Cond 1. Tcomp15 = 685 K
- For the boosted condition, Cond. 3 (Tcomp15 = 590 K), ΔT = 30 K . With ΔT = 10 K , knock onset was predicted to be much later than observed in all 50 cycles.

Knock Onset Point – Prediction vs Comparison - II



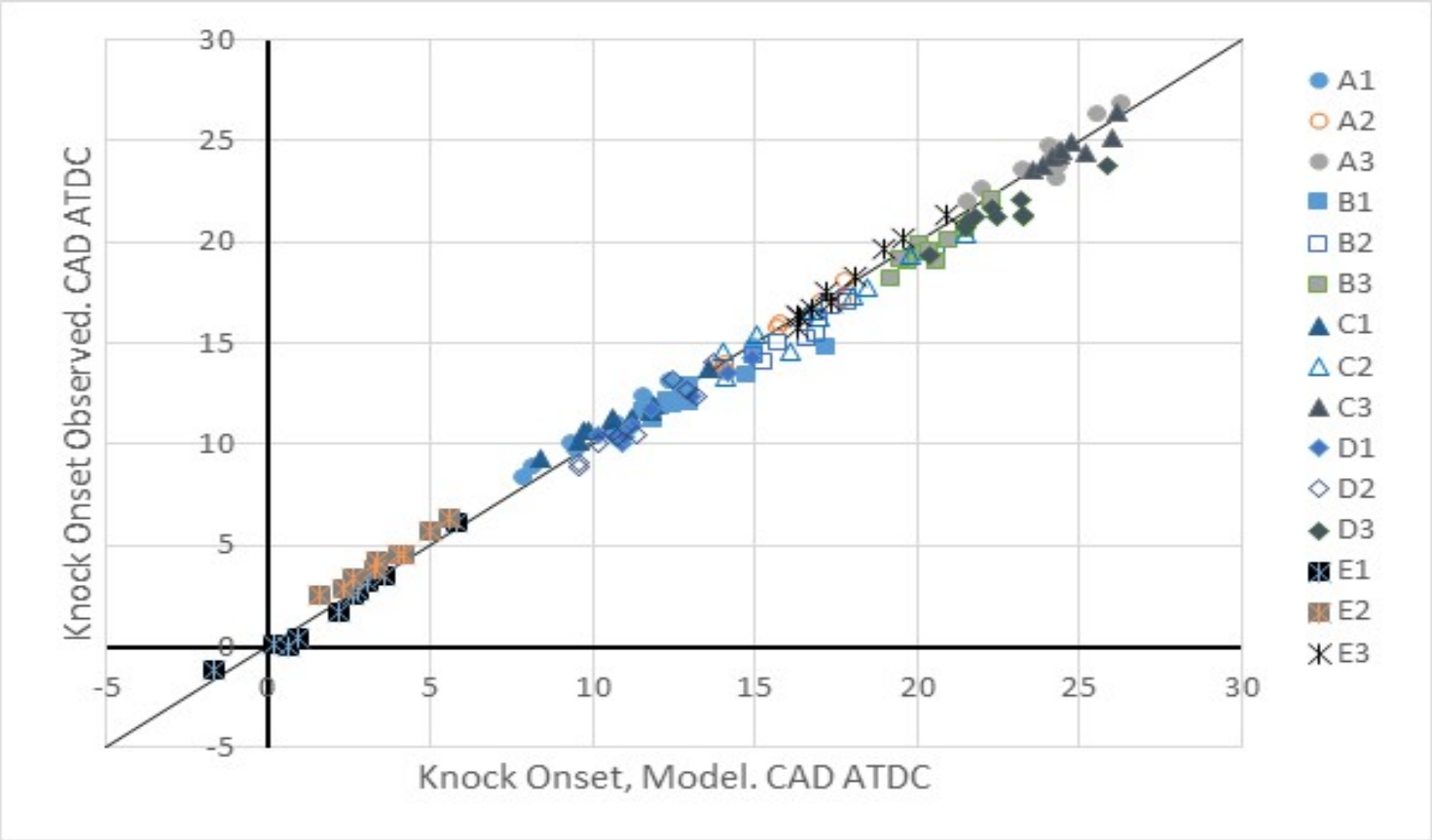


For Fuel A (94.1 RON, 87.5 MON)

$$\tau_i, ms = 0.02454 exp(\frac{7444}{T}) P^{-1.1617}$$

Knock Onset Point – Prediction vs Comparison - III

SAE 2016-01-0702



Excellent agreement between predicted and observed knock onset in all cases

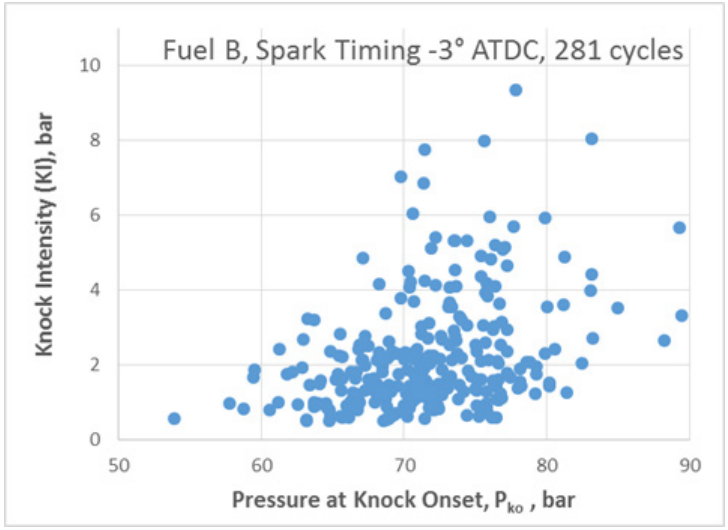
Conclusions

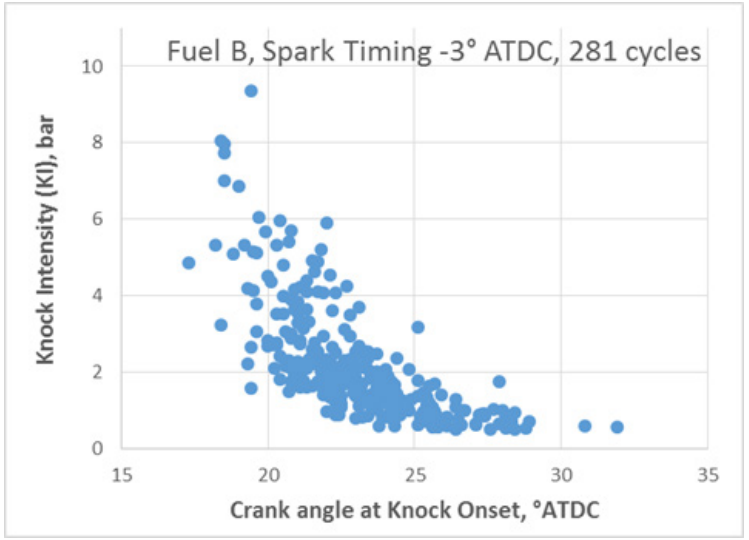
- Model for ignition delay, as a function of P and T established for a given RON and S
  - Uses ignition delays from kinetic model for TPRF surrogates ignoring values greater than 15 ms.
- Five fuels of different RON and S tested in DISI engine for three conditions and knock onset point for individual cycles established
- Using measured pressure and estimated temperature in the hot spot, ignition delay calculated as function of crank angle
- Knock onset point predicted by Livengood-Wu integral agrees very well with observed knock onset point in all 15 cases.

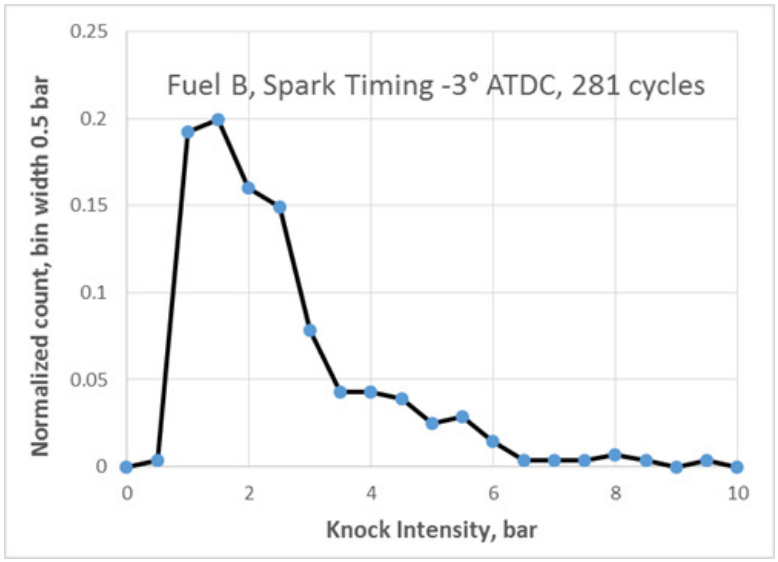
•If the RON and MON of the test fuel is known and variation with crank angle of pressure and temperature are known, knock onset can be predicted with the approach described in the paper

Knock Intensity
(Threshold value for KI = 0.5 bar in the following. Only boosted condition considered SAE 2017-01-0689)

Knock is a stochastic process



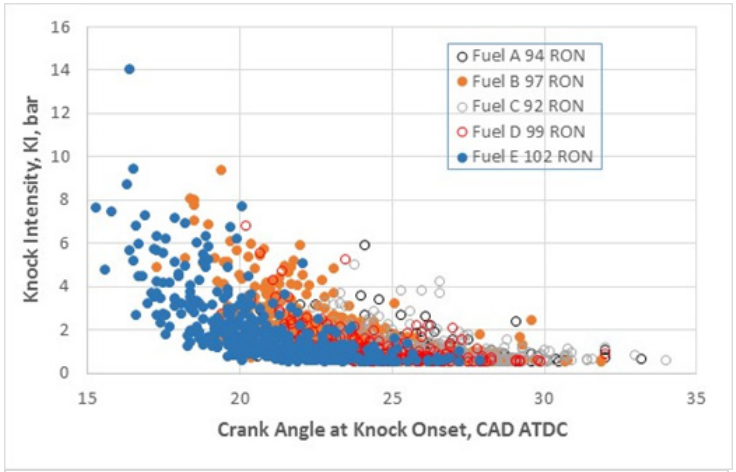


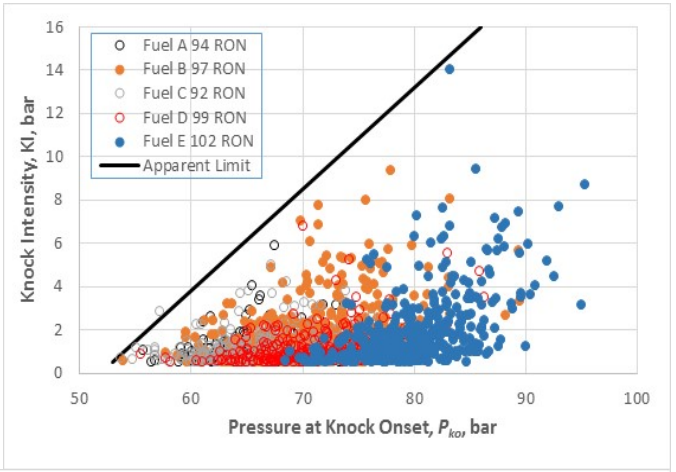


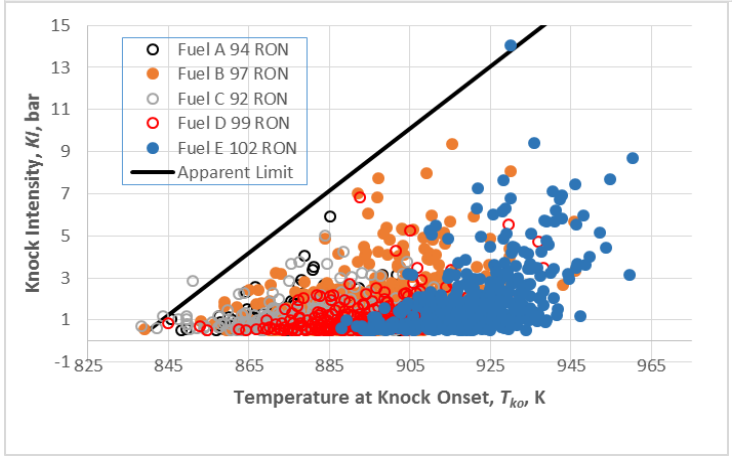
- Even for the same operating condition, fuel and spark timing, phasing and pressure at knock onset varies
- For the same pressure/phasing at knock onset, KI varies
- Distribution of knock intensity not Gaussian (log normal). See also McKenzie and Cheng, SAE 2016-01-0704

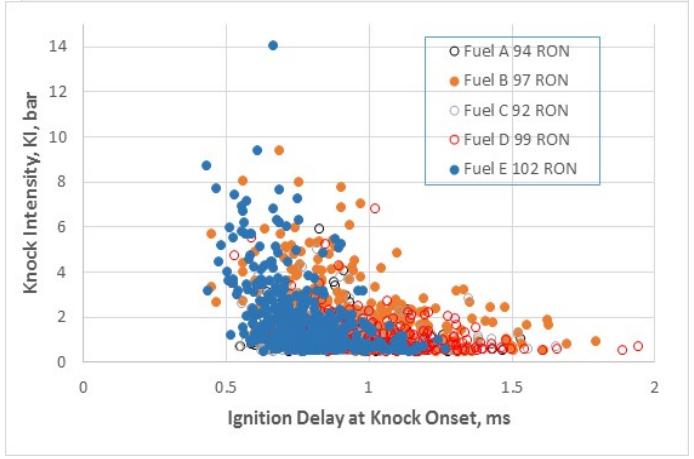
Livengood-Wu or kinetic models enable us to predict knock onset if pressure and temperature history is known but not KI

Knock Intensity and Parameters at Knock Onset









At this boosted condition, T_{ko} is mostly between 845 K and 945 K, lower than 900-1000 K suggested by Westbrook for H_2O_2 conversion (observed for non-boosted conditions). P_{ko} is also higher

Auto-ignition Front Velocity and Knock Intensity

Bradley and co-workers have shown that $u_a = (\partial x/\partial \tau_i) = (\partial \tau_i/\partial T)^{-1}(\partial T/\partial x)^{-1}$, the velocity of the auto-ignition front is critical

In particular, the "resonance parameter", $\xi = \left(\frac{a}{u_a}\right)$ where a (m/s) is the acoustic velocity given by $a = \sqrt{\gamma RT} = \sqrt{375T}$

$\frac{\Delta P_{max}}{P} = \xi^{-2}$ When ΔP_{max} is small .Bradley, D. and Kalghatgi, G.T., Combust Flame, 2009; 156: 2307-2318

$\Delta P_{max} = \frac{KI}{2}$

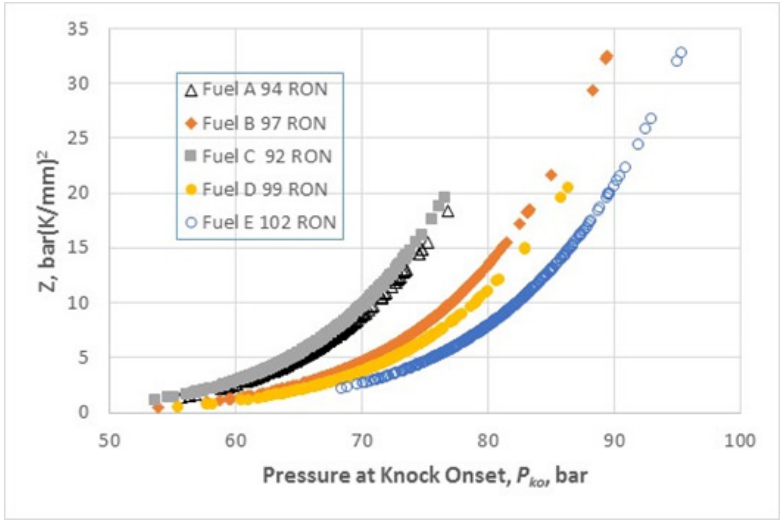
$\tau_i = Aexp(\frac{B}{T})P^{-n}$

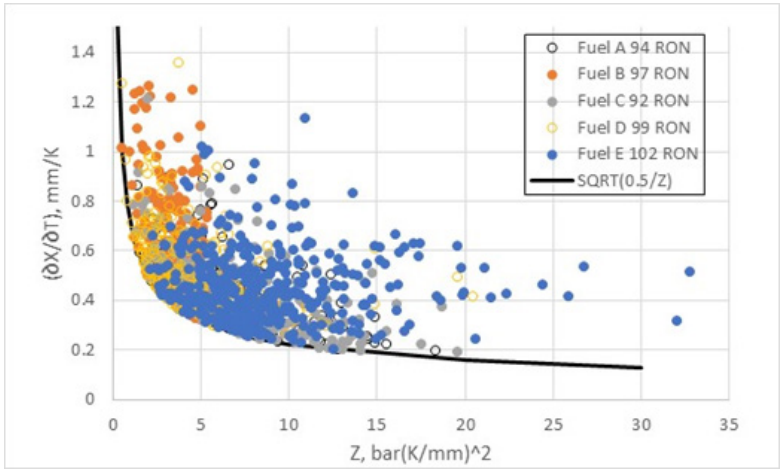
Hence $u_a = -(T^2/B\tau_i)(\partial T/\partial x)^{-1}$

$KI = Z(P)\left(\frac{\partial x}{\partial T}\right)^2$ where $Z = \frac{2PT^3}{375\tau_i^2 B^2}$

Z(P) has the dimensions of bar.K^2.mm^{-2} with *T* in K, *P* in bar and τ_i in ms . All values at knock onset, KI threshold of 0.5 bar

Variation of Z and (∂x/∂T) - Cond 3. For each fuel, combine knocking cycles for all spark timings

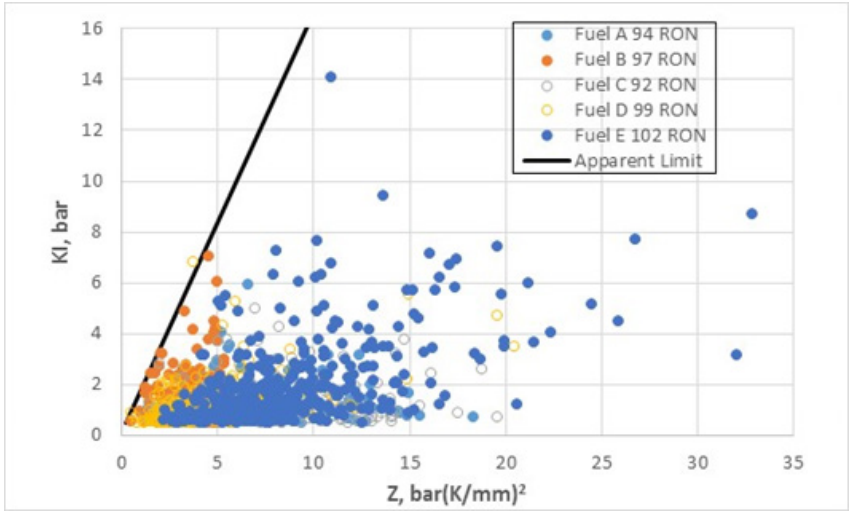


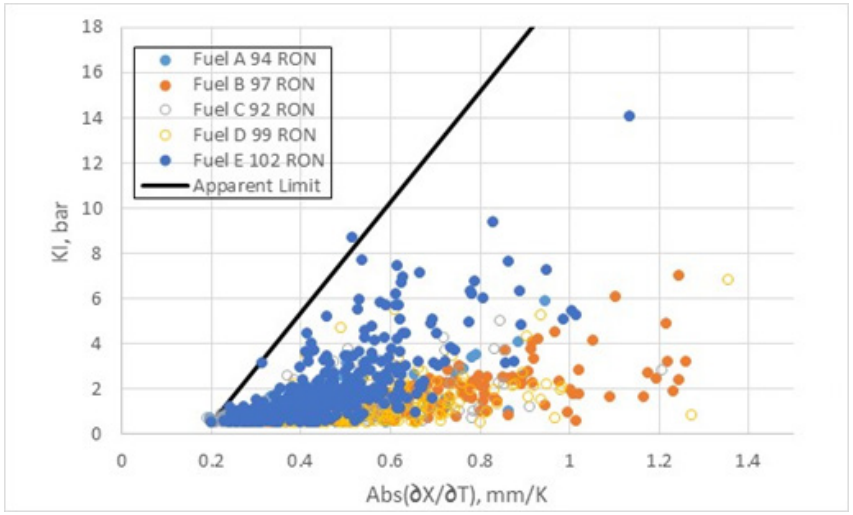


$$KI = Z(P)\left(\frac{\partial x}{\partial T}\right)^2$$

- For each knocking cycle, (∂x/∂T) is calculated from measured KI and *Z*
- For each fuel, *Z* varies because of cyclic variation and spark timing as *P* varies
- For the same knock onset pressure, higher octane fuel has lower value of *Z*
- (∂x/∂T) depends on the evolution of the hot spot and hence on turbulence and mixing
- High value of Z combined with high value of (∂x/∂T) will give high KI

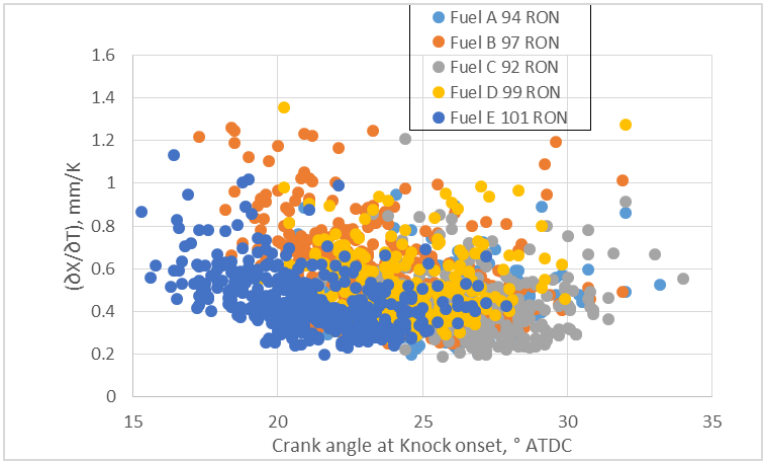
Variation of KI with Z and (∂x/∂T)

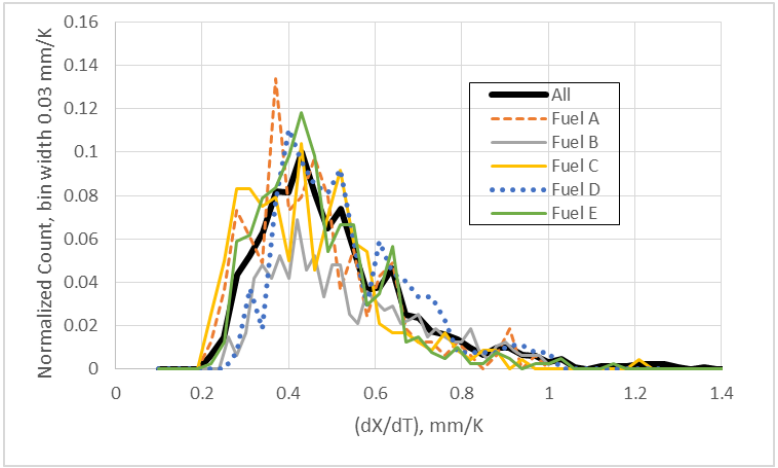




- High value of Z alone or (∂x/∂T) alone does not necessarily lead to a high value of KI
- High KI can result if high value of Z is paired with high value of (∂x/∂T) even if fuel octane number is high – e.g., Point A
- There seems to be a minimum value of Z and (∂x/∂T) required to reach a particular value of KI.

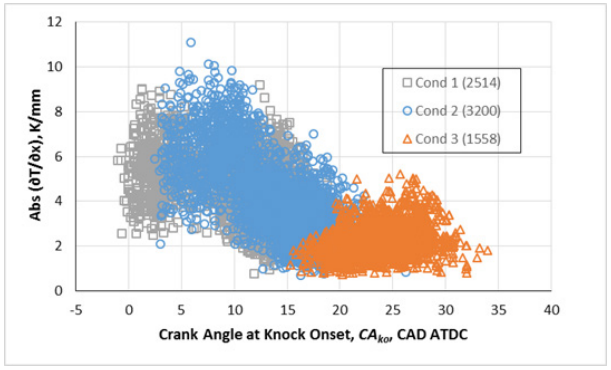
Distribution of (∂x/∂T) - Cond 3

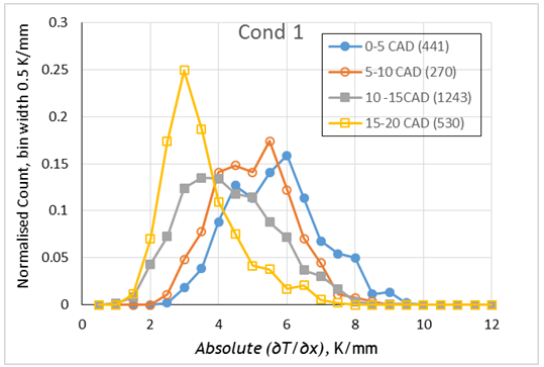


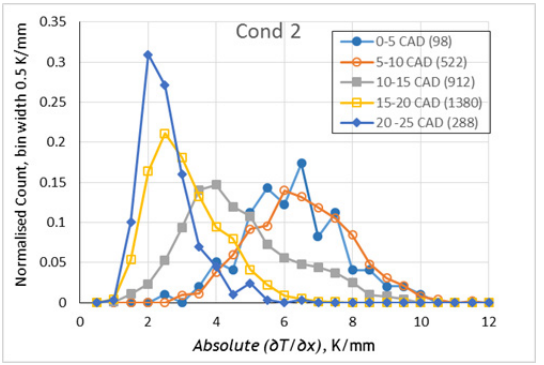


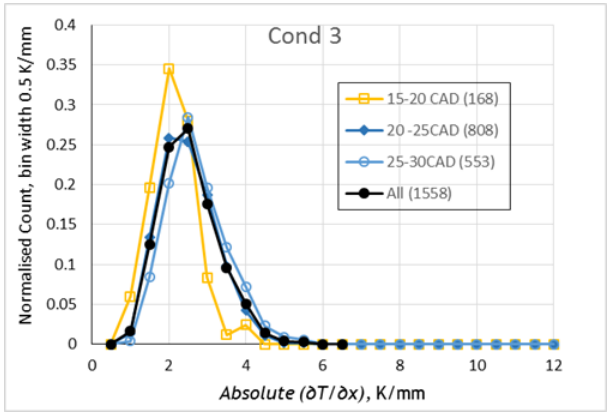
- A hot spot starts because of fresh charge mixing with hot residuals
- Its evolution depends on flow, turbulence and mixing
- If there is more time for mixing i.e. if knock occurs later in the cycle, the temperature difference between the hot spot and the bulk gas should decrease i.e. (∂x/∂T) should increase.
- For Cond 3, there is a significant overlap in the knock onset crank angle for different fuels
- The probability distribution for (∂x/∂T) is similar for different fuels
- Taking all 1558 knocking cycles, the most probable value for (∂x/∂T) is 0.44 mm/K [(∂T/∂x) of 2.2 K/mm]

Distribution of (∂T/∂x) – SAE 2017-01-2233







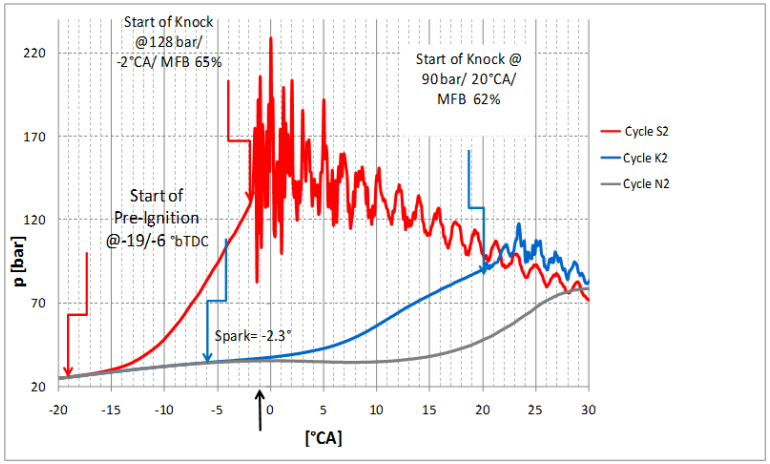


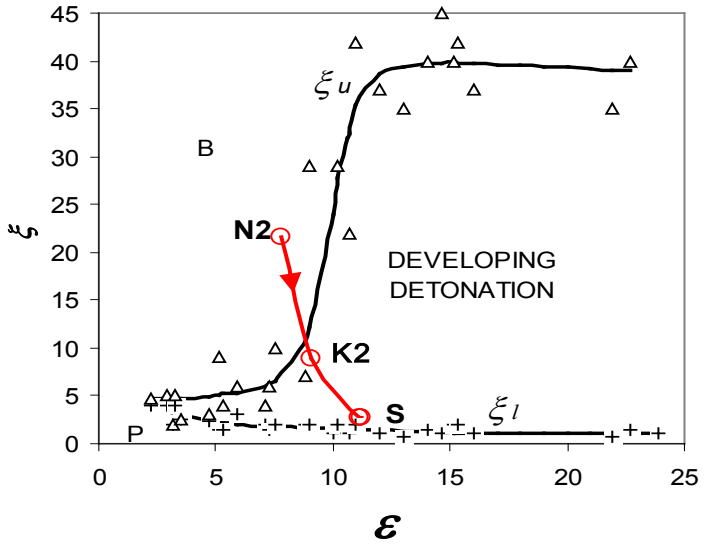
- Crank angle range over which data is available is limited by experimental constraints
- Mean value of $(\partial T/\partial x)$decreases and the distribution narrows with increasing crank angle

The turbulent temperature field, initially set up by the mixing of hot in-cylinder gases with the fresh charge, becomes more homogeneous because of mixing and dissipation of smaller scales

Superknock

Superknock – Developing Detonation (DD)





Extremely violent knock events observed in boosted engines – "Superknock" e.g. KI of 140 bar in cycle S2

- Bradley and co-workers have ascribed superknock to DDs which result when the value of ξ decreases and the pressure wave begins to couple with the autoignition front and gets amplified

(Bradley, Morley, Gu and Emerson SAE 2002-01-2868; Kalghatgi and Bradley, IJER 13(4):399-414; Bradley et al Combust Flame 166:80-85)

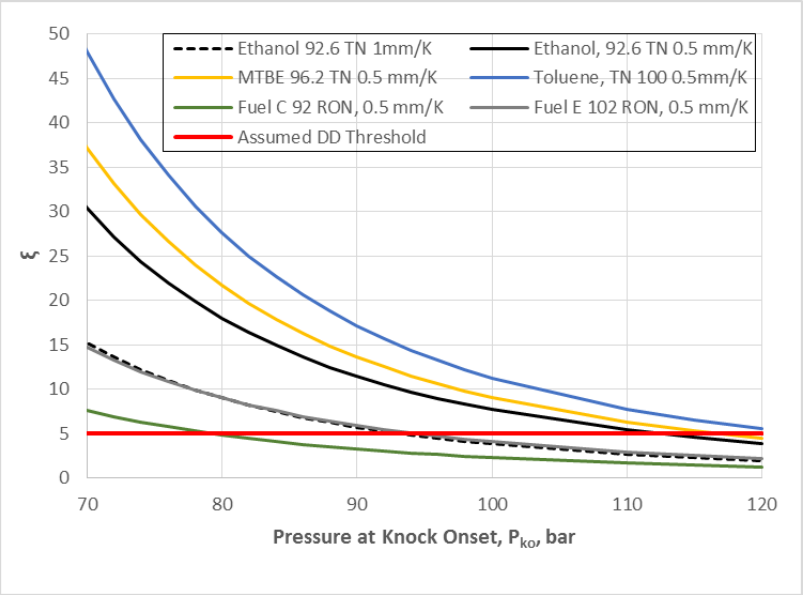
- With a "reactivity parameter", $\epsilon = \frac{r_0}{a\tau_e}$

where r_0 is the radius of the hot spot and τ_e is the excitation time during which most of the energy is released, a peninsula for DD can be identified

- The chances of DD increase as ξ decreases

Possibility of DD with increasing pressure for different fuels

$$\xi = (\partial x/\partial T)^{-1}\sqrt{\frac{2P}{Z}}$$



	TN	A, ms	B, K	n
Ethanol	92.6	0.002118	9887	0.9814
MTBE	96.2	0.000946	10526	0.9276
Toluene	100	0.0004	11200	0.8570

- Chances of DD and Superknock increase as pressure at which knock occurs increases or $(\partial x/\partial T)$ or knock – resistance (RON) of the fuel decreases

Engine operating conditions are chosen so that knock is avoided even allowing for cyclic variation e.g. ξ is greater than 25 (KI of 0.2 bar and P of 65 bar). So how do we get DDs and Superknock?

PREIGNITION increases *P* and hence *Z*!

Preignition – A stable flame is initiated before the spark fires

Criteria For Successful Flame Initiation

Ignition Criterion – Local temperature must reach a minimum level so that runaway chemical reactions start

• Initiation Criterion - The incipient flame must reach a critical radius, r_f, before it becomes self-sustaining

Initial Ignition – **CANNOT BE BECAUSE OF AUTOIGNITION IN FUEL/AIR MIXTURE - τ_i too large during compression stroke**

In older studies, with carburetter engines, pre-ignition started at surfaces.

•Combustion Chamber Deposits played a big role.

• Hot spark- plug electrodes

In Modern, boosted DISI engines – pre-ignition seems to originate away from surfaces (e.g.SAE 2010-01-0355)

•Droplets of Lubricant/Fuel mixture undergo chemical kinetic and catalytic reactions to release heat during the compression stroke

•Lubricant much more prone to auto-ignition than fuel (more like n-heptane)

•Calculations suggest catalytic reactions are necessary (experiments show important role of metallic lubricant additives)

Higher pressures make all these reactions more likely

Criteria For Successful Flame Initiation

Initiation Criterion - The incipient flame must reach a critical radius, r_f, before it becomes self-sustaining

Assuming a Lewis number of unity, $r_f = \delta$, where δ is the laminar flame thickness (Zeldovich et al. *Combustions and Explosions*, 1985)

The larger the r_f or δ , the more difficult it is to initiate a flame

δ is given by $\delta = D / S_L$ where D is the thermal diffusivity and S_L is the laminar burning velocity.

Further, $D = \mu/\rho$ where μ is the dynamic viscosity (assuming Prandtl Number ~1) and $S_L/S_{L0} = (T/T_0)^x (P/P_0)^{-y}$ (e.g. Metaghalchi and Keck, Combustion and Flame, v38(1980) 143)

$x \sim 2$, $y \sim 0.2$, subscript 0 denotes an arbitrary standard condition

Also, Pressure, $(P/P_0) = (\rho/\rho_0)(T/T_0)$. and $(\mu/\mu_0) = (T/T_0)^{0.5}$

Pre-ignition criterion

Hence $\delta = (\mu_0/\rho_0 S_{L0})(T/T_0)^{1.5-x}(P/P_0)^{y-1}$

The larger the δ , the more difficult it is to initiate a flame

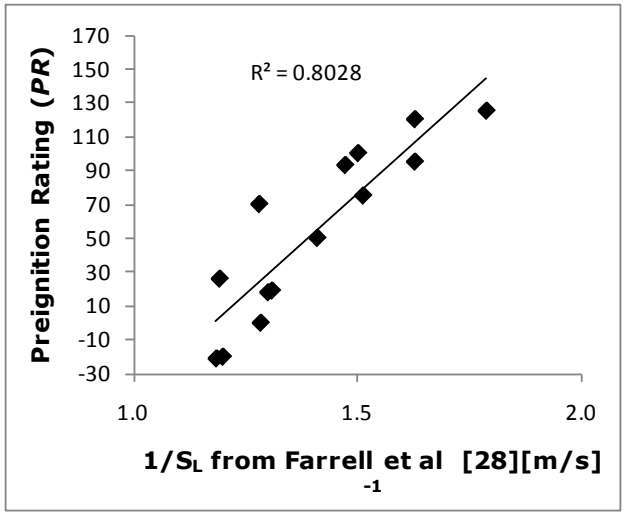
$x \sim 2.0$, $y \sim 0.2$

- For a given fuel, as pressure increases, δ decreases and pre-ignition becomes more likely
- For a given fuel and operating condition,a) S_{L0} is maximum at slightly rich mixture strength b) S_{L0} decreases as more cooled EGR is used

Fuel	PR	S_{Lmax} , m/s	RON	MON	Source of RON/MON
1-pentene	-21	0.845	90.9	77.1	API
1-hexene	-20	0.835	76.4	74	API
cyclohexane	0	0.78	83	78	API
ethyl benzene	18	0.77	109	97.9	rated
cumene (isopropylbenzene)	19	0.765	113.1	99.3	API
benzene	26	0.84	105	97	API
2-methylbutene	50	0.71	98	82	API
cyclopentane	70	0.782	102.8	85.7	rated
isopentane	75	0.662	93.5	93	API
toluene	93	0.68	117	102	ASTM
p-xylene	95	0.615	113	100.6	rated
isooctane	100	0.667	100	100	ASTM
o-xylene	120	0.615	105.4	88.8	rated
ethanol	-28	0.87	110	91	[25]
m-xylene	125	0.56	117	101.3	rated

Maximum burning velocity S_{Lmax} and Pre-ignition Rating, *PR*, for different hydrocarbon fuels .
S_{Lmax} is from Fig. 15 of Farrell et al. [SAE 2004-01-2936] and is the maximum laminar burning velocity measured at a pressure of 0.304 MPa and a temperature of 450K. *PR* is from Fig. 4.9 of [Ricardo, H.R., and Hempson, J.G.G., " The high-speed internal combustion engine", Ch. 4, Blackie and Son Ltd., Fifth edition,1972] and for ethanol, from [SAE 831685].

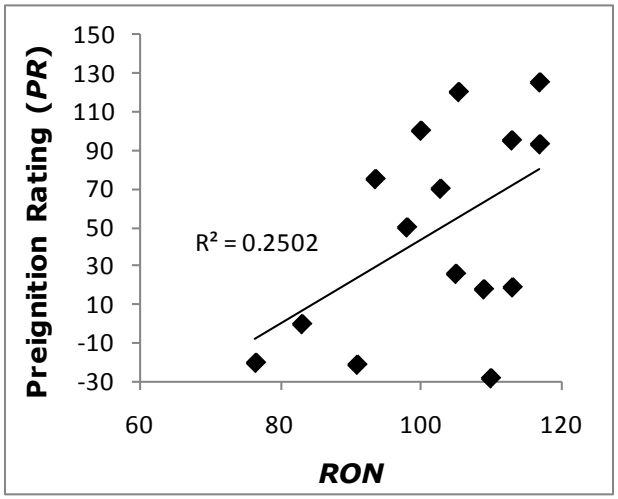
Fuel Effects on Pre-ignition

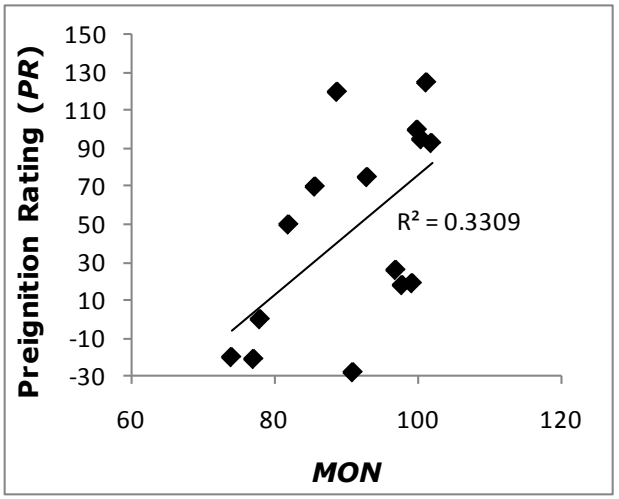


$\delta = (\mu_0/\rho_0 S_{L0})(T/T_0)^{1.5-x}(P/P_0)^{y-1}$

Assume μ_0/ρ_0, x and y are the same for different fuels.

For a given T and P, as $(1/S_{L0})$ increases, the laminar flame thicknes, δ increases, and pre-ignition resistance (PR) increases.





CONCLUSION - Knock Intensity

Knock is a stochastic process which occurs in hot spots. Should really be described in probabilistic terms

- Knock onset can be predicted using the Livengood-Wu approach if, ignition delay variation with pressure and temperature (and P and T) are known but not knock intensity (KI)
- KI depends on $\xi = \left(\frac{a}{u_a}\right)$, u_a is the speed of the autoignition front and a is the speed of sound, u_a when is small
- KI can be related to the product of a parameter Z, which depends on the pressure, P, at knock onset and the square (∂x/∂T), the inverse of the gradient of temperature in the hot spot
- For a given fuel and operating condition, Z varies because P varies because of cyclic variation – a stochastic process
- Z increases and hence the probability of high KI increases as P increases, e.g., by boosting or increased ignition advance
- For a given P, Z is lower for a fuel with more autoignition resistance (higher RON)
- (∂x/∂T) depends on the evolution of the hot spot which depends on flow and turbulence – stochastic processes

CONCLUSION – Superknock and Preignition

- Superknock is caused by developing detonation which results when the value of ξ decreases and the pressure wave begins to couple with the autoignition front and gets amplified
- Engine operating conditions are chosen (e.g., spark is retarded) to avoid knock, autoignition in the fuel/air mixture, and hence very far away from conditions required for superknock
- Preignition, which is also governed by stochastic processes, can cause knock onset to occur at high pressures and increase the chances of superknock
- For preignition to occur, the local temperature has to increase beyond a critical value. This cannot be because of autoignition of the fuel/air mixture and hence does not depend on RON or MON of the fuel.
- A further initiation criterion has to be satisfied for a stable flame to be established. All else being equal, the chances of preignition (establishing a flame) increase as laminar burning velocity increases
- All else being equal, the probability of superknock decreases as fuel RON is increased.
- Increased pressure increases the probability of both preignition and superknock
- However, even with high RON, high KI AND superknock can occur with the right combination of Z and $(\partial x/\partial T)$