Co-Optimization of
Fuels & Engines

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Technical Deep-Dive

Co-Optimia Stakeholder Conference Call

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VTO Management: Gurpreet Singh, Kevin Stork, Leo Breton, and Mike Weismiller

The Use of Transient Operation to Evaluate Fuel Effects on Knock Limits Well Beyond RON Conditions in Spark-Ignition Engines

David Vuilleumier and Magnus Sjöberg
Sandia National Laboratories

SAE Paper 2017-01-2234

SAE INTERNATIONAL
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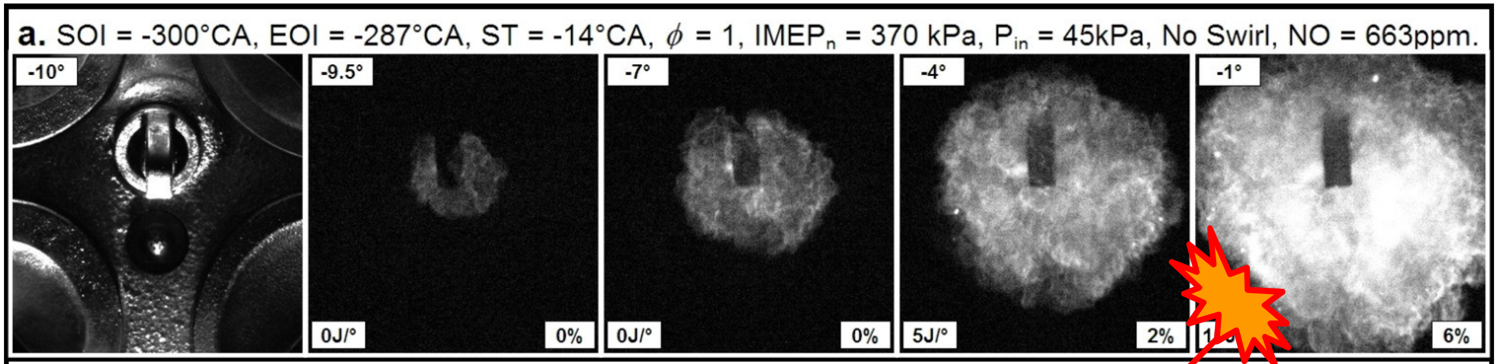
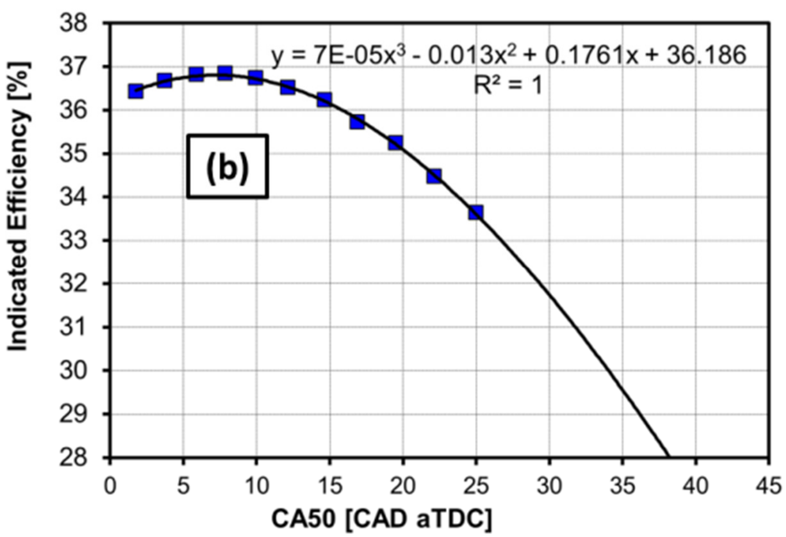
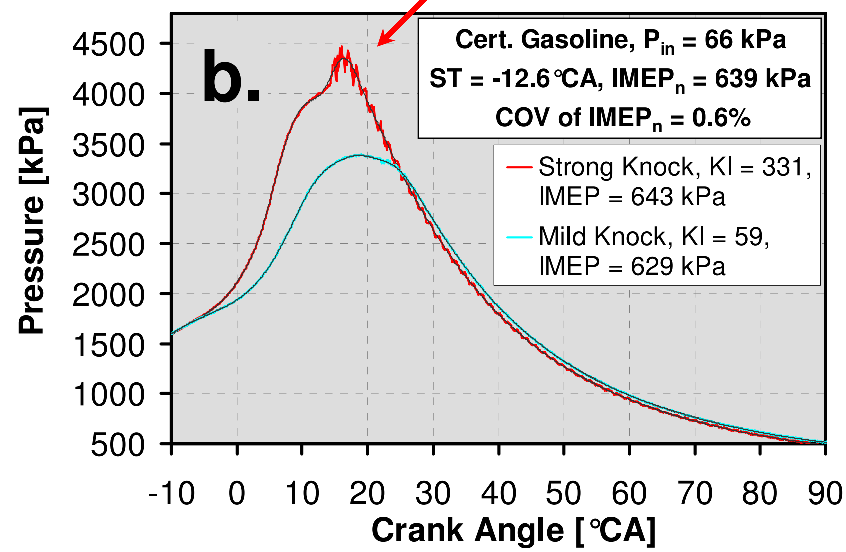
Introduction







- Efficient operation of SI engines requires combustion phasing near 10°CA.
- In practice, knocking significantly inhibits SI engine efficiency by forcing delayed combustion phasing.
- Knocking also prevents increases in engine compression ratio.
- Anti-knock quality of fuel is important.

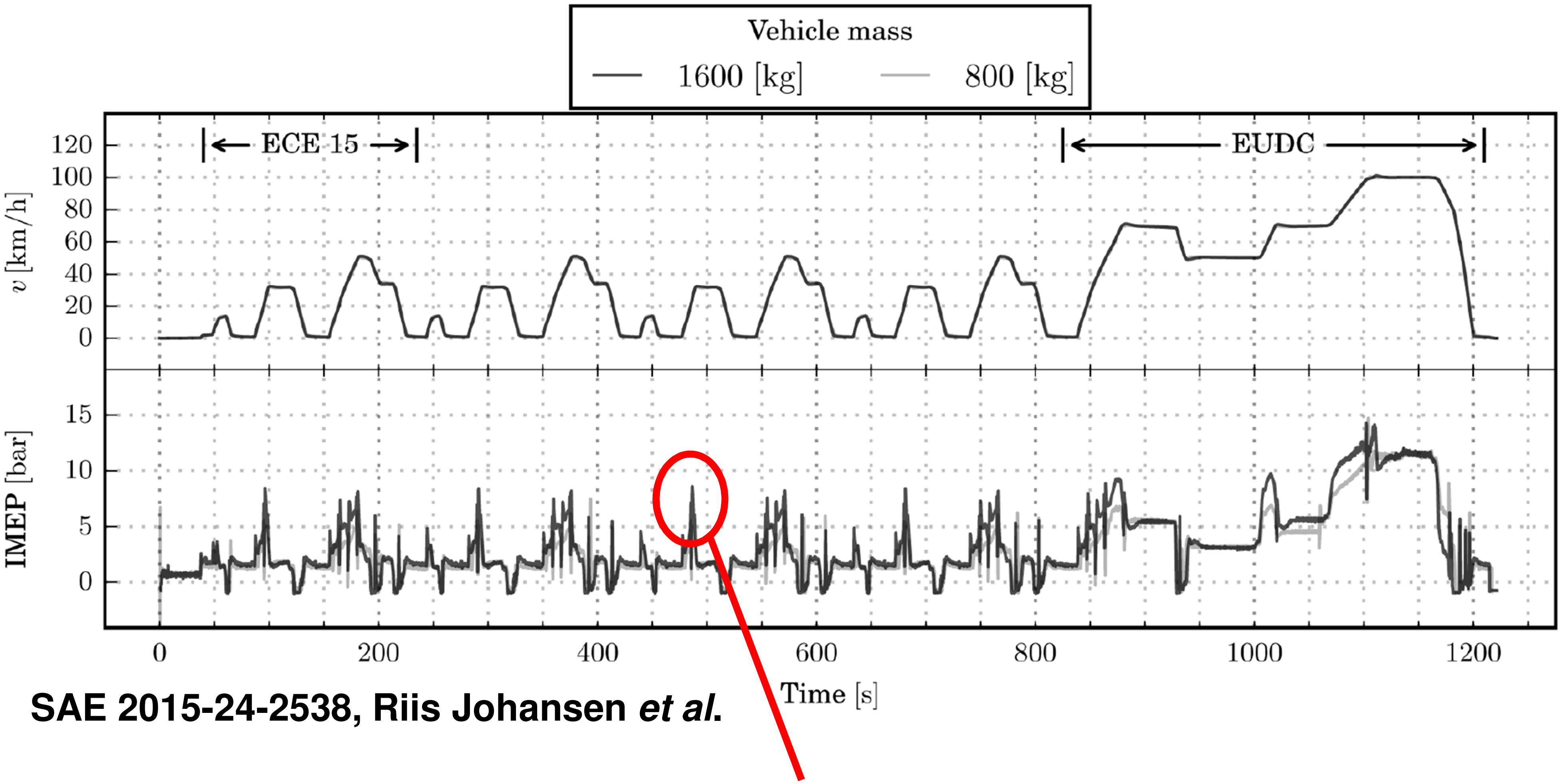
Fuels Matrix

- Customer selects fuel based on AKI or RON.
- However, RON and MON are both important.
- Here, study three RON = 98 fuels, and one regular E10 gasoline.
- S = RON – MON.
- Octane sensitivity and composition vary greatly.

	E10 RD5-87	Alkylate	E30	High Aromatic
AKI	88	97	93	93
S	7	1	10	11
RON	92	98	98	98
MON	85	97	88	87
Ethanol [vol.%]	11	0	30	0
Aromatics [vol.%]	21	0	8	31
T90 [℃]	?	106	155	158

Relevance of RON & MON for Transients?

- RON and MON are determined for steady-state conditions.
- Actual vehicle operation is usually not steady-state.

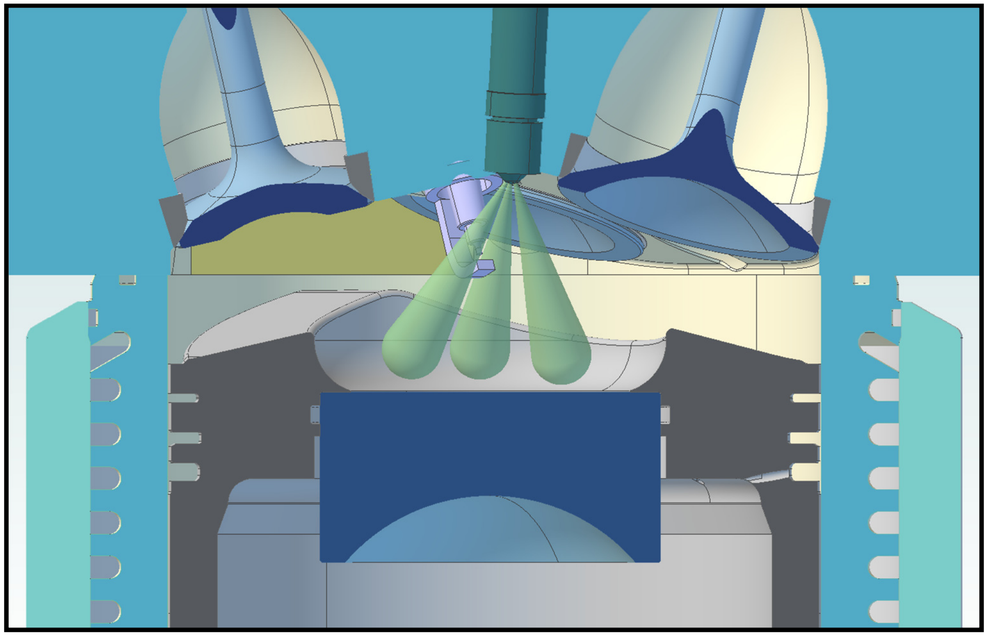


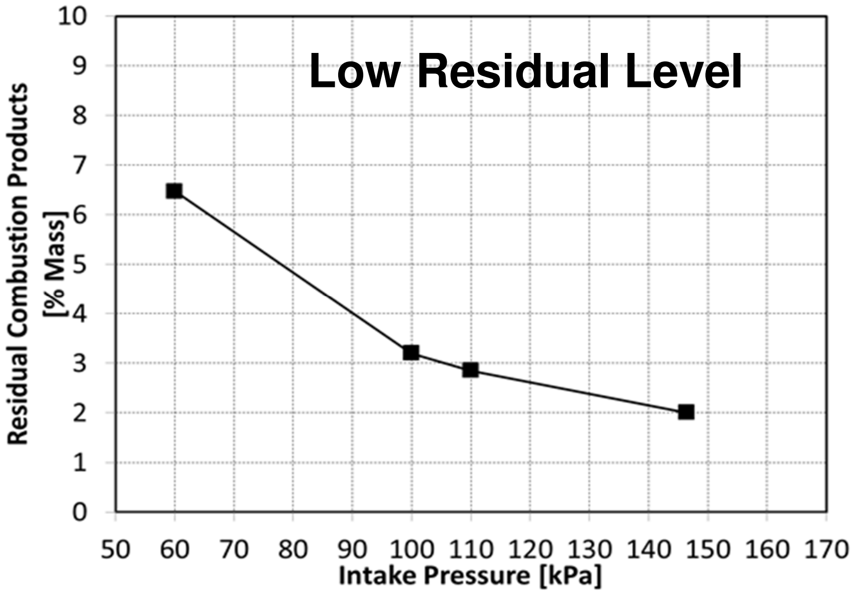
SAE 2015-24-2538, Riis Johansen *et al.*

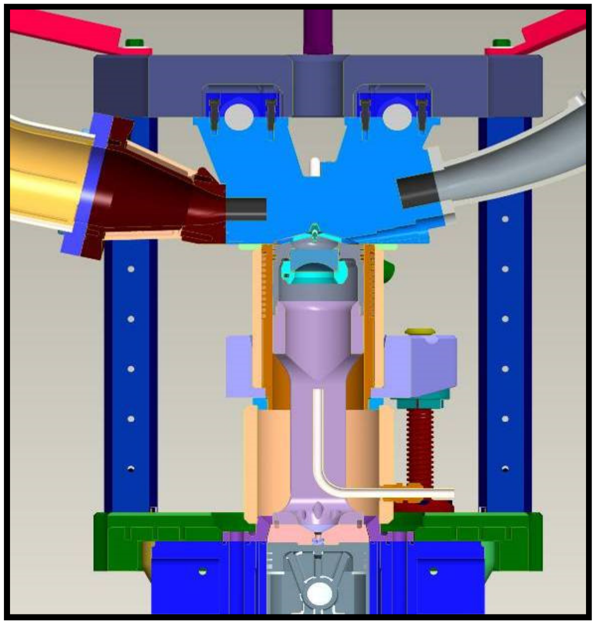
- What is the relevance of RON and MON for load transients?

Research Engine Characteristics

- DISI, CR = 12:1, 0.55 L.
- Well-mixed charge operation.
  - 3- or 4- injection strategy for low PM emissions.
- Single intake valve.
  - Intake swirl.
  - No valve overlap.

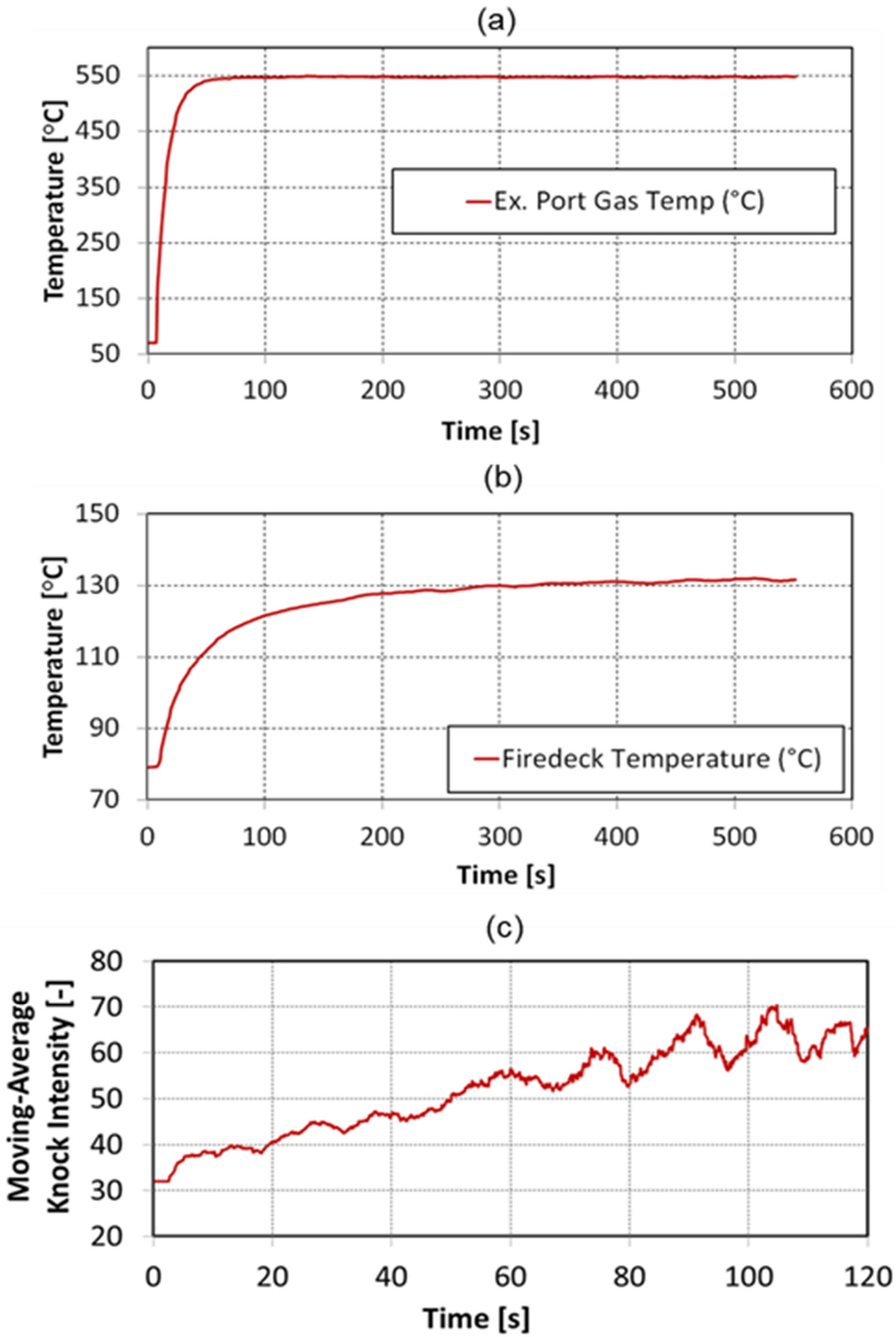






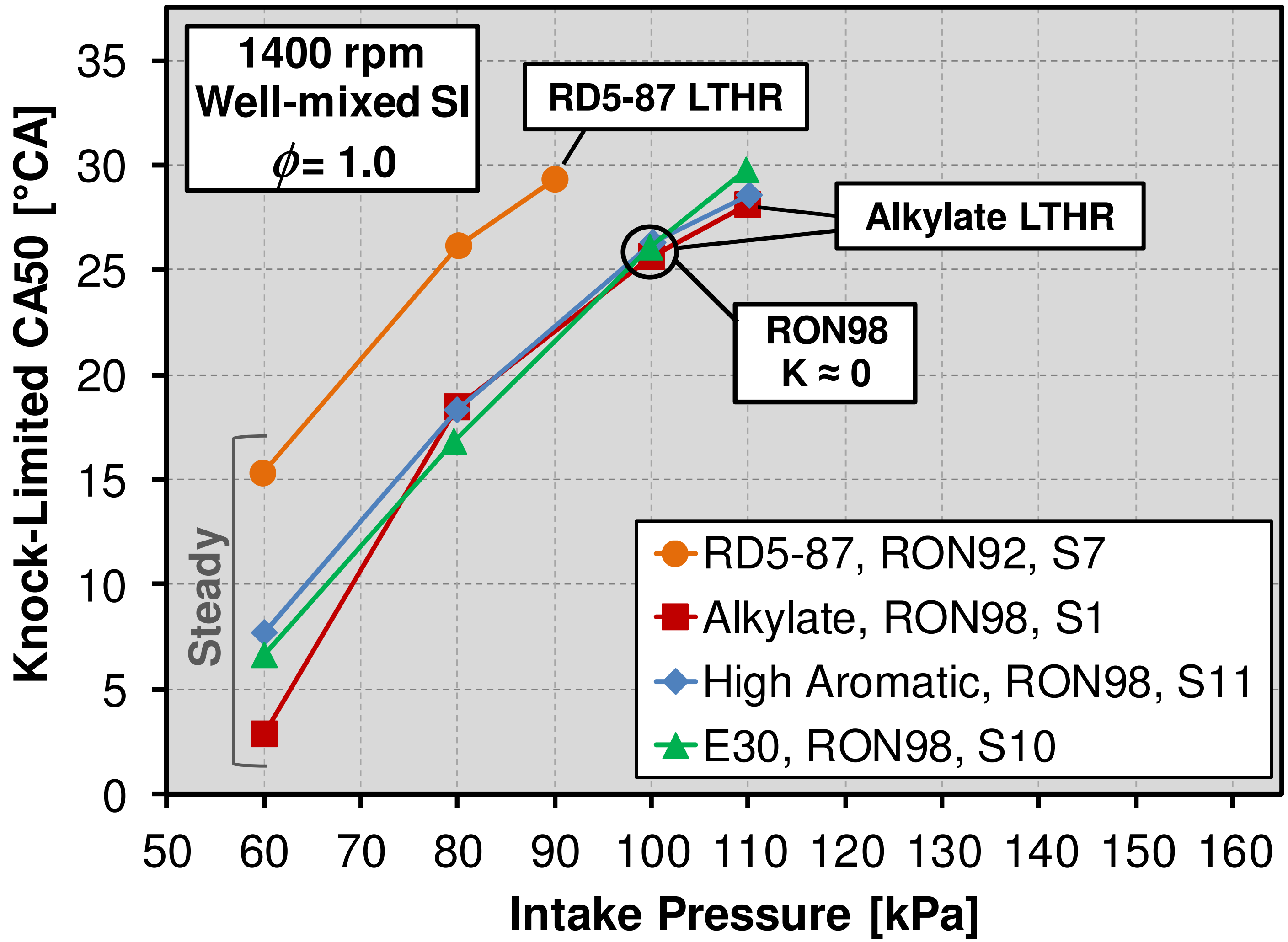
Establish Steady-State

- Motored to steady-fired operation.
- E30 fuel, P_{in} ≈ 79 kPa, ST = -5.6°CA.
- Time constants ≈ 10's of s.
- True steady-state KL operation is not achieved for many minutes.
- Adjust Spark Timing (ST) to achieve Knock Intensity (KI) ≈ 70 kPa.
- Record 500 consecutive cycles.
- Report average CA50 as KL-CA50.

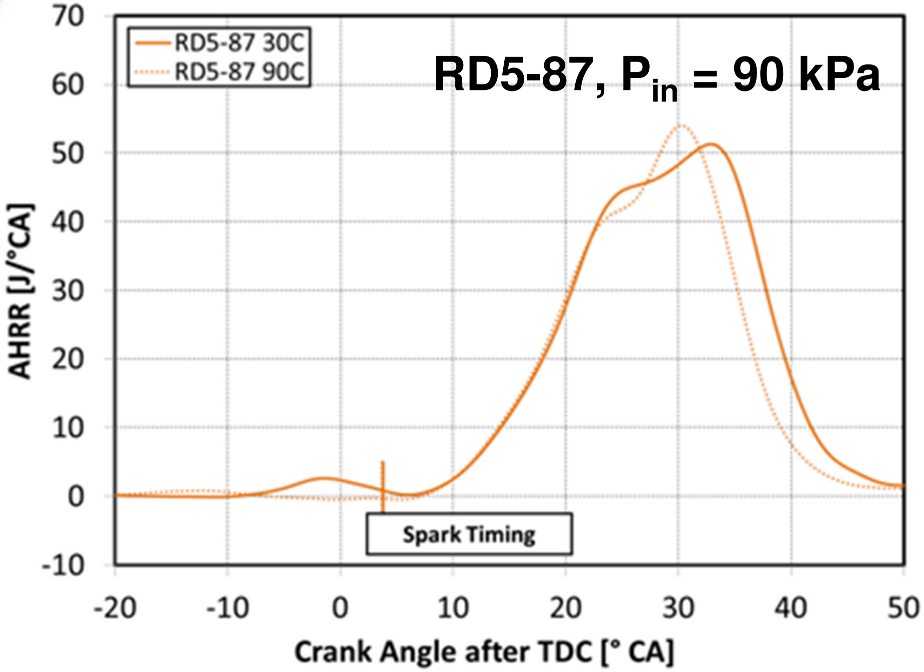


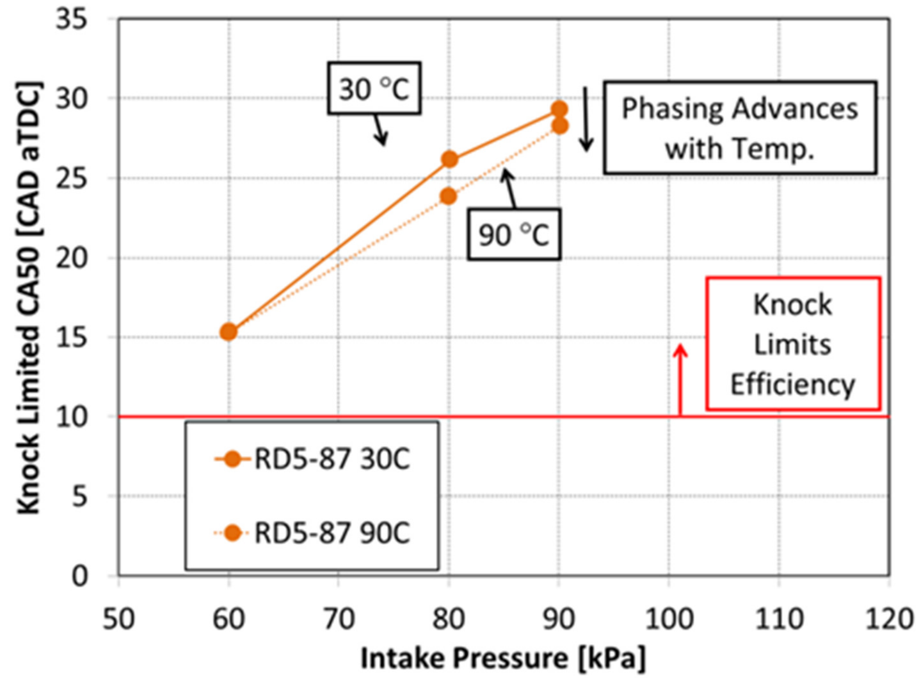
Steady-State Operation Reveals Benefit of High-RON Fuels

- RON98 fuels provide knock suppression benefits, compared to RON92 fuel.
- RD5-87 develops low-temperature heat release (LTHR) at highest P_{in}.



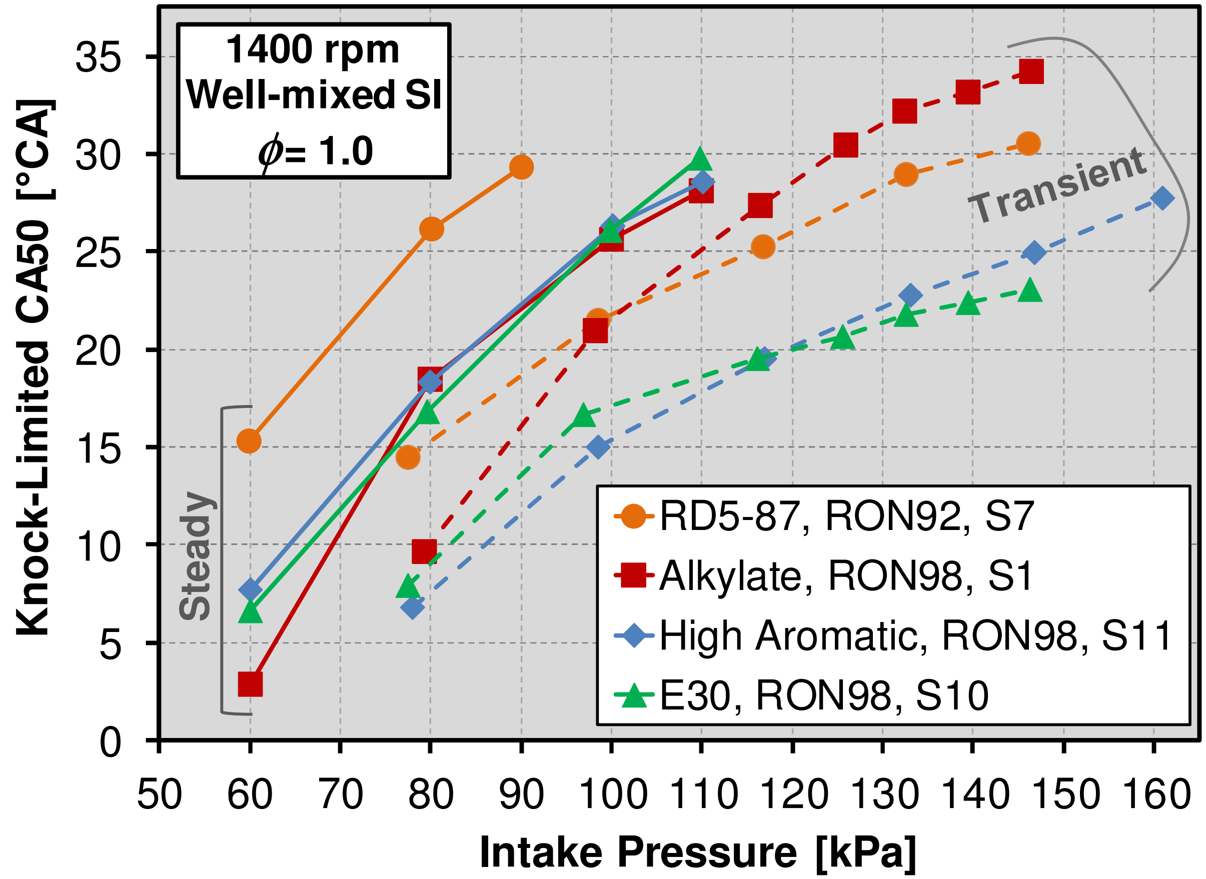
RD5-87 and Alkylate Exhibit NTC Behavior





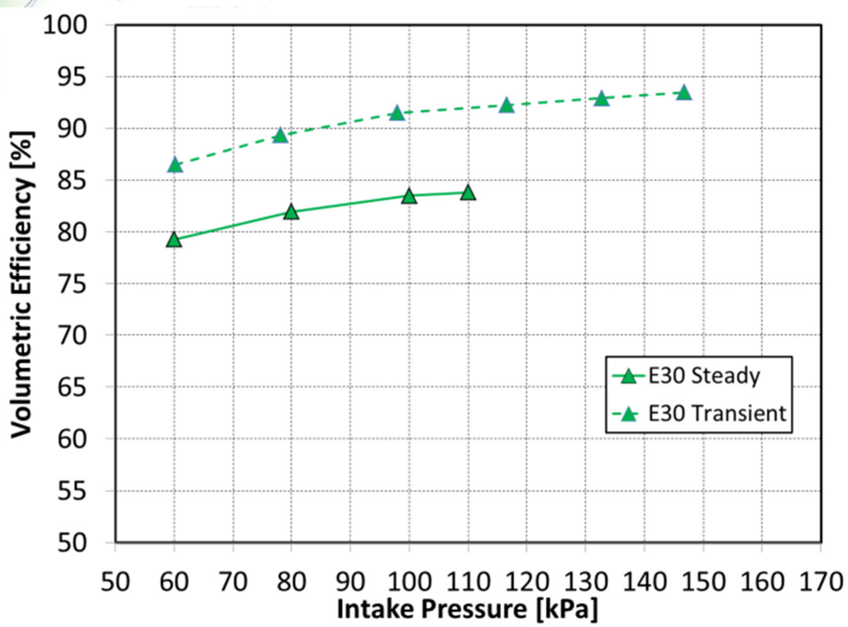
- RD5-87 develops LTHR at highest P_{in}.
- Increased T_{in} suppresses LTHR, and KL-CA50 advances.
- RD5-87 and Alkylate both show clear NTC behavior in this regime.
  - See SAE Paper 2017-01-0662 for detailed examination of RON98 fuels.
- Even so, the reduction of temperatures for load-transient operation provides strong knock-suppression benefit for all fuels ⇒

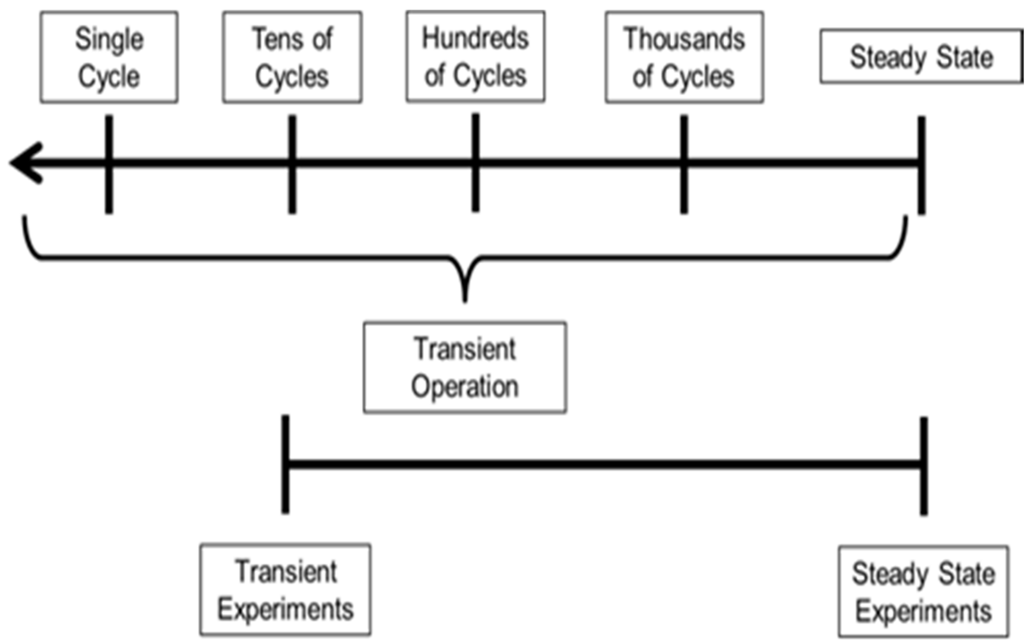
Load-Transient Operation Reveals Benefit of High-S Fuels



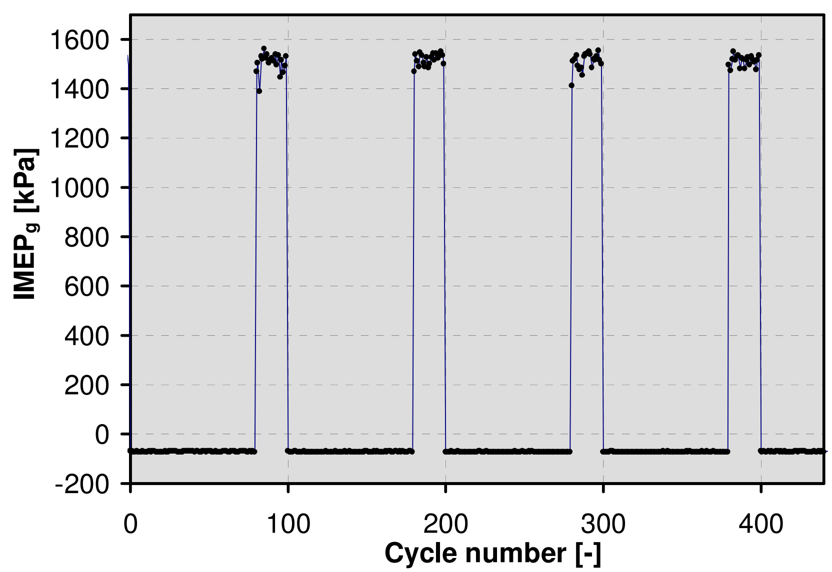
- The reduction of temperatures for load-transient operation provides strongest knock-suppression benefit for fuels with moderate to high S.
- Smallest benefit for low-S Alkylate.
  - Alkylate fuel is deep into NTC regime for steady-state operation.
  - Displays LTHR even for cooler transient operation.

Test Regimes: Steady State and Transient

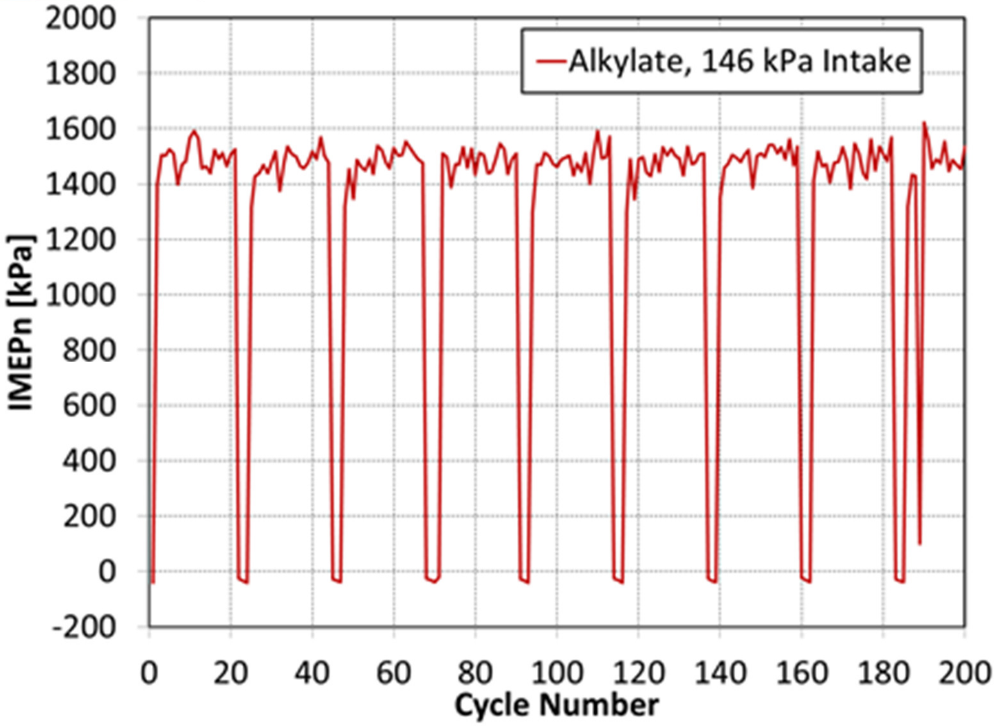


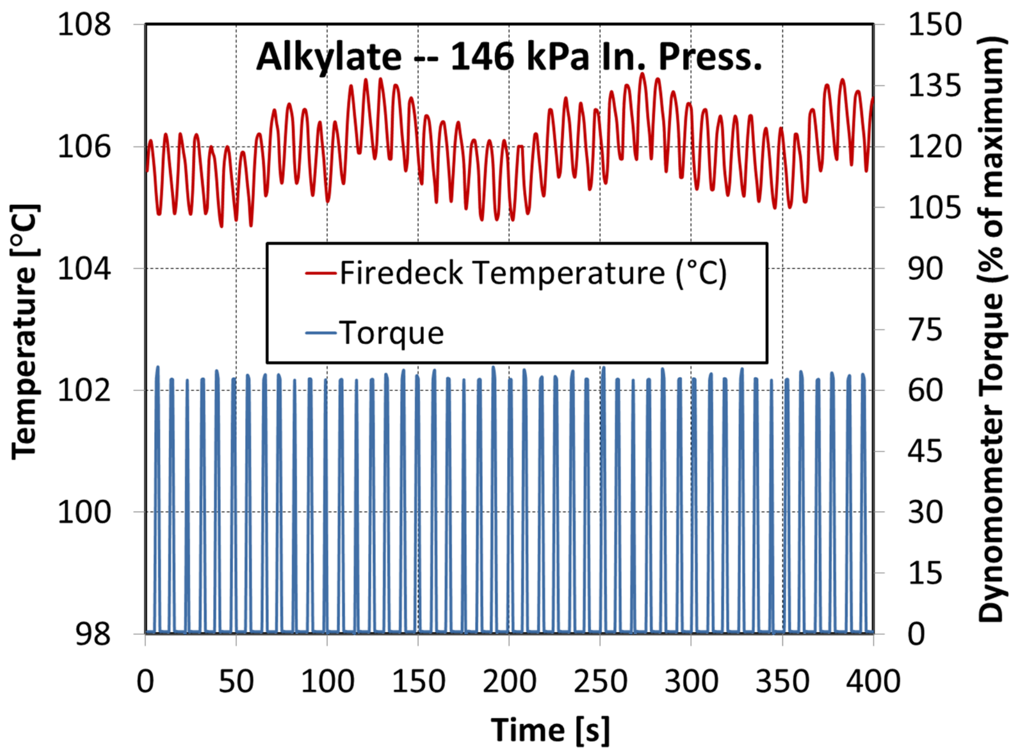


- First fired cycle likely not representative of real operation.
  - Cold air-only residuals.
- Consider 10's of cycles, by operating in a 20 fired / 80 skipped mode.
- Lower thermal state is evidenced by higher volumetric efficiency.



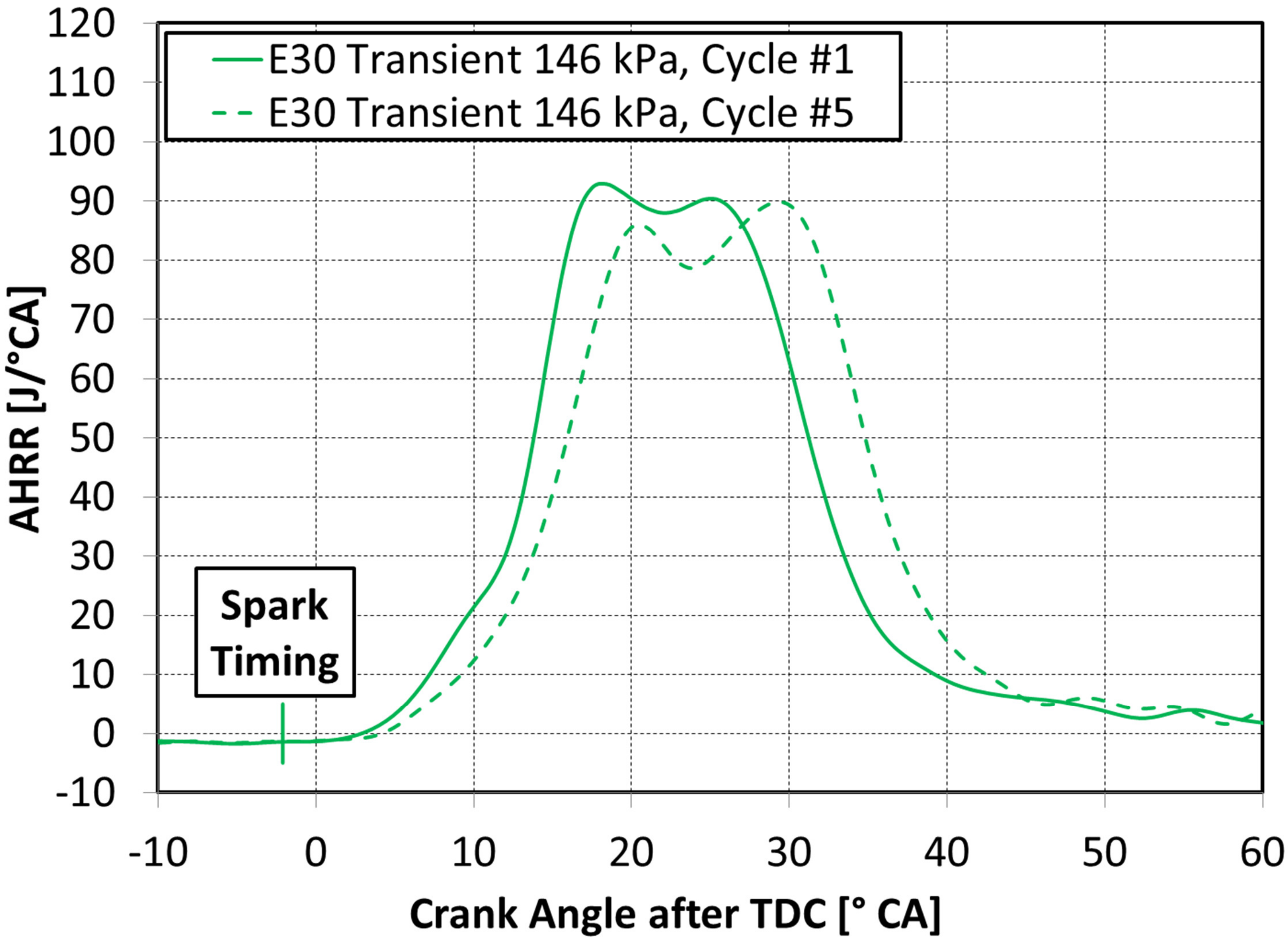
Data Collection: 20/80 Firing Cycle





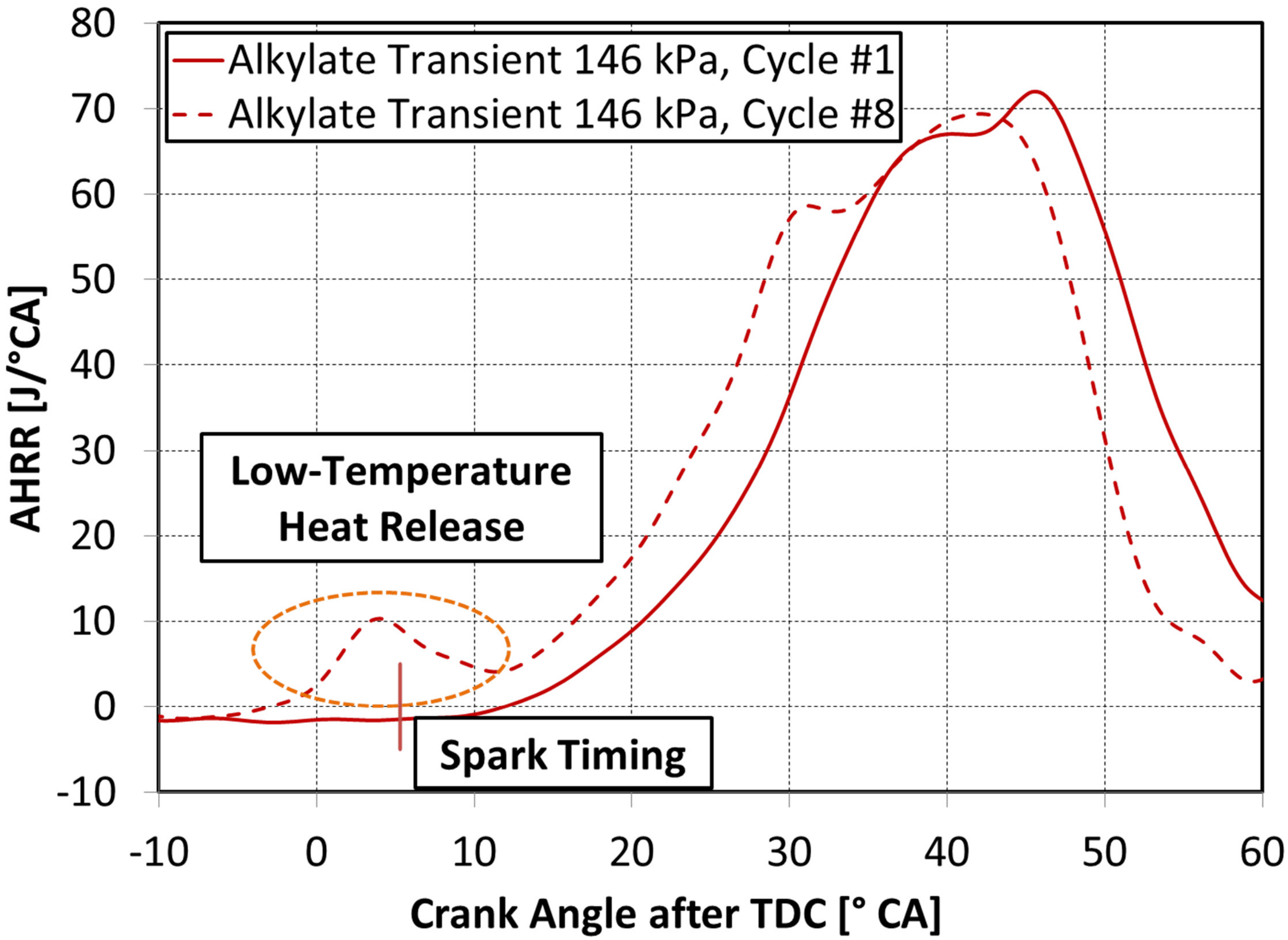
- 20 fired cycles followed by 80 motored cycles
  - Only 3 motored cycles are recorded – 1 ahead of sequence and 2 afterwards.
  - **50 repetitions** of 20/80 sequence are recorded = **1000 fired cycles**.
- Fluctuations seen in both firedeck temperature and dynamometer torque
  - Effects of 20/80 sequence and cooling-water control.
  - Firedeck temperatures 25°C lower than steady-state KL operation.

E30 Heat Release



- E30 exhibits consistent AHRR across batch of 20 cycles
- Highly repeatable end-gas autoignition observed, which leads to light knock

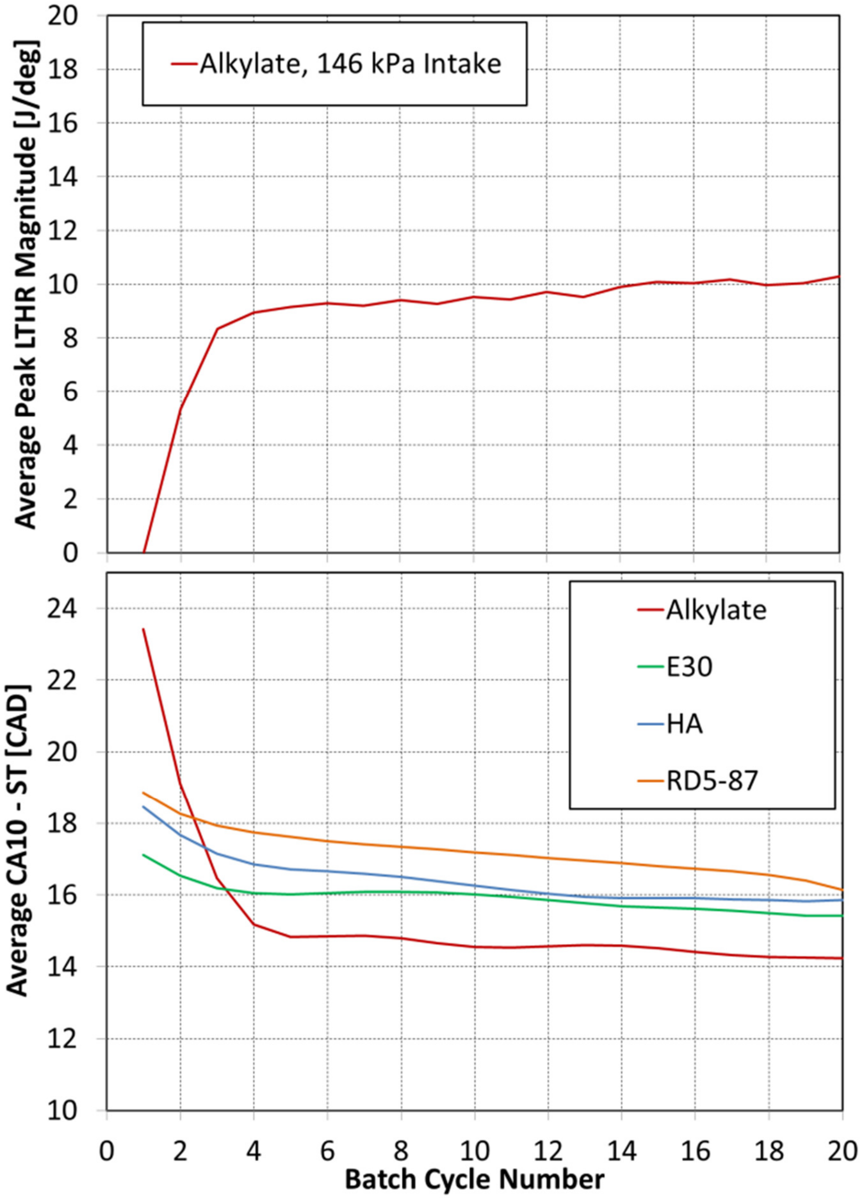
Alkylate Heat Release



- Alkylate AHRR exhibits strong transient behavior for each 20-cycle batch.
- LTHR never occurs on first cycle, but occurs on all subsequent cycles.
- End-gas autoignition exhibit greater variation $\Rightarrow$ occasional strong knock.

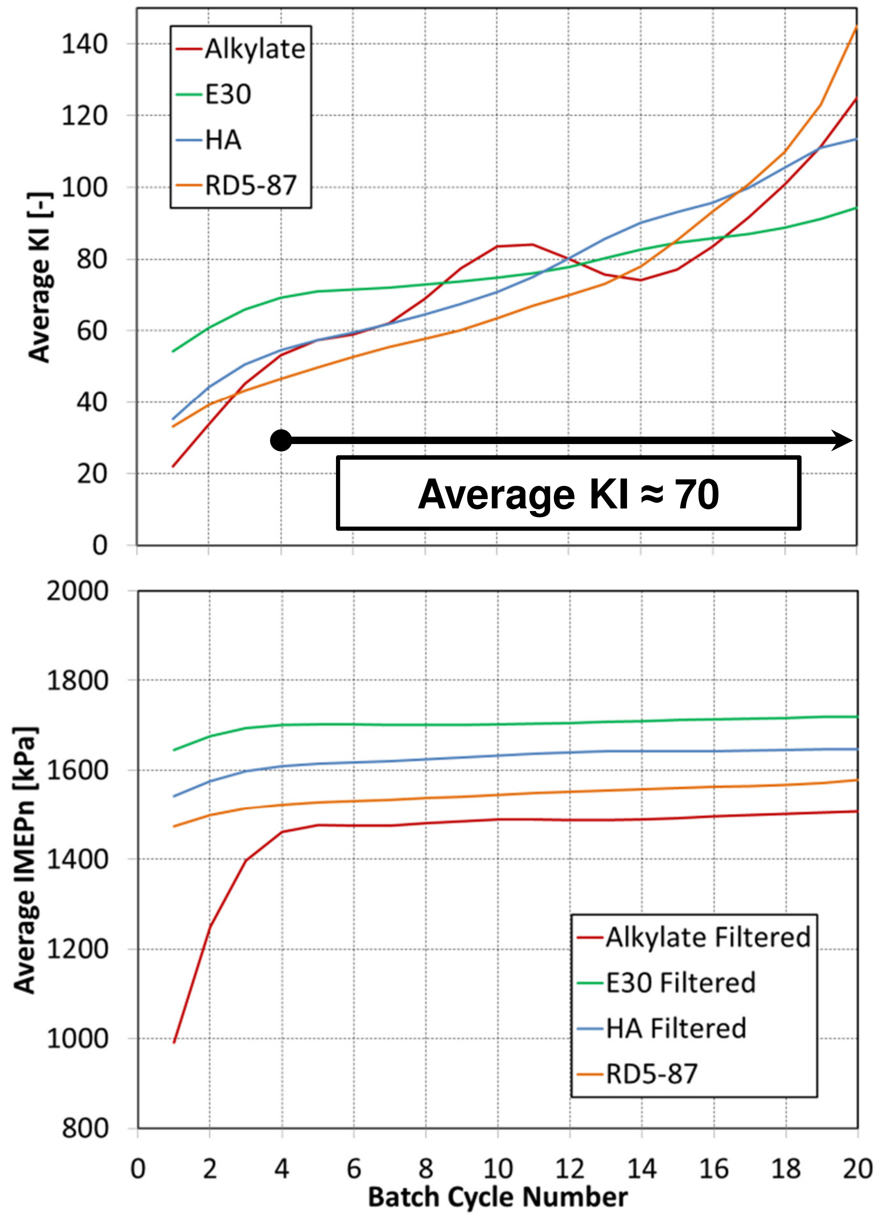
20-Cycle Transient

- Only Alkylate shows clear LTHR for 20/80 load-transient operation.
- LTHR magnitude builds rapidly when firing starts for each 20-cycle batch.
- Alkylate flame development is very slow without LTHR.
- Averages are based on 50 repetitions.



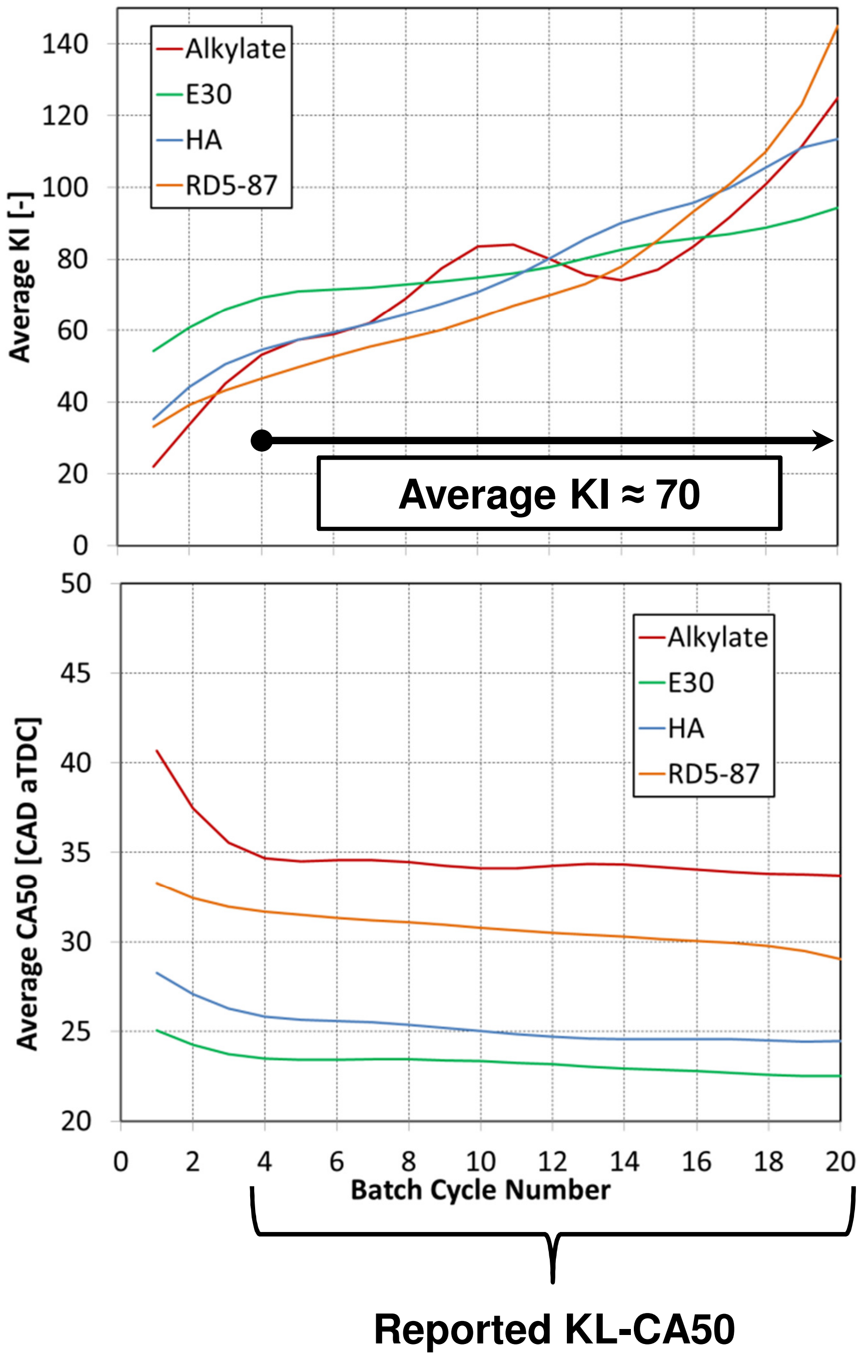
20-Cycle Transient

- IMEP approaches quasi-steady state surprisingly quickly.
- Alkylate was prone to misfire on the first cycle.
  - Slow flame development.
  - Alkylate never knocks on first cycle.
- Generally, Knock Intensity increases steadily for all fuels.
- Spark timing adjusted for KI ≈ 70 for last 17 cycles.



20-Cycle Transient

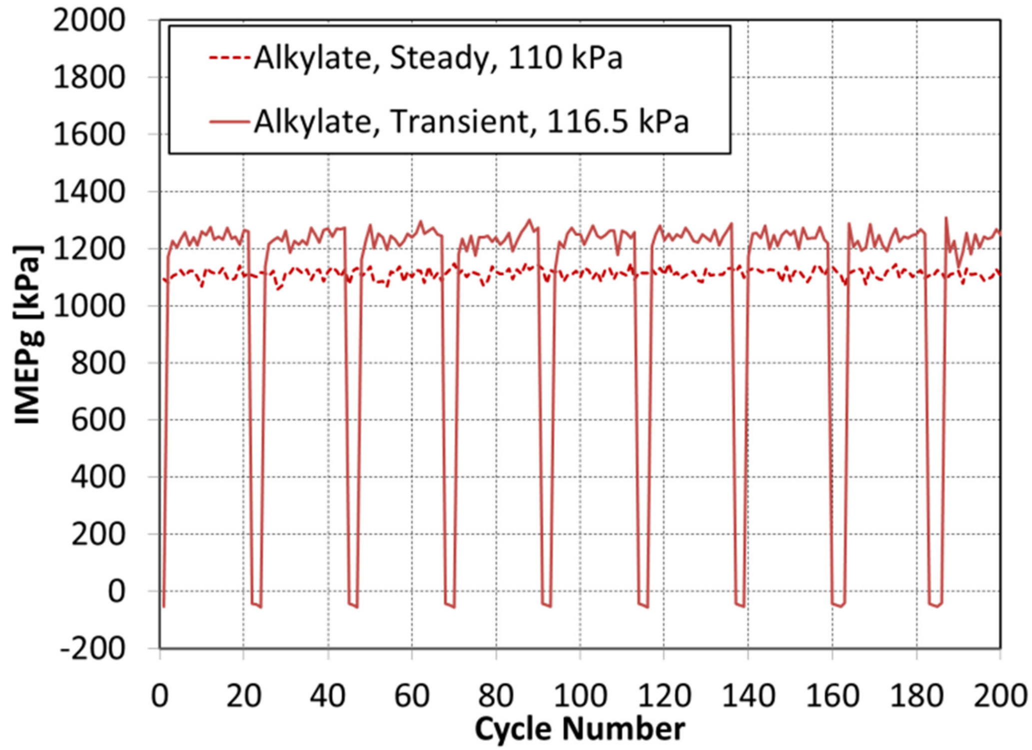
- Spark timing adjusted for KI ≈ 70 for last 17 cycles.
- Average of last 17 cycles reported as KL-CA50.
  - Eliminates effect of residual transient.



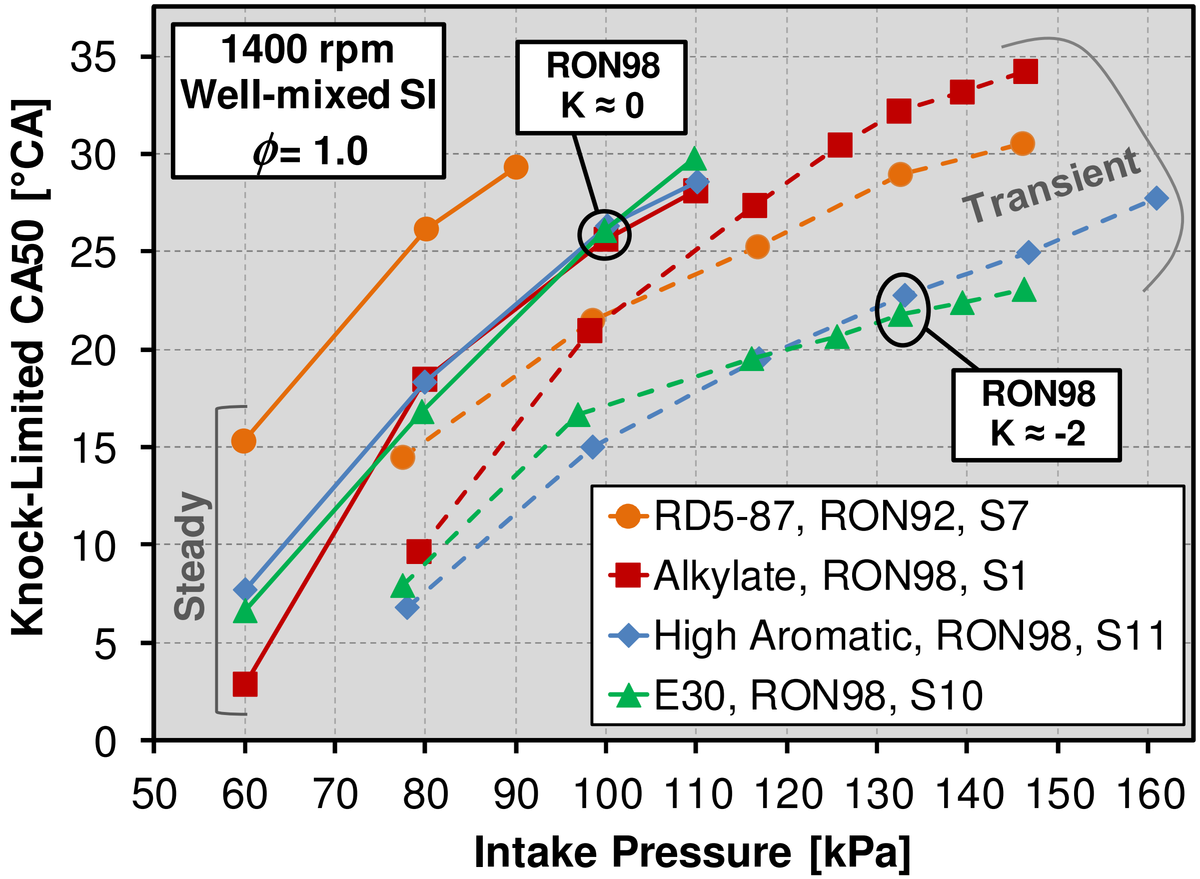
Stability of 20-Cycle Transient

- Across full 20-cycle batch, IMEP variability is higher than steady-state.
- However, COV of last 17 cycles is comparable to steady-state.
  - When residual transient is excluded.

Fuel	Alkylate	Alkylate
Intake Pressure	110 kPa	116.5 kPa
Operation	Steady State	Transient
KL-CA50	28.1 CAD aTDC	27.3 CAD aTDC
COV IMEP	1.6 %	-
COV IMEP All 20 Fired	-	7.8 %
COV IMEP Final 17 Fired	-	1.9 %

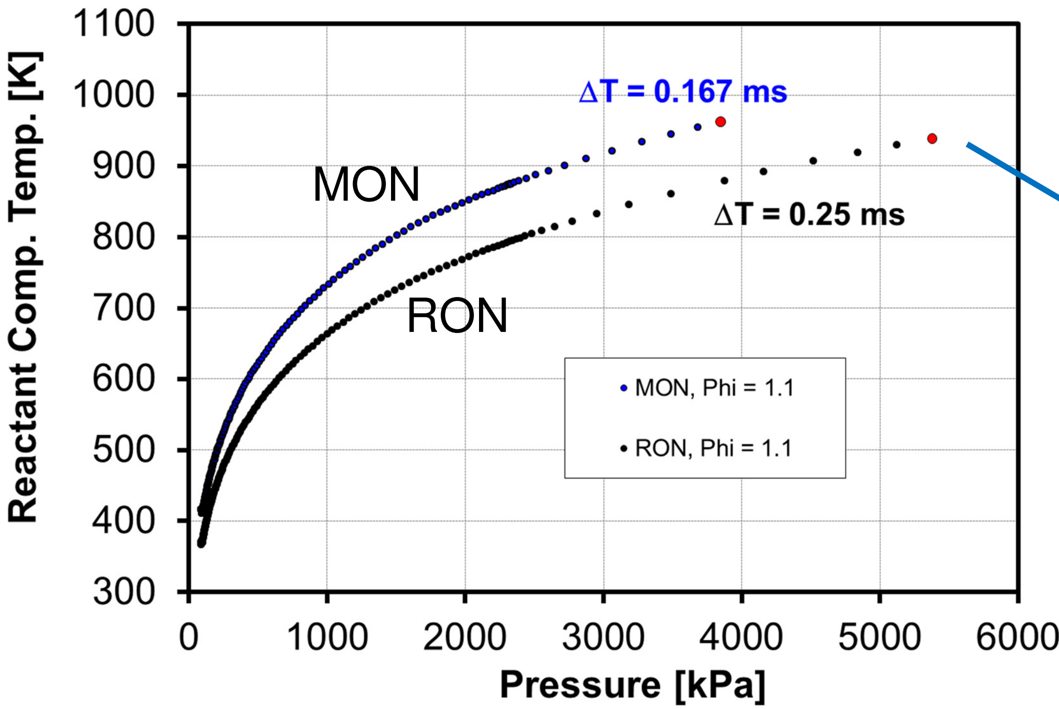


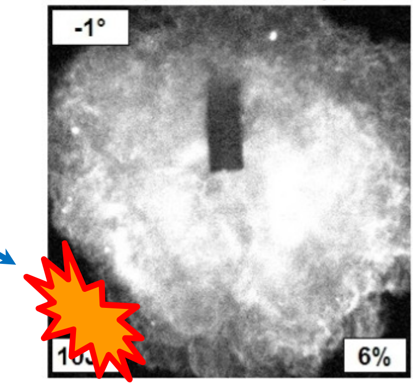
Load-Transient Operation Reveals Benefit of High-S Fuels



- Steady-state: All RON98 fuels provide knock suppression benefits, compared to RON92.
- Load Transient: RON98 low-S Alkylate fuel (AKI = 97) is outperformed by RON92 RD5-87 (AKI = 88).
- Put these results in context of Octane-Index framework.

Octane Index Framework



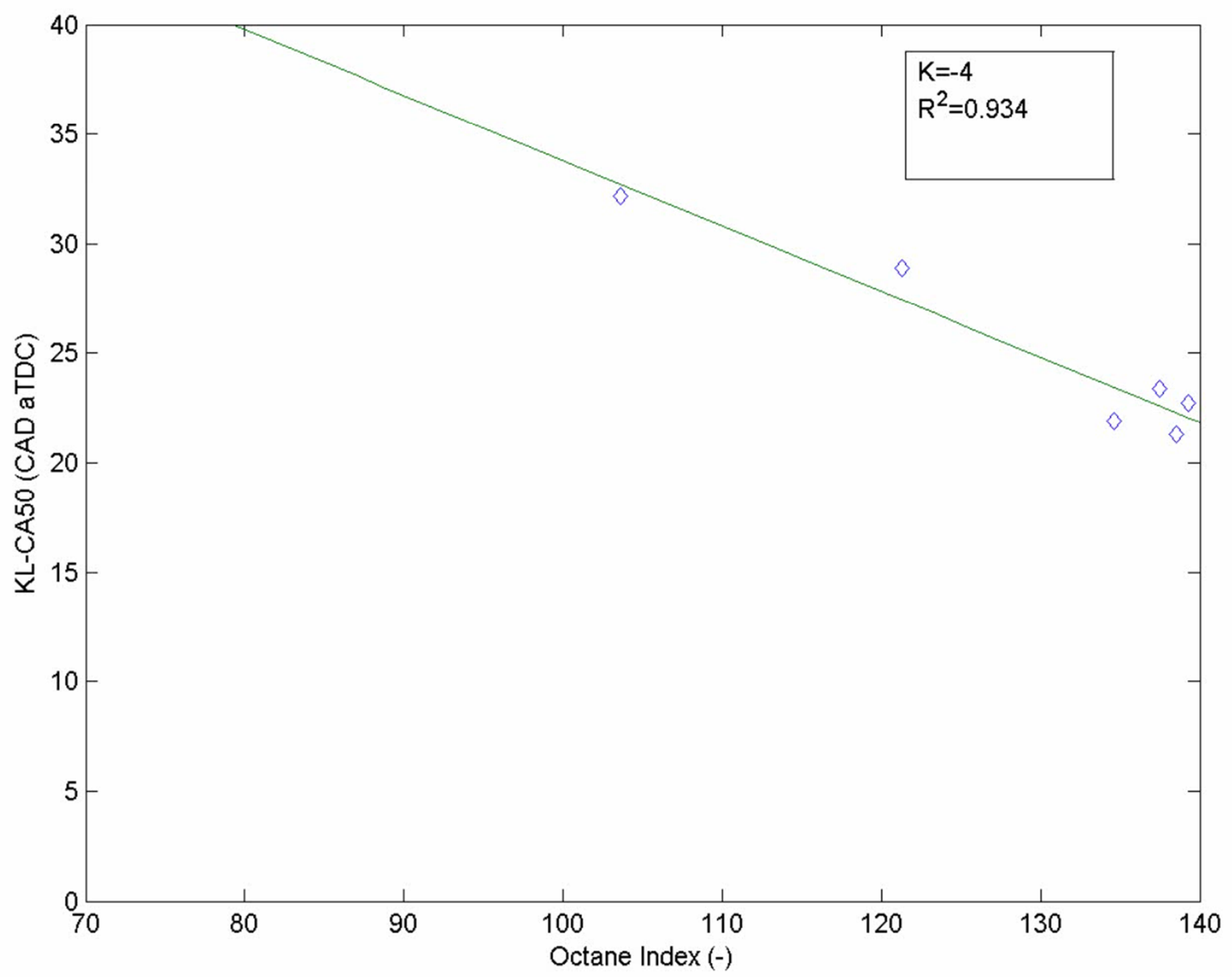


Beyond MON ← → **Beyond RON**

K > 1 Ex: Heated intake / high residuals HCCI	Lower pressure for a given temperature K=1	Higher pressure for a given temperature K=0	K < 0 Ex: Boosted SI, GCI

OI Reference: Kalghatgi, SAE 2001-01-3584.

Calculation of K



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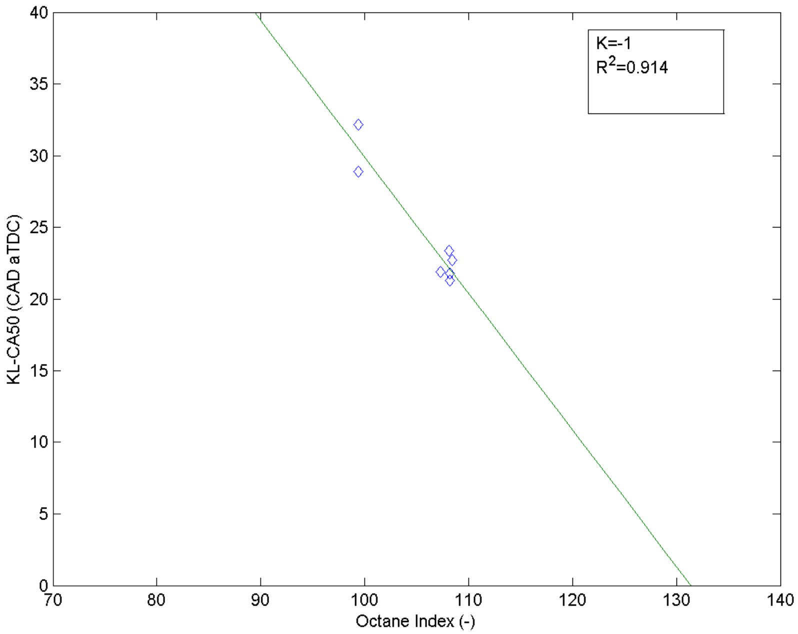

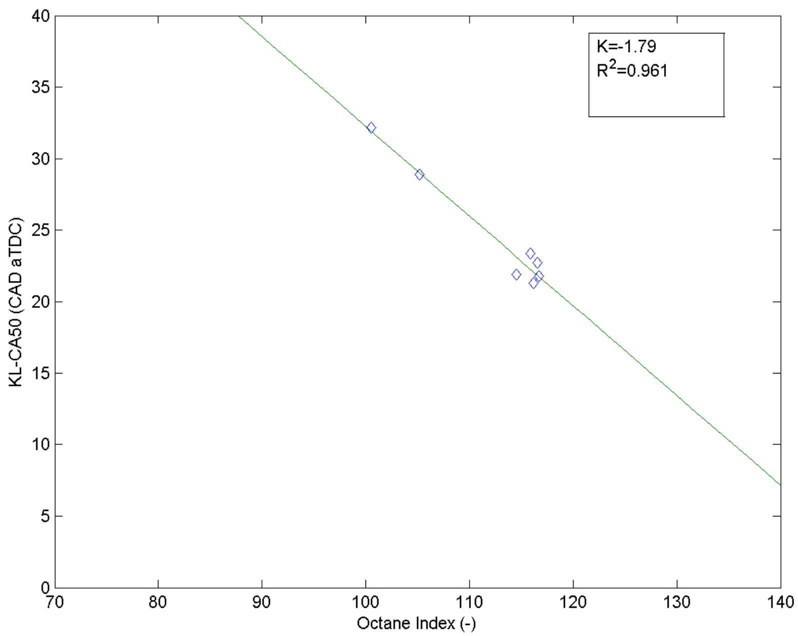

$$\text{Octane Index} = \text{RON} - K \cdot S$$

- Linear regression between KL-CA50 and Octane Index (OI) values to determine K at each operating condition
- Sweep across range of K values
- Calculate OI for each fuel for each K value
- Determine which K value yields best fit between OI and KL-CA50 data

K-Factor

- Steady-state operation falls between K = 0 and K = 0.5.
  - T_{in} = 30 °C or 90 °C
- Only for heated and throttled that AKI97 fuel is superior.
  - Customers hoping for a winning race fuel may be disappointed.
- Transient operation result in K < 0, "beyond RON" conditions.
- Realistic?

	E10 RD5-87	Alkylate	E30	High Aromatic
AKI	88	97	93	93
S	7	1	10	11
RON	92	98	98	98
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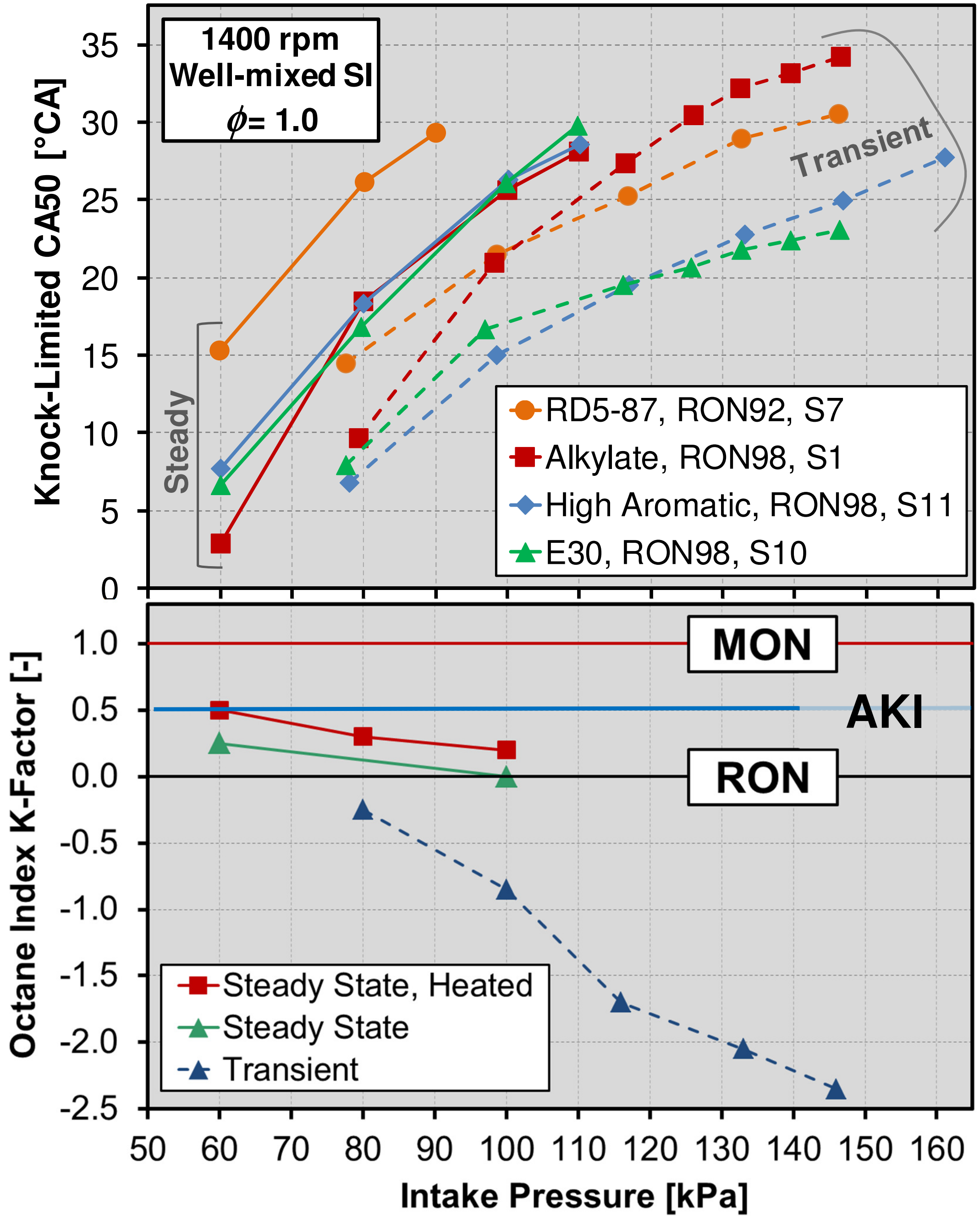
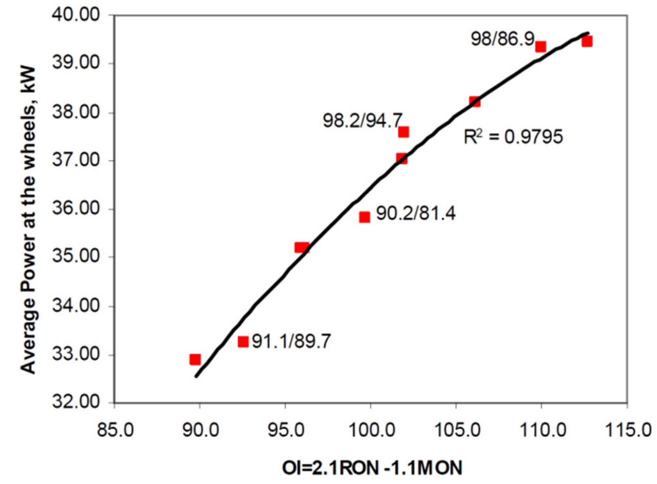
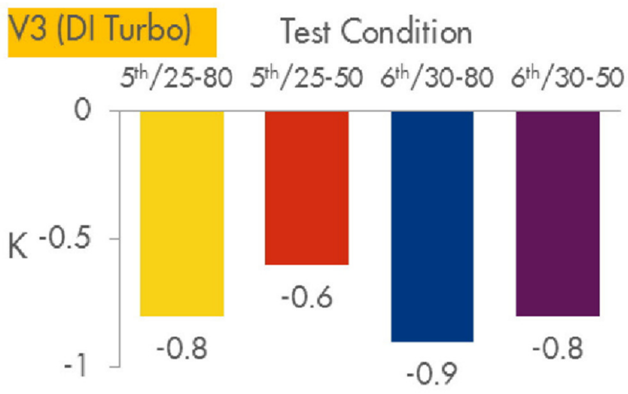


K-Factors for Actual Vehicle Operation

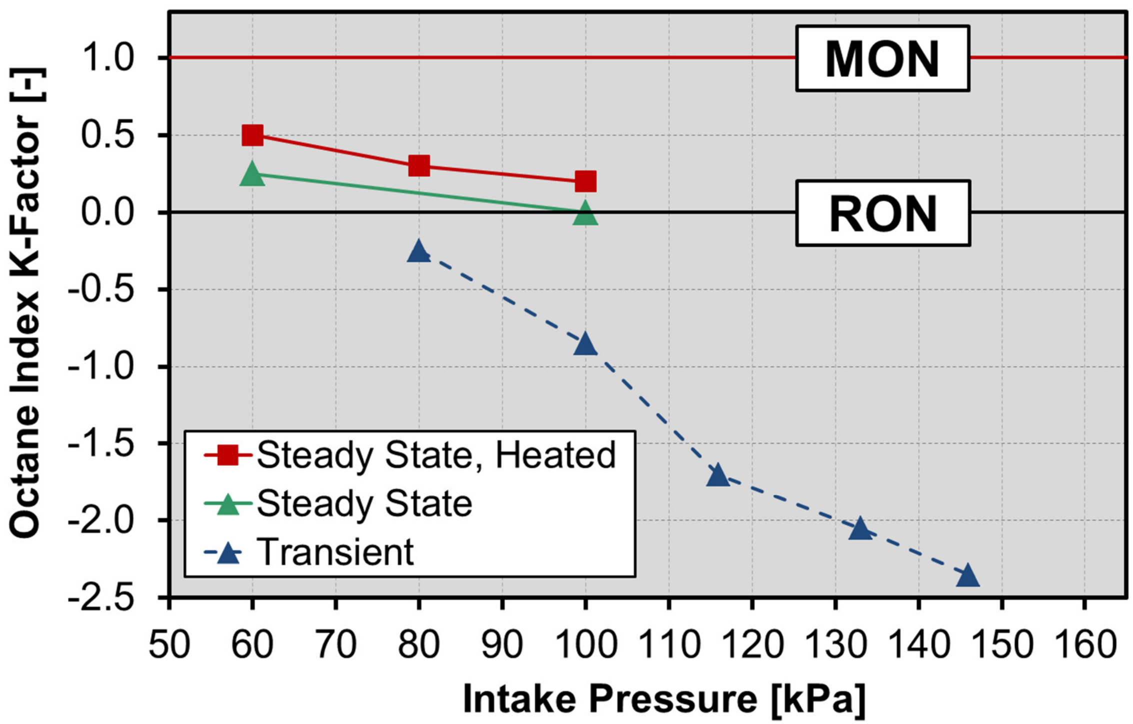
- These highly negative K-factors are consistent with literature.
- Naturally aspirated PFI 2003 Mercedes CLK1: K = -1.1 during high-gear acceleration.
- Turbocharged DISI 2012 vehicle: K = -0.6 to -0.9

Kalghatgi, SAE 2005-01-0239

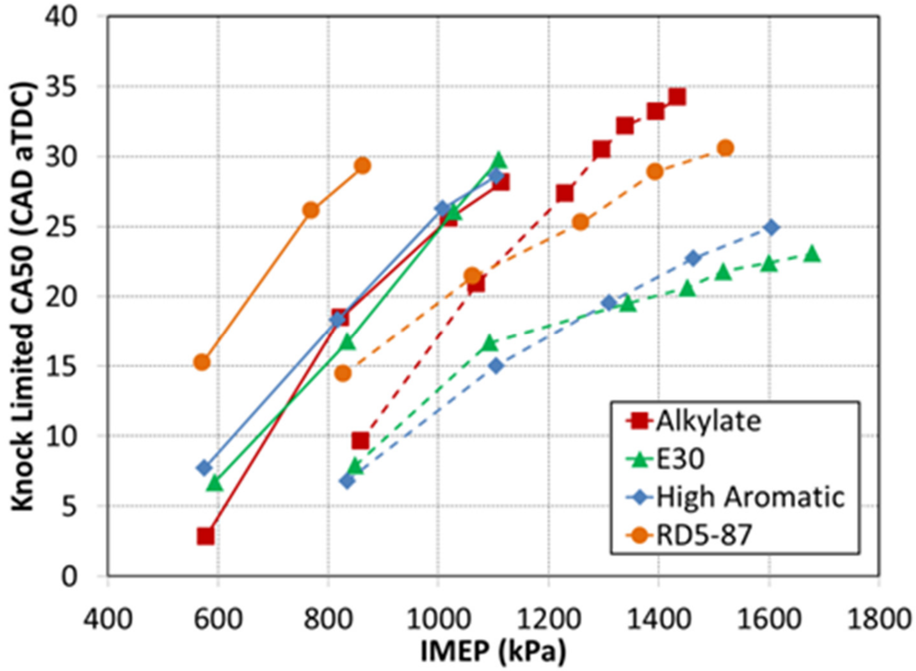


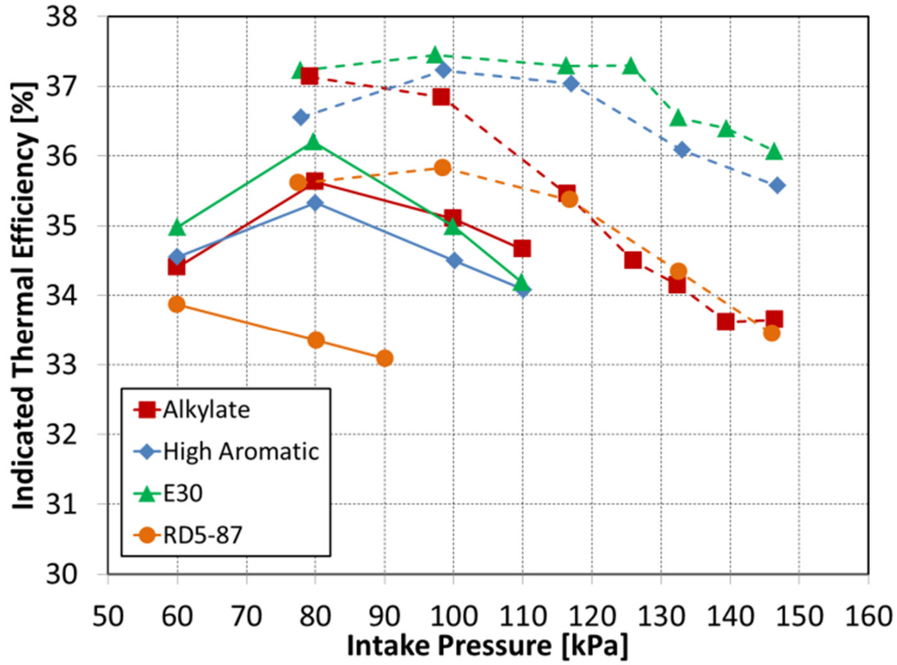


Prakash *et al.*, SAE 2016-01-0834



Fuel Performance





- Higher load of high-S fuels is consistent with other studies showing faster acceleration.
- Higher efficiency is an important benefit, and justifies further fuels research.

Conclusions

- Load-transient operation results in significantly improved KL-CA50's relative to steady-state performance for all tested fuels.
  - Due to the lower thermal state of the engine structure under transient operation.
- Transient operation allows the exploration of a wide range of Octane Index K values, from 0.5 to -2.3.
- Boosted conditions lead to "beyond RON" conditions in which high-RON, **high-S fuels** exhibit **improved performance** over a high-RON, low-S fuel.
- Efficiency gains warrant more examination of these types of gasoline fuels.
- With non-controlled S, AKI may be a poor indicator of acceleration performance for downsped-downsized SI engines.
  - Examined AKI97 Alkylate is the most knock limited fuel under cool boosted conditions.

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U.S. DEPARTMENT OF ENERGY

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