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

Gautam Kalghatgi

- 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

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

\( \tau_0 \) is the ignition delay at \( T \) and \( p_0 \)

\( n \) is \( \sim 1.5 \) 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.

\[ I = \int \left( \frac{1}{\tau} \right) dt = 1 \]
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

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

*(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]

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


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($\tau_i$) 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 $\tau_i = A \exp\left(\frac{B}{T}\right)P^{-n}$ was fitted to these data for $\tau_i < 15$ ms.

<table>
<thead>
<tr>
<th>RON</th>
<th>MON</th>
<th>S</th>
<th>(R+M)/2</th>
<th>TN</th>
<th>Isooct</th>
<th>n-hep</th>
<th>toluene</th>
<th>A</th>
<th>B</th>
<th>n</th>
<th>(P in bar)</th>
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</thead>
<tbody>
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<td>88</td>
<td>78</td>
<td>10</td>
<td>83</td>
<td>69.6</td>
<td>8.0</td>
<td>28.5</td>
<td>63.5</td>
<td>0.03146</td>
<td>7023</td>
<td>1.125</td>
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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 \( \tau_i = A \exp\left(\frac{B}{T}\right)P^{-n} \) where \( Z \) is A, B or n and

\[ X = RON + \delta S \]

Best fit values for \( \alpha, \beta, \gamma \) and \( \delta \)

<table>
<thead>
<tr>
<th>( Z )</th>
<th>( \delta )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, ms</td>
<td>0.6464</td>
<td>0</td>
<td>-0.00174</td>
<td>0.1957</td>
<td>0.9757</td>
</tr>
<tr>
<td>B, K</td>
<td>0.3125</td>
<td>3.4615</td>
<td>-568.140</td>
<td>30068</td>
<td>0.9833</td>
</tr>
<tr>
<td>n</td>
<td>8.0000</td>
<td>0</td>
<td>-0.00166</td>
<td>1.4056</td>
<td>0.9920</td>
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</table>
Engine Experiments and Predictions of Knock onset Using the Ignition Delay Equation (SAE 2016-01-0702)
Knock tests were conducted in a single cylinder (10.5 CR) DISI engine at three different operating conditions.

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

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

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

* 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

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Cond 1</th>
<th>Cond 2</th>
<th>Cond 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-15</td>
<td>-10</td>
<td>-1</td>
</tr>
<tr>
<td>B</td>
<td>-11</td>
<td>-8</td>
<td>-3</td>
</tr>
<tr>
<td>C</td>
<td>-14</td>
<td>-8</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>-14</td>
<td>-13</td>
<td>-3</td>
</tr>
<tr>
<td>E</td>
<td>-27</td>
<td>-21</td>
<td>-6</td>
</tr>
</tbody>
</table>
Knock Metrics - Experimental determination

- For each knocking cycle

To get the knock signal from the pressure trace –
- Find smoothed pressure, $P_s(i)$, at a crank angle position $i$, given by:

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

(Running average of three adjacent points)

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

$$P_k(i) = P(i) - P_s(i)$$

Knock Intensity, $K_I - (\text{Max} - \text{Min})$
of knock signal. Not truly objective measure

- The crank angle at knock onset, $\text{CA}_{k}$, is defined as the crank angle position when the knock signal, $P_k$, first deviates from zero by 0.05 bar
- Cycles with $K_I > 0.5$ 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.

- \( \tau_i = A exp\left(\frac{B}{T}\right) P^{-n} \) 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 \( T_{comp15} \) by \( \Delta T \) i.e \( T15 = T_{comp15} + \Delta T \). \( \Delta T = 10 \text{ K for Cond.s 1 and 2}, 30 \text{ K for boosted Cond. 3} \)
Find T at other pressures from

\[
\frac{T}{T_{15}} = \left(\frac{P}{15}\right)^{(1-\frac{1}{x})}
\]

x was determined to be 1.31 in these tests from ln (P) vs ln (V) near TDC before ignition
• 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 $\Delta T = 10$ K and $x = 1.31$. Fuel A, Cond 1. $T_{\text{comp}15} = 685$ K.
• For the boosted condition, Cond. 3 ($T_{\text{comp}15} = 590$ K), $\Delta T = 30$ K. With $\Delta T = 10$ 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)
\[ \tau_i, ms = 0.02454 \exp\left(\frac{7444}{T}\right)P^{-1.1617} \]
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
At this boosted condition, $T_{ko}$ is mostly between 845 K and 945 K, lower than 900-1000 K suggested by Westbrook for $\text{H}_2\text{O}_2$ 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 
\[ u_a = \left( \frac{\partial x}{\partial \tau_i} \right) = \left( \frac{\partial \tau_i}{\partial T} \right)^{-1} \left( \frac{\partial T}{\partial x} \right)^{-1}, \]
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 
\[ a = \sqrt{\gamma RT} = \sqrt{375T} \]

\[ \frac{\Delta P_{\text{max}}}{P} = \xi^{-2} \quad \text{When } \Delta P_{\text{max}} \text{ is small} \]
\[ \Delta P_{\text{max}} = \frac{KI}{2} \]

\[ \tau_i = A \exp \left( \frac{B}{T} \right) P^{-n} \]

Hence 
\[ u_a = -\left( \frac{T^2}{B \tau_i} \right) \left( \frac{\partial T}{\partial x} \right)^{-1} \]

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

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 \( \tau_i \) in ms. All values at knock onset, \( KI \) threshold of 0.5 bar.
Variation of Z and $(\partial x/\partial T)$ - 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, $(\partial x/\partial T)$ 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 $Z$
- $(\partial x/\partial T)$ depends on the evolution of the hot spot and hence on turbulence and mixing
- High value of $Z$ combined with high value of $(\partial x/\partial T)$ will give high $KI$
Variation of $K_I$ with $Z$ and $(\delta x/\delta T)$

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

![Graph showing variation of $K_I$ with $Z$ and $(\delta x/\delta T)$](image-url)
Distribution of $(\partial x/\partial T)$ - 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. $(\partial x/\partial T)$ should increase.
- For Cond 3, there is a significant overlap in the knock onset crank angle for different fuels
- The probability distribution for $(\partial x/\partial T)$ is similar for different fuels
- Taking all 1558 knocking cycles, the most probable value for $(\partial x/\partial T)$ is 0.44 mm/K [$(\partial T/\partial x)$ of 2.2 K/mm]
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. Kl of 140 bar in cycle S2

- Bradley and co-workers have ascribed superknock to DDs which result when the value of $\xi$ 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 $\tau_e$ 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 $\xi$ decreases
Possibility of DD with increasing pressure for different fuels

\[ \xi = \left( \frac{\partial x}{\partial T} \right)^{-1} \sqrt{\frac{2P}{Z}} \]

- 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.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>TN</th>
<th>A, ms</th>
<th>B, K</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>92.6</td>
<td>0.002118</td>
<td>9887</td>
<td>0.9814</td>
</tr>
<tr>
<td>MTBE</td>
<td>96.2</td>
<td>0.000946</td>
<td>10526</td>
<td>0.9276</td>
</tr>
<tr>
<td>Toluene</td>
<td>100</td>
<td>0.0004</td>
<td>11200</td>
<td>0.8570</td>
</tr>
</tbody>
</table>

Engine operating conditions are chosen so that knock is avoided even allowing for cyclic variation e.g. \(\xi\) 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** - $\tau_i$ too large during compression stroke

In older studies, with carburettor 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 $\delta$ is the laminar flame thickness (Zeldovich et al. *Combustions and Explosions*, 1985)

The larger the $r_f$ or $\delta$, the more difficult it is to initiate a flame.

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

The larger the $\delta$, the more difficult it is to initiate a flame $x \sim 2.0$, $y \sim 0.2$

- For a given fuel, as pressure increases, $\delta$ 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

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

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

\[ \delta = \left( \frac{\mu_0}{\rho_0 S_{L0}} \right) \left( \frac{T}{T_0} \right)^{1.5 - x} \left( \frac{P}{P_0} \right)^{y-1} \]

Assume \( \mu_0/\rho_0, x \) and \( y \) are the same for different fuels.
For a given \( T \) and \( P \), as \( (1/S_{L0}) \) increases, the laminar flame thickness, \( \delta \) 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 ($\partial x/\partial T$), 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)
- $(\partial x/\partial T)$ 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 $\xi$ 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 $\frac{\partial x}{\partial T}$. 