THE BENEFITS OF INCREASING OCTANE NUMBER ON GASOLINE ENGINE EFFICIENCY

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Analysis Overview

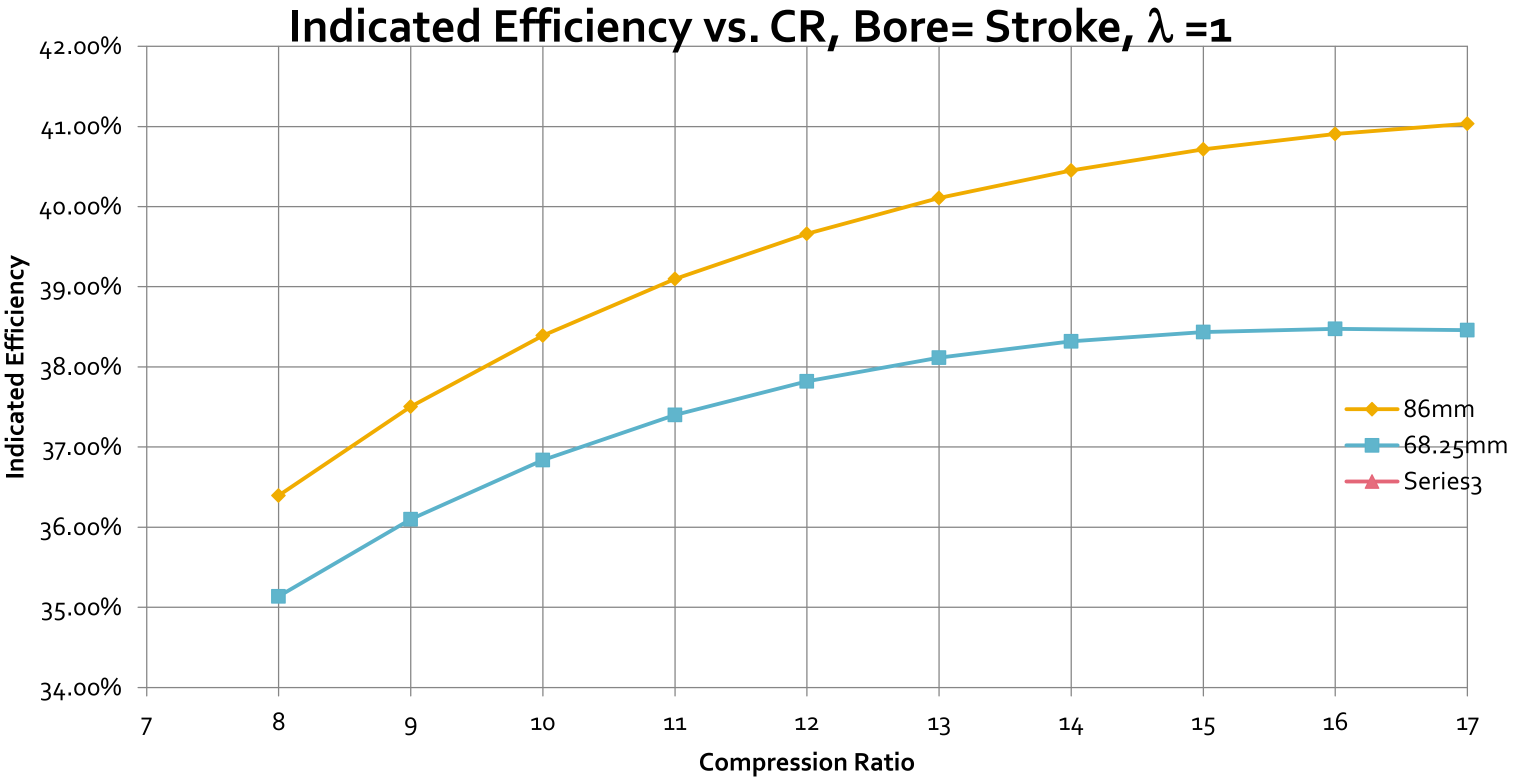
- Study was originally conceived with the idea that efficiency was linked to compression ratio (CR) and higher CR engines require higher octane.
- Engine octane number requirement (ONR) is also affected by a number of other variables including engine design parameters operating conditions, engine calibration (AF ratio and spark timing)as well as fuel composition.
- In turbocharged engines, octane may benefit torque and power more than engine thermal efficiency
- Vehicle efficiency (miles per kWh of fuel) introduces other parameters since engine specific power increase can be used to downsize the engine.

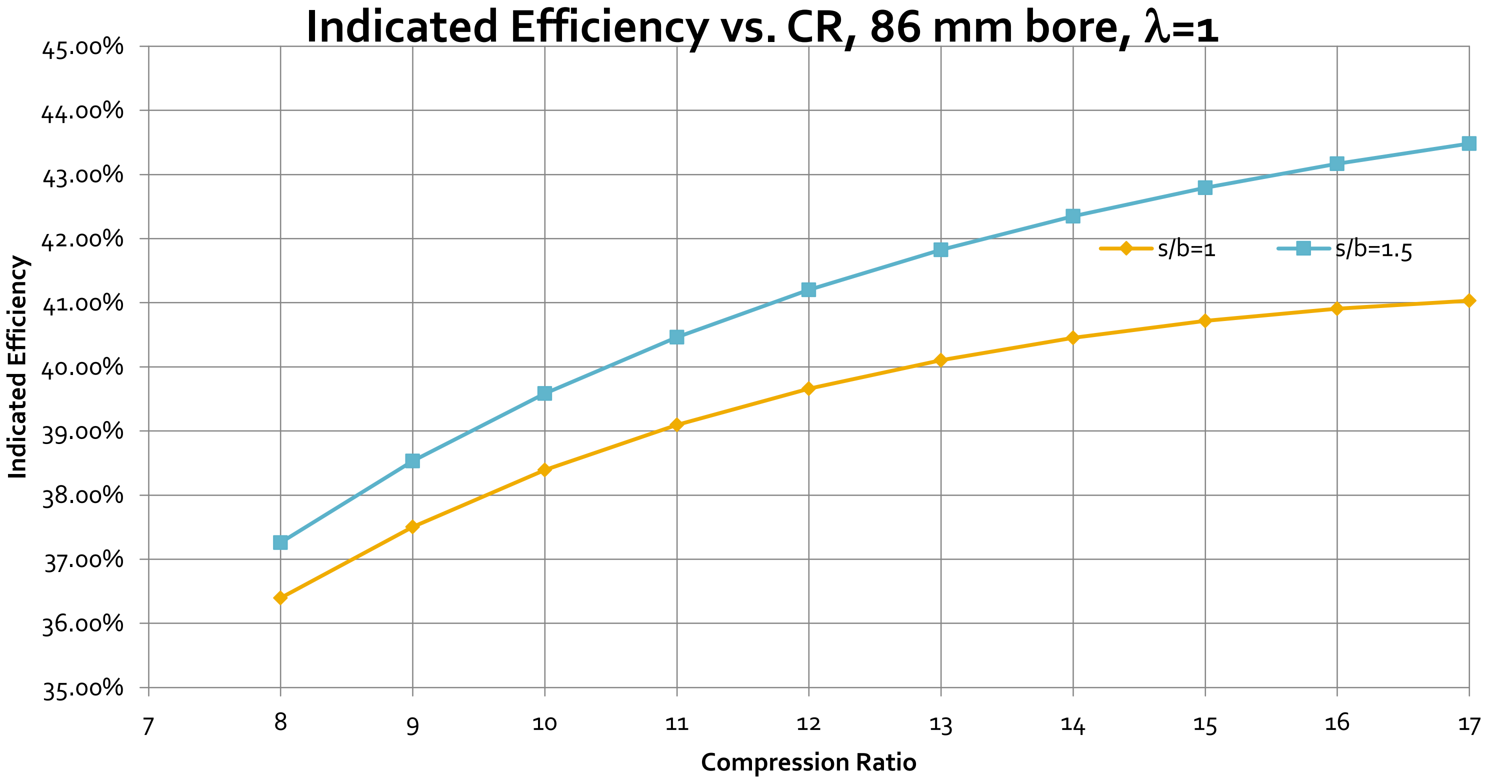
Study methodology

- Focus was on engine studies and we divided engines into boosted and naturally aspirated, with further subdivision of each into PFI and DI variants.
- We utilized a 2 stage model, first linking CR to engine thermal efficiency and second, linking CR and other variables to fuel octane, sensitivity and LHE.
- We focused mostly on WOT/low RPM (<2000) conditions at λ=1 as this is usually the highest engine ONR condition.
- The division by engine type/fuel properties/ operating conditions resulted in very few data points at the detail level; hence, no statistical analysis is possible.

Engine Thermal Efficiency vs. CR

- Ideal Otto cycle provides simple connection of efficiency to CR:
  - $\eta = 1 - CR^{**}\text{-}\gamma$
- Many analyses have shown that for an engine operating at $\lambda=1$, data is best fit by a γ of 1.27 at stoichiometric AF ratio.
- The combustion chamber surface to volume ratio has a strong effect on indicated efficiency, as does unburned fuel loss. This implies that efficiency decreases with smaller cylinder volume or bore size when bore = stroke.
- When stroke/bore ratio is higher efficiency improves at constant bore size. Honda analysis shows stroke = 1.5 x bore results in optimum efficiency.
- We developed a simple linear model of heat transfer and unburned fuel loss as a function of combustion chamber surface/volume which fit the available data well.


Indicated Efficiency vs. CR, Bore= Stroke, λ =1
Indicated Efficiency
42.00%
41.00%
40.00%
39.00%
38.00%
37.00%
36.00%
35.00%
34.00%
7
8
9
10
11
12
13
14
15
16
17
Compression Ratio
86mm
68.25mm
Series3



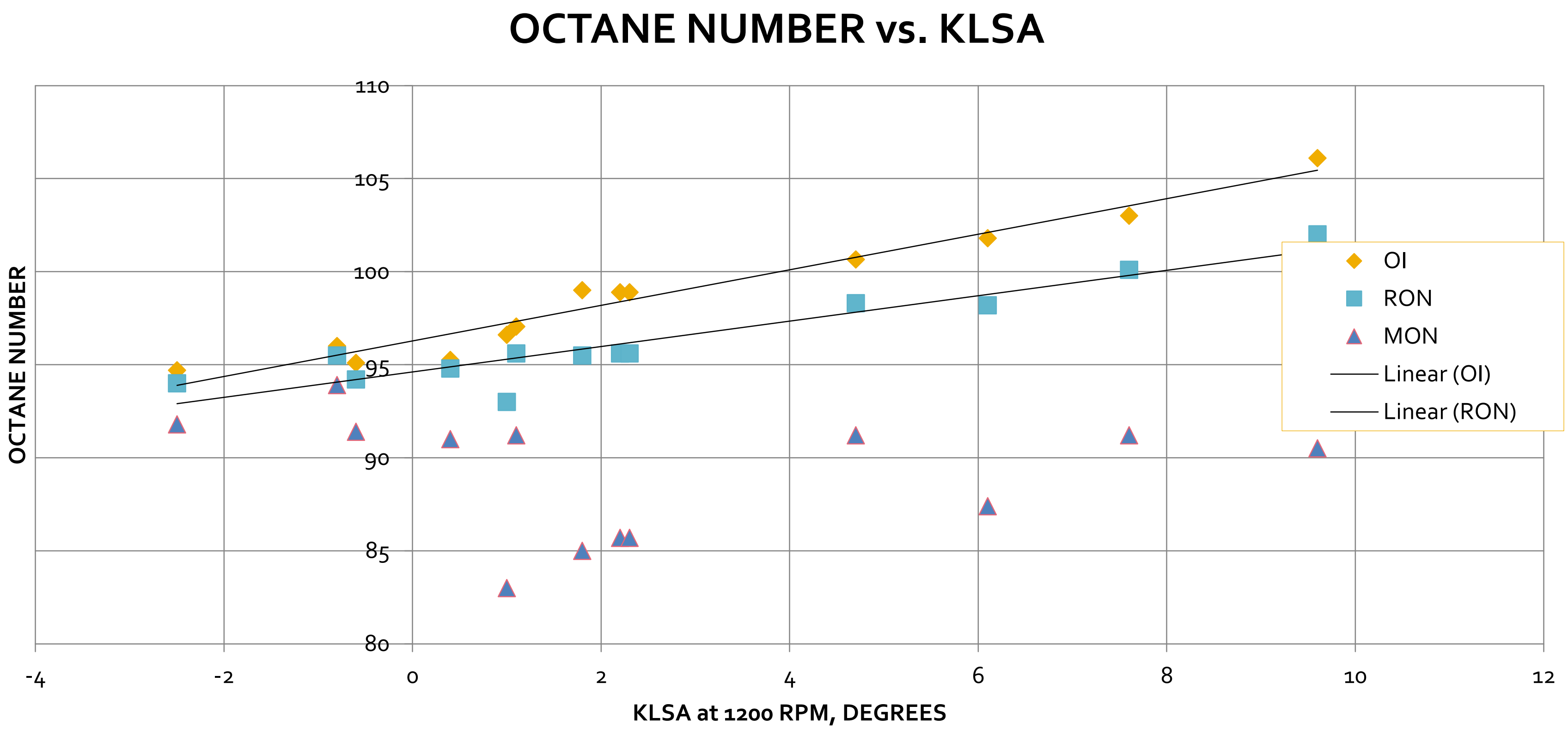
Indicated Efficiency vs. CR, 86 mm bore, λ=1
Indicated Efficiency
45.00%
44.00%
43.00%
42.00%
41.00%
40.00%
39.00%
38.00%
37.00%
36.00%
35.00%
7
8
9
10
11
12
13
14
15
16
17
Compression Ratio
s/b=1
s/b=1.5

CR analysis results

- The analysis of efficiency vs.CR found strongly declining benefits of CR increases for small bore engines, with little benefit (less than 0.5%/CR) beyond a CR of 14.Manufacturers confirmed this based on their production engines.
- For large bore engines, increasing CR and increasing the stroke to bore ratio can provide benefits up to a CR of 16.
- Both ideal engine equations and experimental observations show that efficiency benefits of increasing CR are obtained at part load conditions as well. Honda's recent research suggests that combustion duration decreases as well.
- Higher CR also leads to greater torque which can be used to increase vehicle efficiency by engine down-sizing/ speeding.

Fuel Octane Index (OI)

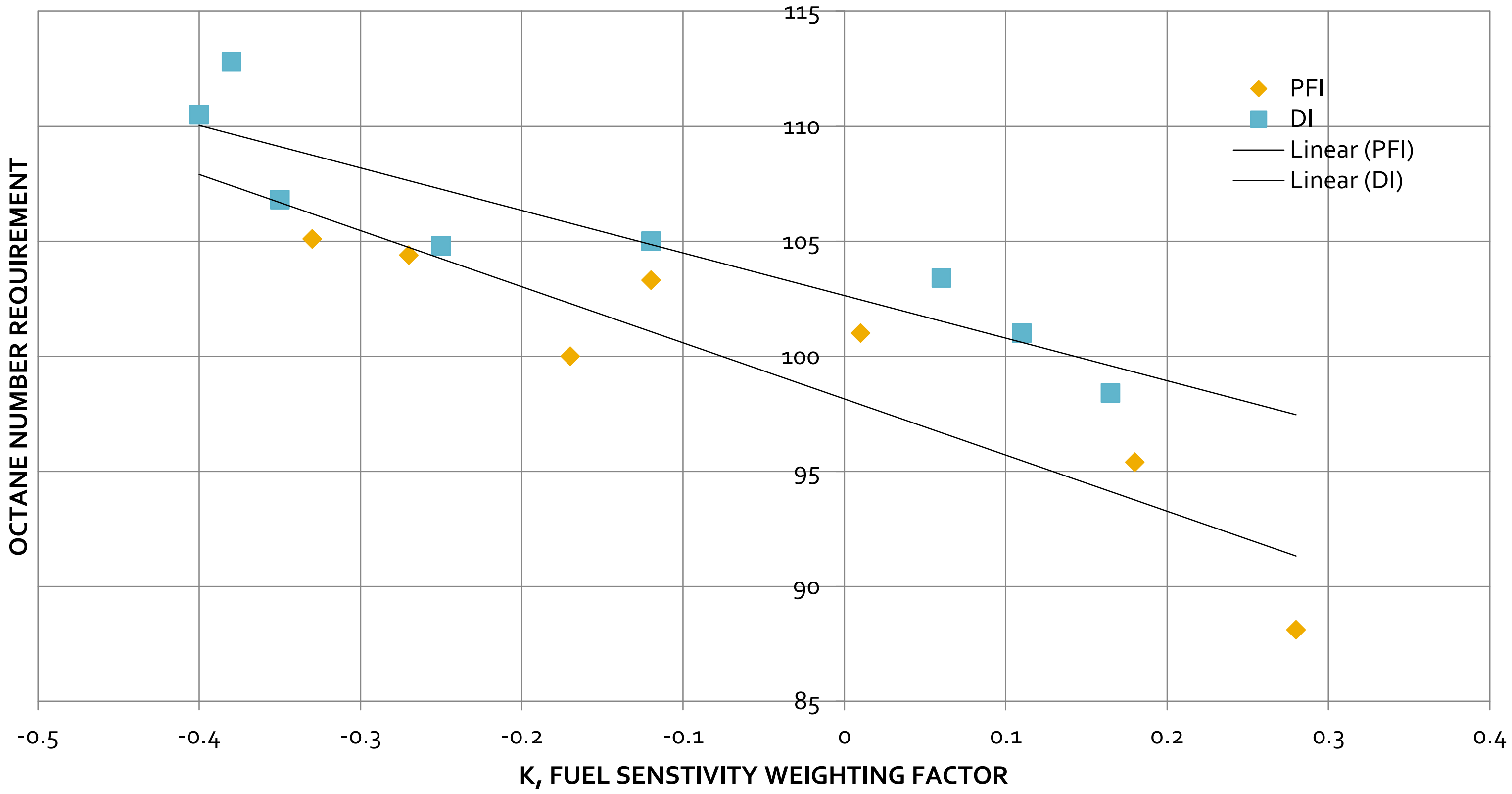
- The fuel octane index OI = RON – K*S, where S in the difference between RON and MON.
- In modern engines K has been found to be negative at low RPM implying that a given RON fuel with lower MON provides better engine torque and efficiency. In fact K is most negative under conditions where ONR is the highest,
- Most studies have found that K increases with engine RPM implying MON’s importance increases at high RPM.
- The relationship between CR, efficiency and fuel octane is complicated since modest levels of spark retard from MBT reduce the octane requirement significantly but reduces efficiency only slightly.


OCTANE NUMBER vs. KLSA
OCTANE NUMBER
KLSA at 1200 RPM, DEGREES
110
105
100
95
90
85
80
-4
-2
0
2
4
6
8
10
12
OI
RON
MON
Linear (OI)
Linear (RON)

Implications of negative K

- A negative K implies that the octane of most pump fuels with a sensitivity of 8 to 10 is actually higher than the RON.
- Research by Shell and MIT have shown that the K values are decreasing over time and engines with a higher octane requirement have even more negative K. Current engines have K values of -0.3 to -0.4.
- These factors suggest that higher CR is possible with the same RON fuel as engine designs gravitate to lower K values.
- However, the effects of K increasing with RPM suggest that high RPM knock will limit CR advances.
- The effect of engine design factors on K have not been examined but could be a fruitful area of research.

OCTANE NUMBER REQUIREMENT vs. K



Efficiency, KLSA and OI

- Under throttled conditions, engines have lower octane requirements than at WOT and spark can be set to MBT.
- Current PFI engines with about 10.5 CR can operate at MBT timing up to about 8 bar BMEP with 91 RON fuel, beyond which spark is retarded from MBT. At WOT, both spark retard and rich air fuel ratios are used to prevent knock. This results in efficiency loss and power loss at high load.
- Higher CR provides the benefits at part throttle with moderate efficiency loss at high load which is less frequently encountered in driving.
- The trade-off between CR, enrichment, spark retard and octane requirements varies between manufacturers so that actual vehicle effects of changed octane can vary between models

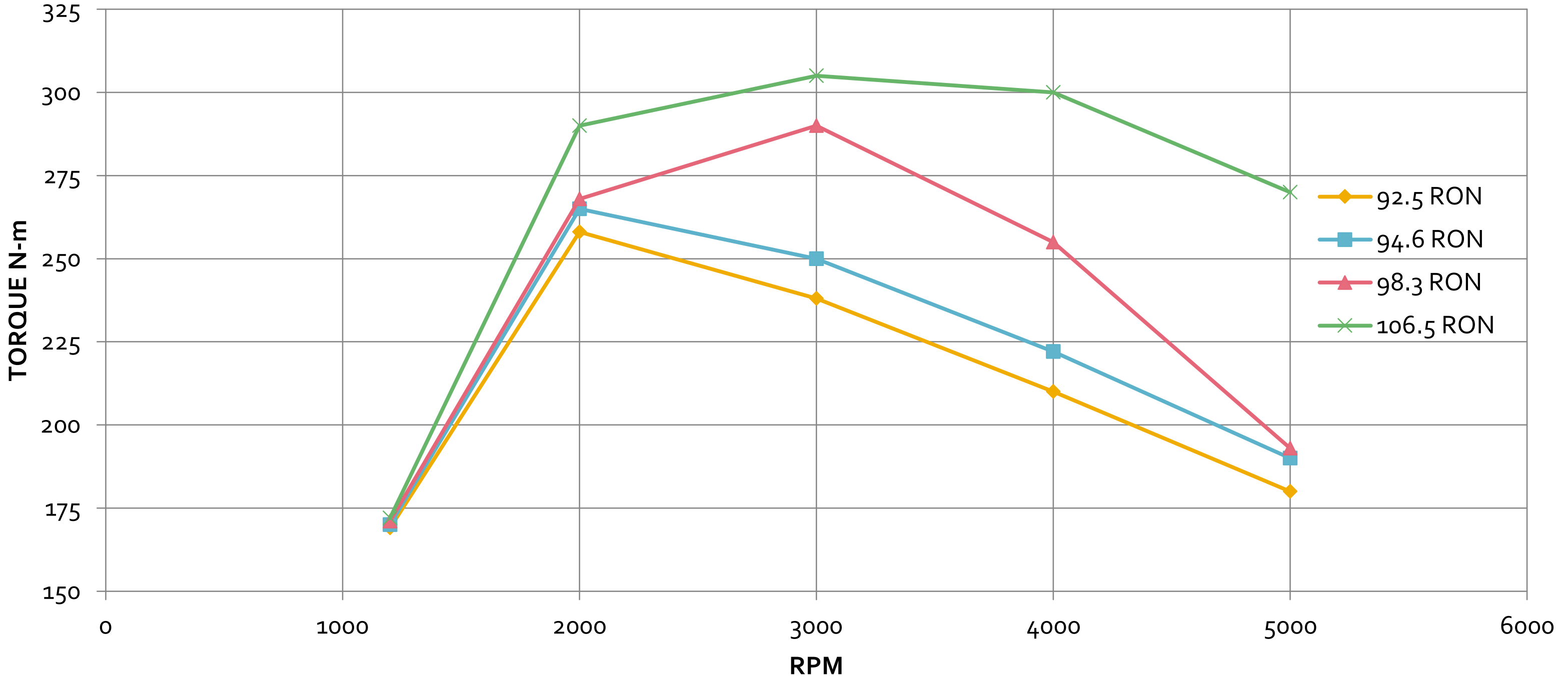
Engine Design Factors Affecting ONR

- Engines can also incorporate design solutions to overcome the knock limit and the most popular are
  - Direct Injection
  - High tumble intake ports
  - Improved exhaust gas scavenging by valve timing and tuned exhausts
- In PFI engines, the fuel LHE is lost but in a DI engine, the fuel charge is cooled by about 20° C. This level of cooling reduces the engine octane requirement by 4 to 5 octane numbers. Actual data on production engines shows that DI engines have almost exactly 1 CR increase over PFI engines on average.
- The Mazda Skyactive engine employs high tumble ports and long runner exhaust system for a CR of 14 on 95 RON gasoline.

Turbocharged Engines

- Turbocharged engines are knock limited over a greater portion of the engine map since BMEP can be twice as high as for non-boosted engine in typical driving.
- However, there are many constraints on a turbo engine – at low RPM, there is a limitation on available boost, while turbine inlet temperature rather then fuel octane number can be the limiting factor. The low RPM limitation can be overcome by the use of a twin scroll or sequential turbo or turbo+ supercharger combinations.
- Since the turbo and reciprocating engine operate as a system, spark retard can result in improved power up to a point while allowing reduced octane requirement. Hence, response to fuel octane number can be complex.

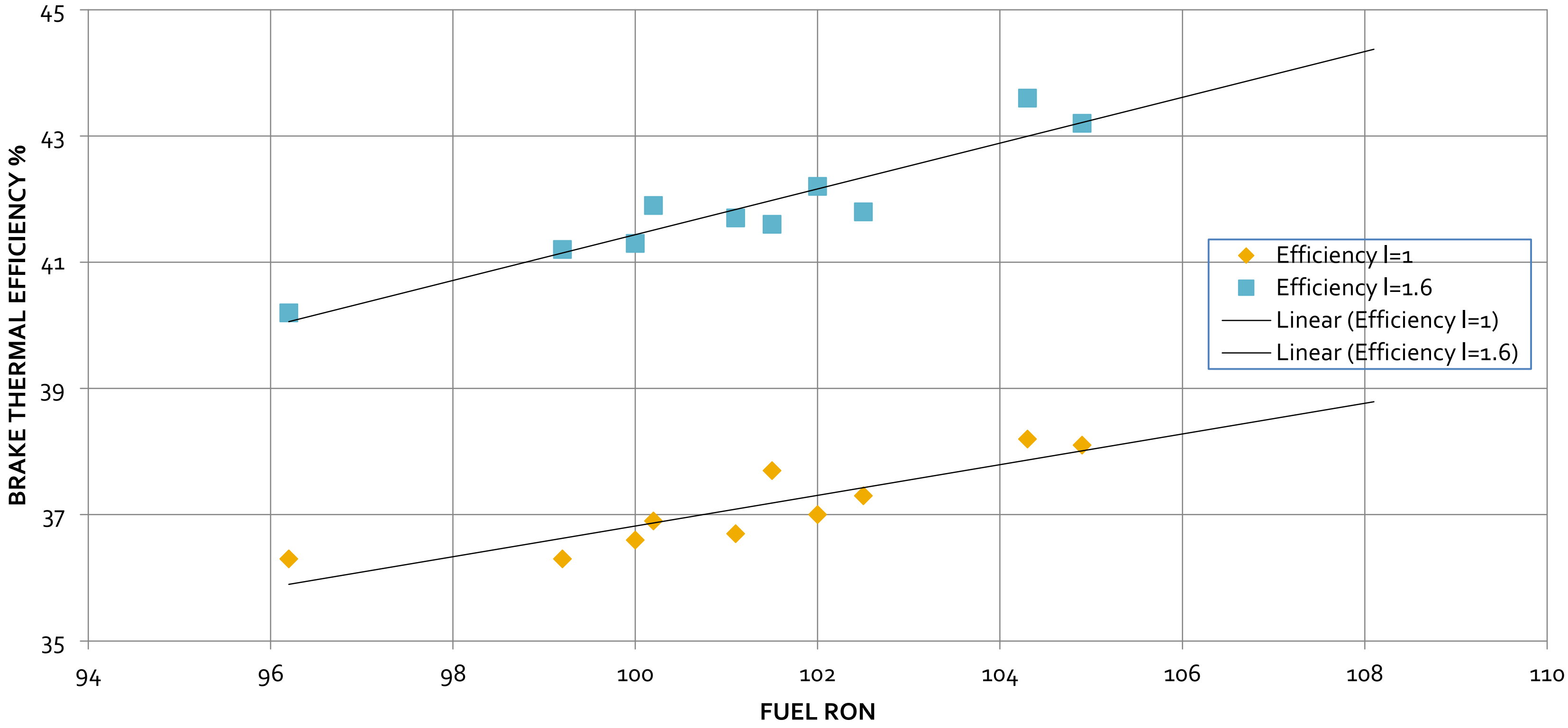
TORQUE vs. RPM WITH DIFFERENT FUEL
TURBOCHARGED PFI ENGINE CR = 9.5



Response to Octane

- While the response of turbocharged engines to fuel octane is complex, octane has a favorable effect on peak power and torque, which also implies improved efficiency.
- Modern PFI and DI engines with turbo-charging can have a significant boost in efficiency at mid-range RPM levels of 1500 to 4000 RPM. Typically a turbocharged DI engine employs a CR of 10 to run at 19 bar BMEP, but higher CR reduces maximum output due to spark retard.
- At the mid RPM range, the IMEP can increase by 5 bar for every 4 to 5 points increase in octane number. Limited data on thermal efficiency and octane number shows almost a 0.5% increase in efficiency per octane point.

EFFICIENCY vs. FUEL OCTANE NUMBER TURBOCHARGED PFI ENGINE, CR = 13



Two Fuel Strategy

- At part loads below 8 bar BMEP, the engine ONR is quite low, below 90 RON. The vast majority of driving time is at light load implying that the fuel octane is wasted. A new solution is to separate tank fuel into low octane and high octane components, like separating E10 into E3 and E50. The fuel separator stores the lower volume high octane fuel and uses the low octane fuel directly.
- The high octane fuel is used only as needed but the relative volumes of fuel used will depend on the drive cycle requirement.
- Honda compared a 1.5L engine with 12.5 CR using the two-fuel system to a 1.8L engine with 10.5 CR and found very large benefits in fuel economy of ~25%. Some of this benefit is due to the use of Atkinson cycle on the 12.5 CR engine.

Findings for Naturally Aspirated Engines

- The benefits of increased octane for naturally aspirated engines is reasonable clear from the data.
- The data shows that a 4 to 5 point increase in octane number allows a one point increase in CR, or a spark advance increment of 5 to 7 degrees.
- The benefits to engine thermal efficiency from increased CR or spark advance are non-linear and depend on the starting point.
- The benefits are lowest for small bore engines which have lower octane requirements relative to medium bore or large bore engines. For a medium bore engine starting at 10 CR, a 4 to 5 octane point can allow a 2% to 3% improvement in thermal efficiency. Vehicle efficiency improvement can be larger since engine output increases with increased CR.

Findings for Turbocharged Engines

- Turbocharged engines have multiple limitations on boost and efficiency so the response to fuel octane number is critically dependent on the operating condition.
- At mid-range RPM, increases in fuel octane can lead to significant improvements in available torque and efficiency. Limited data suggests that IMEP can increase by 4 bar for a 4 to 5 point increase in fuel octane number, and efficiency can increase by almost 0.5% per unit increase in octane number.
- In this context, it may be preferable to increase boost at constant CR with higher octane fuel and downsize the engine more to improve fuel efficiency. Increasing boost from 19 bar to 23 bar BMEP with higher octane fuel allows almost 20% engine downsizing with a 5% vehicle fuel economy benefit.

Implication of Engine Technology

- While octane benefits starting at a base engine with 10.5 to 11CR are reasonable, the benefits decline with increasing CR.
- Average engine CR has been increasing continuously for the last 30 years and new technologies suggest that they will increase by 1.5 to 2.0 CR from 2010 to 2025. This implies decreasing value of octane in the future.
- Octane waste at part load suggests that the fuel splitting solution into low and high octane components, if proven, may provide engine designers more flexibility without having to introduce new high octane fuels.

Final

- Thank You!