Hardware and Operating Condition Impacts on SPI

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2020 CRC Stochastic Pre-Ignition Workshop

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Preamble

- This presentation will attempt to cover "everything else" related to the frequency of (L)SPI with *all else being equal*
  - May still not be exhaustive and omissions were not intentional
  - There may be contradictory observations, but a general view is presented
- It is a collection of observations from literature and the various authors are fully acknowledged
  - Additional sources are SwRI Internal Research and P3 Consortium
- Much of our understanding of LSPI is based on steady-state testing
  - Please accept *for now* that it is a reasonable representation of real-world behavior

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Working Hypothesis

- There are numerous publications that point to the crevice fluid as a likely cause of LSPI
  - Mixture of fuel and oil in right proportion
- Combustion related soot and/or particulates appear to have a contributing/complementary impact, as do engine deposits

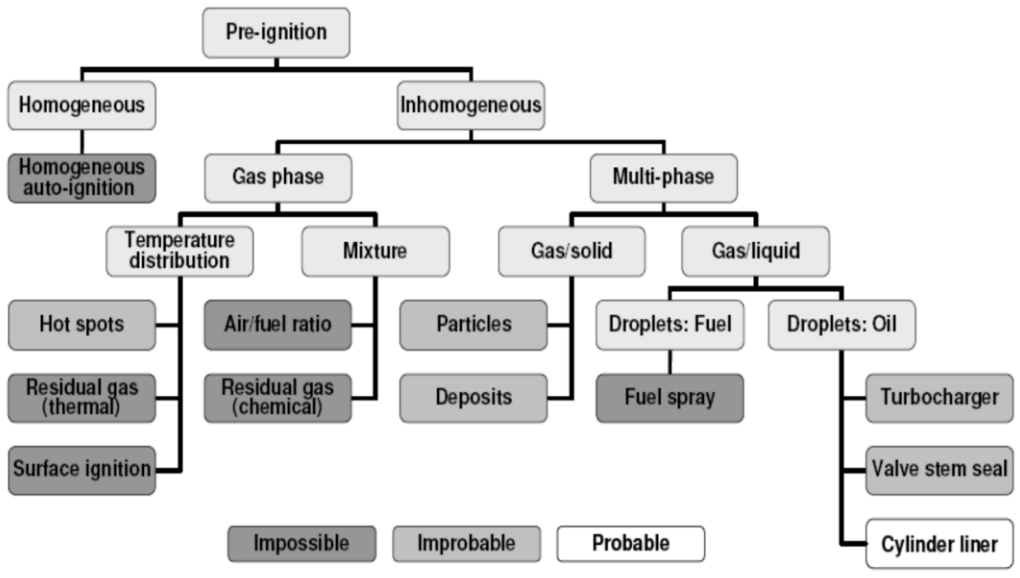
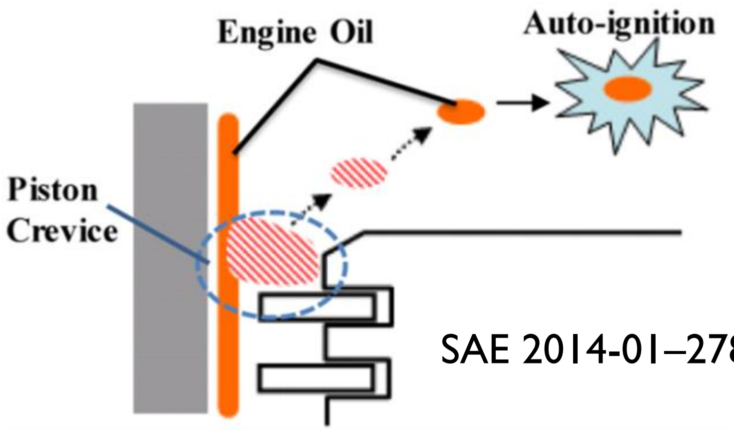


Figure 16: Estimation of pre-ignition mechanisms

SAE 2010-01-0355



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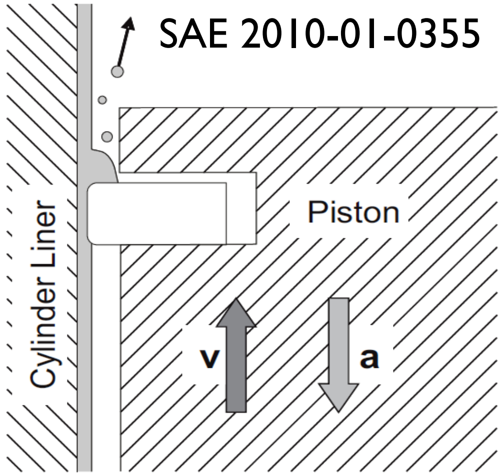

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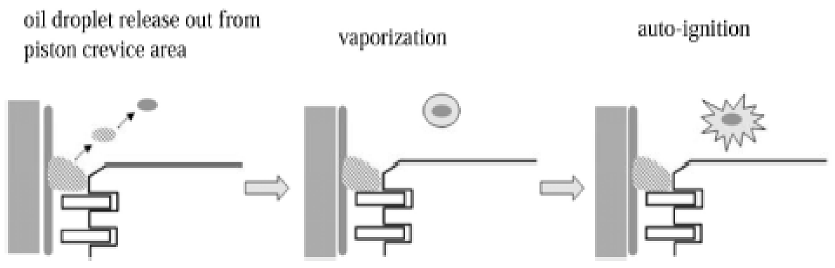

Figure 4. Mechanism for auto-ignition of oil droplet from piston crevice

SAE 2012-01-1615

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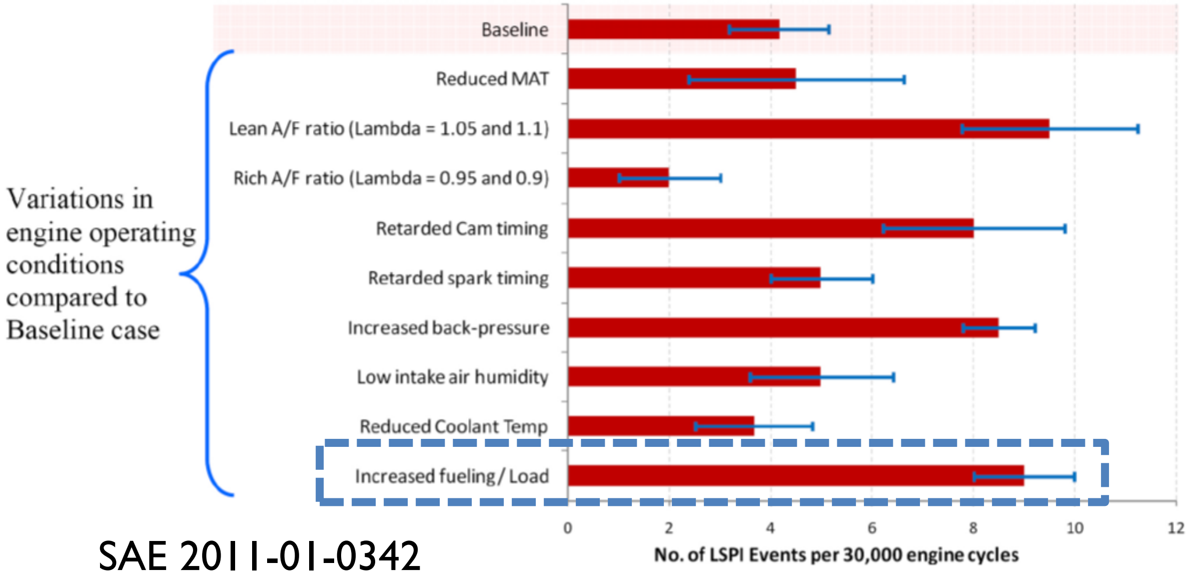
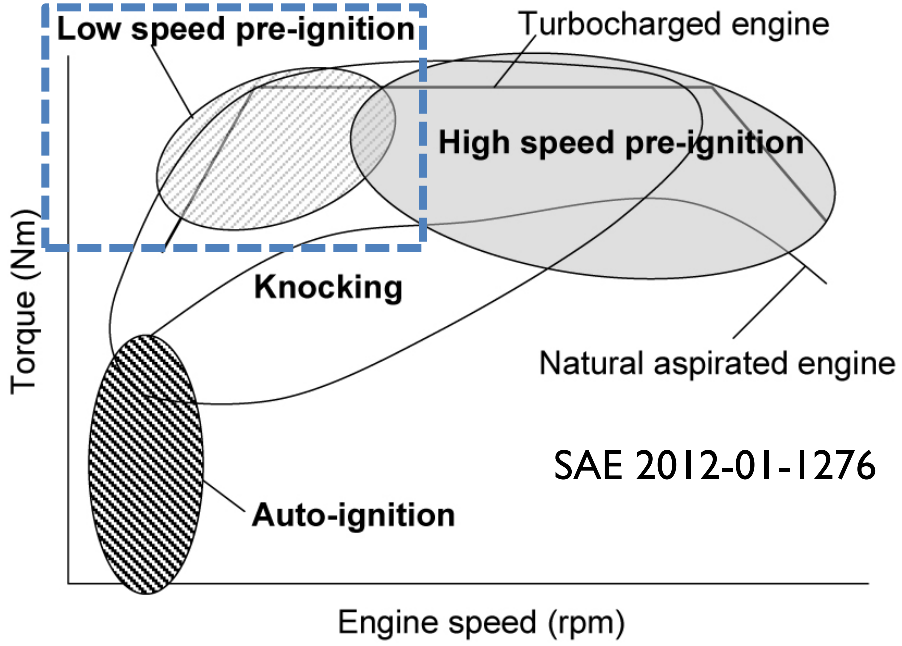
Speed / Load Demands

- LSPI encountered in low speed, high load parts of the engine map
  - Typical of forced induction, direct injection spark ignition engines with retarded spark



SAE 2011-01-0342



SAE 2012-01-1276

SAE 2012-01-1141	Low	Frequency of SuperKnock	High
Intake air Pressure	Low	□□	High
Lambda	Rich	□□	Lean
Intake air Temperature		No Influence (26～42degC)	
Ignition Timing	Retard	□□	Advance
Injection Timing	Advance	□□	Retard
Intake Open Timing	Retard	□□	Advance
Blow-by Oil	Little	□□	Much

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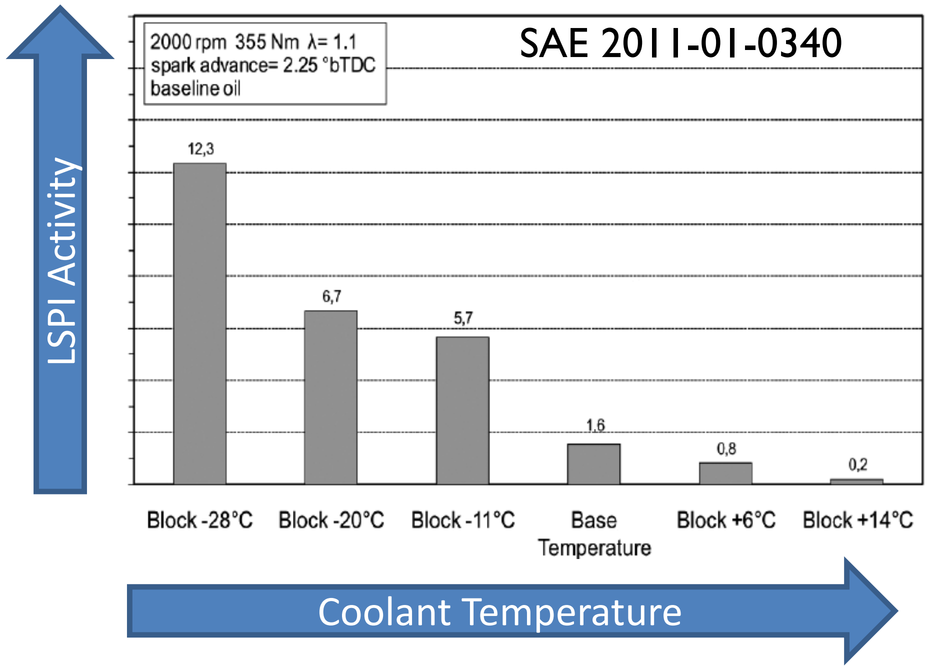
Calibration - Engine Coolant Temperature

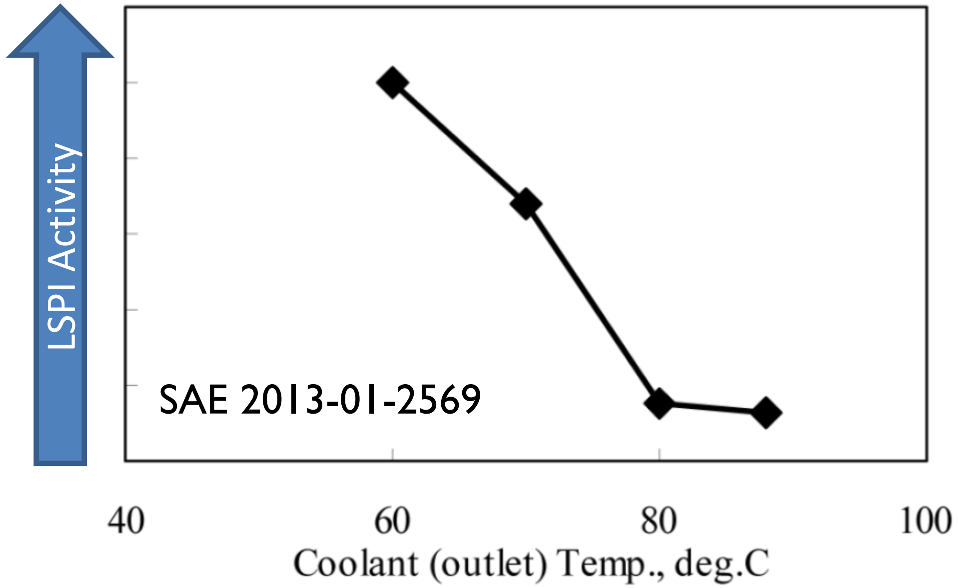
- Multiple papers have shown that LSPI increases with lower coolant temperatures
  - This is engine / design specific
  - Correlation between wall temperatures and fuel evaporation (EXX) that corresponds to LSPI frequency



Coolant temp.	◎
Inj. start timing	◎
Fuel pressure	○
Ig. timing	×
A/F (Exhaust)	×
Blow-by gas	△
Deposit	○
Top ring gap location	◎
Low oil cetane number (and w/o Ca)	◎
Oil w/ & w/o Ca	◎

◎: Strong effect
○: effect
△: weak effect
×: no effect

SAE 2015-01-0756



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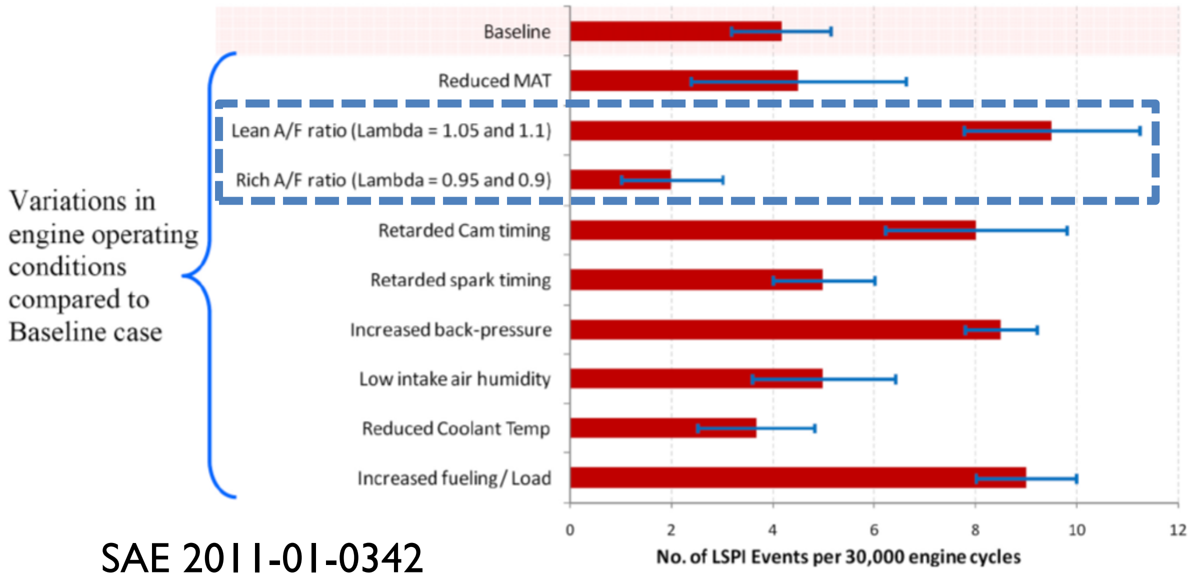
Calibration - Air-Fuel Ratio

- Lean mixtures generally increase LSPI
  - Either by direct fueling action or indirectly by engine breathing
  - Mechanism is not clear
- This response can be used both to accelerate LSPI during research and testing but also to mitigate in LSPI in real-life calibration



SAE 2011-01-0342

SAE 2012-01-1141	Low Frequency of SuperKnock High
Intake air Pressure	Low → High
Lambda	Rich → Lean
Intake air Temperature	No Influence (26～42degC)
Ignition Timing	Retard → Advance
Injection Timing	Advance → Retard
Intake Open Timing	Retard → Advance
Blow-by Oil	Little → Much

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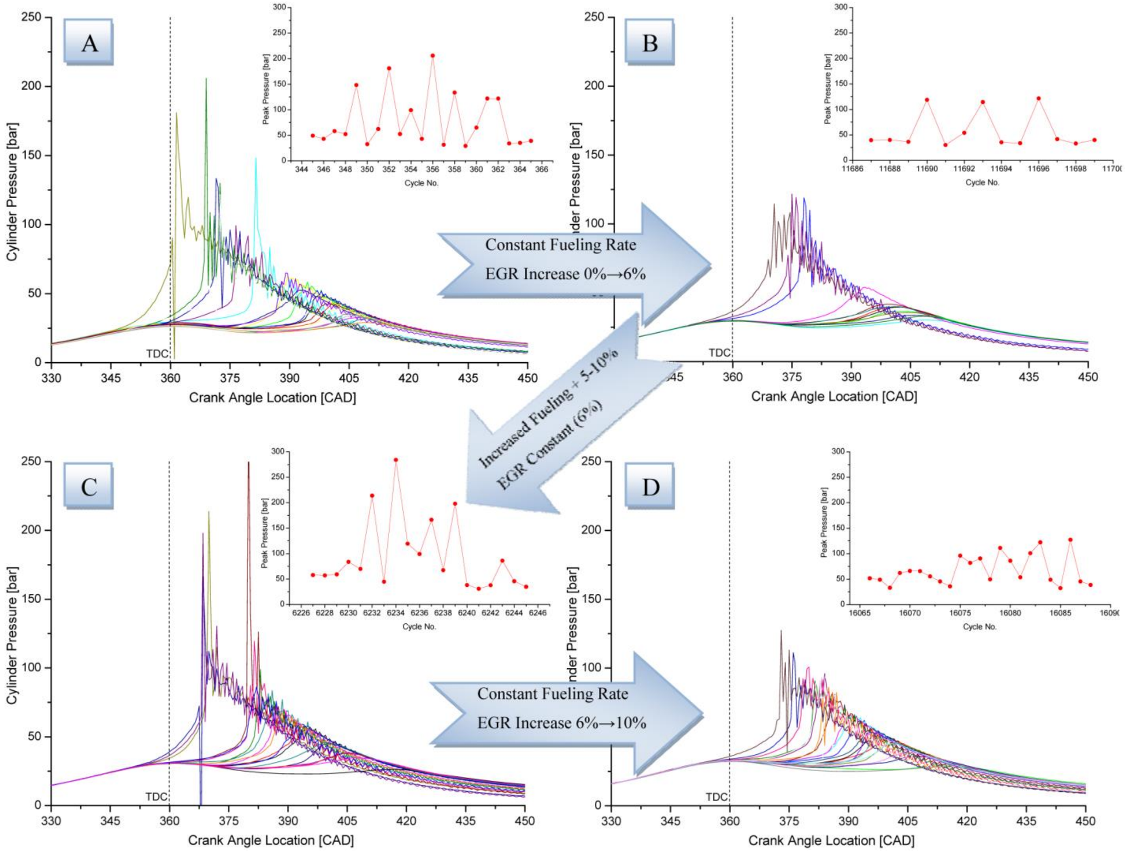
Calibration - EGR

- LSPI frequency is reduced with increasing levels of EGR
  - EGR levels may not be production feasible



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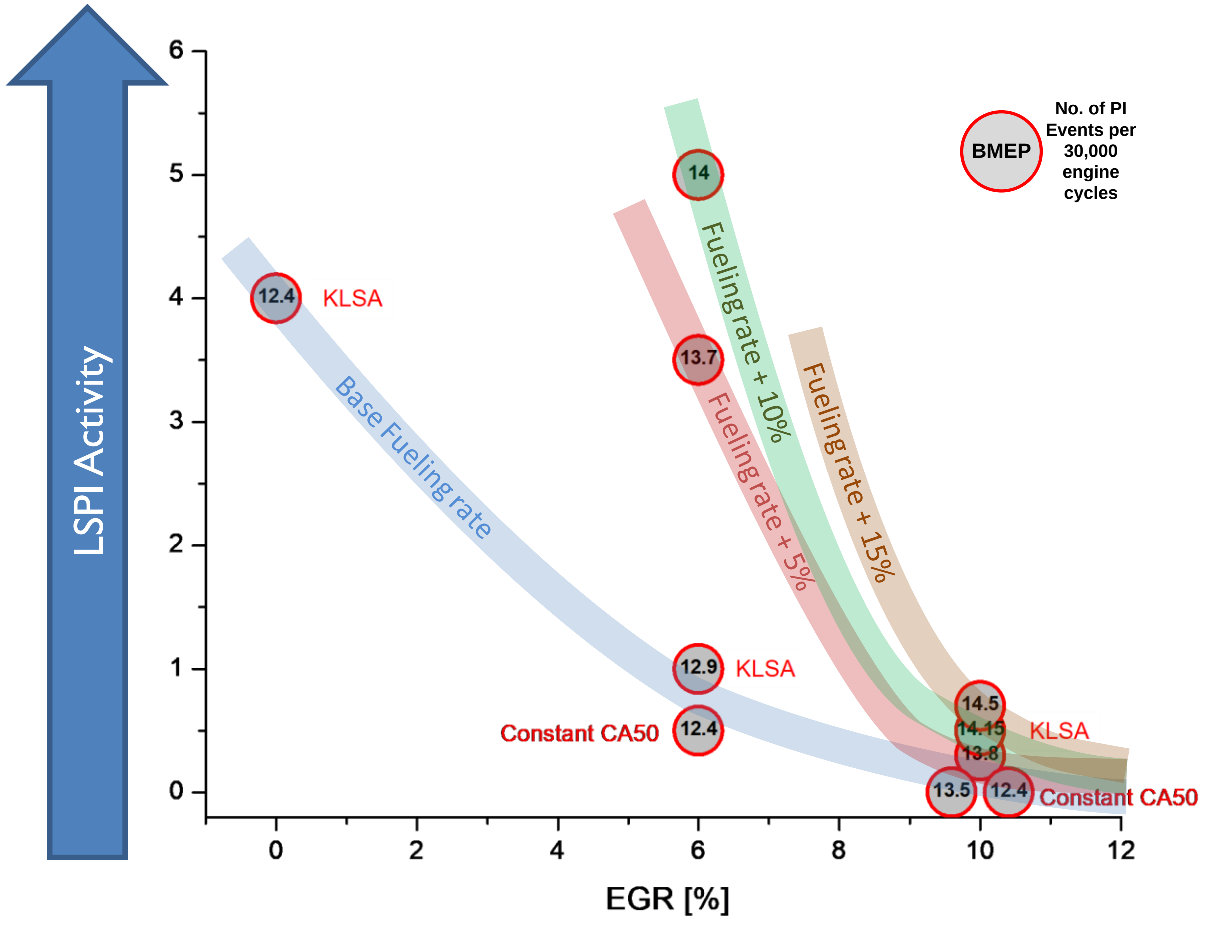

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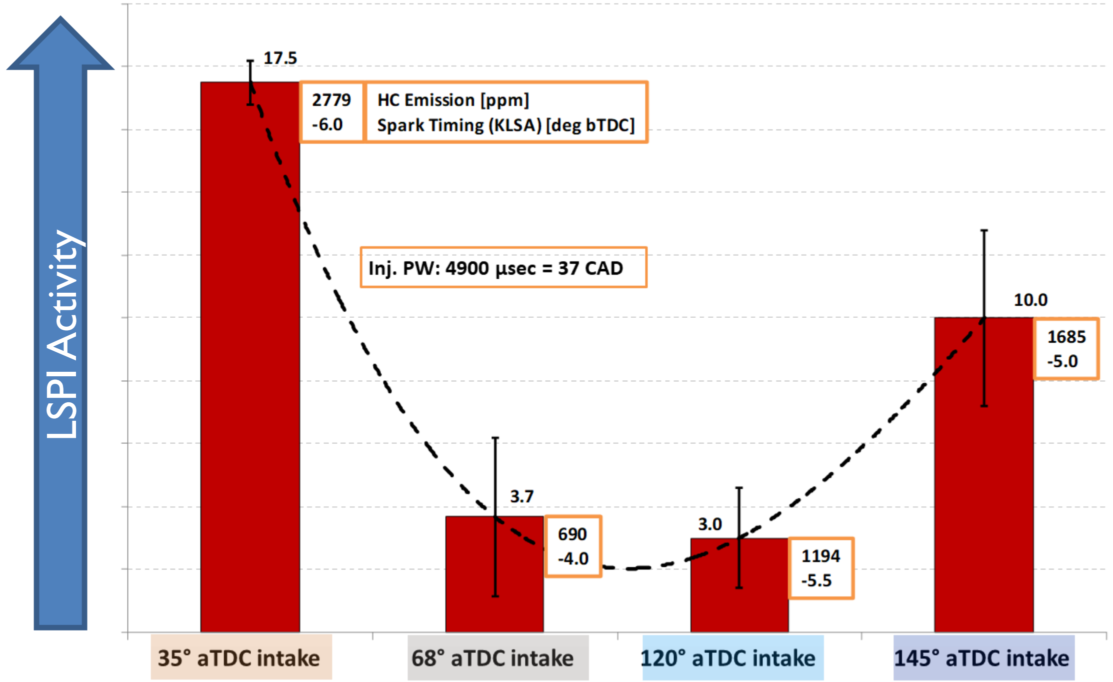
Calibration - Injection Timing and Pressure

- LSPI is affected by fuel injection timing due to wall impingement and mixing
  - Production calibration also needs to consider durability, emissions, NVH and performance
- Similar impact of injection pressure
  - Trade-off between atomization and penetration depth

Coolant temp.	◎
Inj. start timing	◎
Fuel pressure	○
Ig. timing	×
A/F (Exhaust)	×
Blow-by gas	△
Deposit	○
Top ring gap location	◎
Low oil cetane number (and w/o Ca)	◎
Oil w/ & w/o Ca	◎

◎: Strong effect
○: effect
△: weak effect
×: no effect

SAE 2015-01-0756



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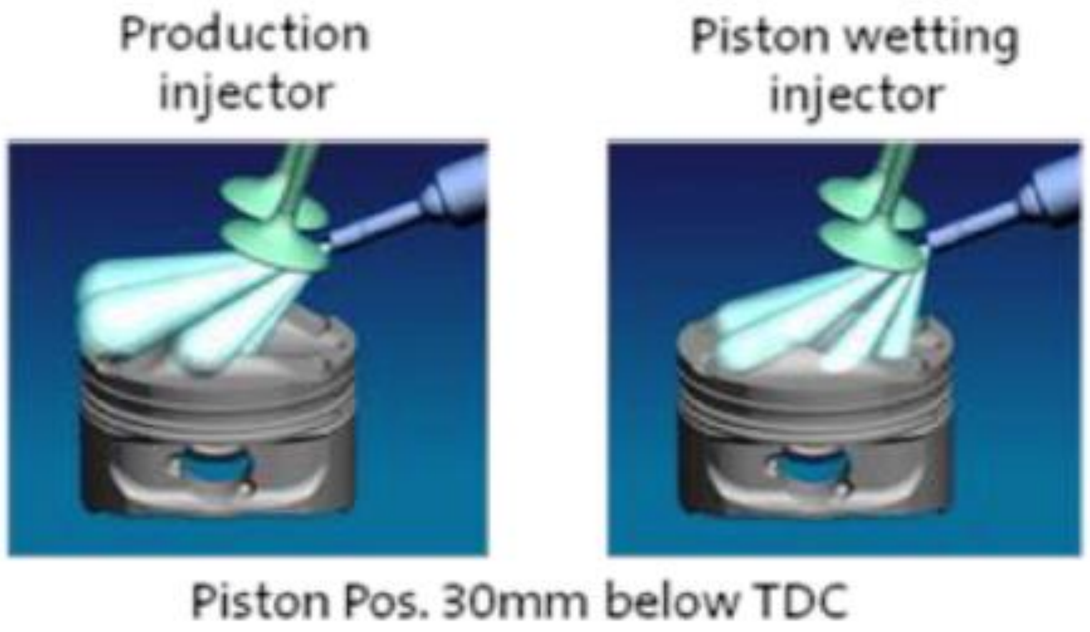
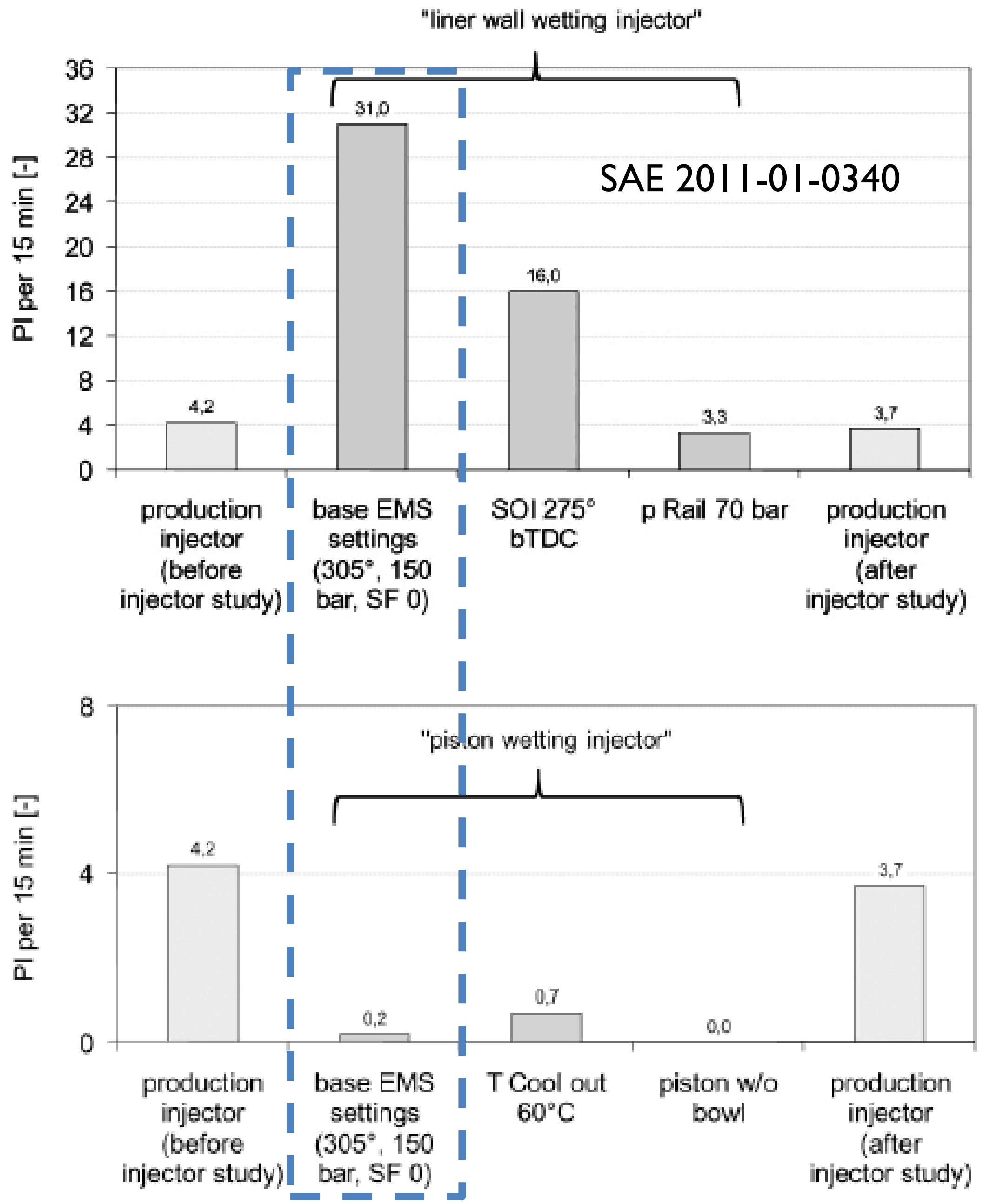
Design - Injection Targeting

- Changing injector targeting to place liquid fuel on piston not liner decreased LSPI
  - Consistent with lowest hydrocarbon emissions at minimum LSPI





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Design – Injector Location

- Central DI and PFI generally worsens LSPI compared to side DI
  - Attributed to increased wall wetting
- Results are confounded by piston design and injection pressure that are matched to injector type and location

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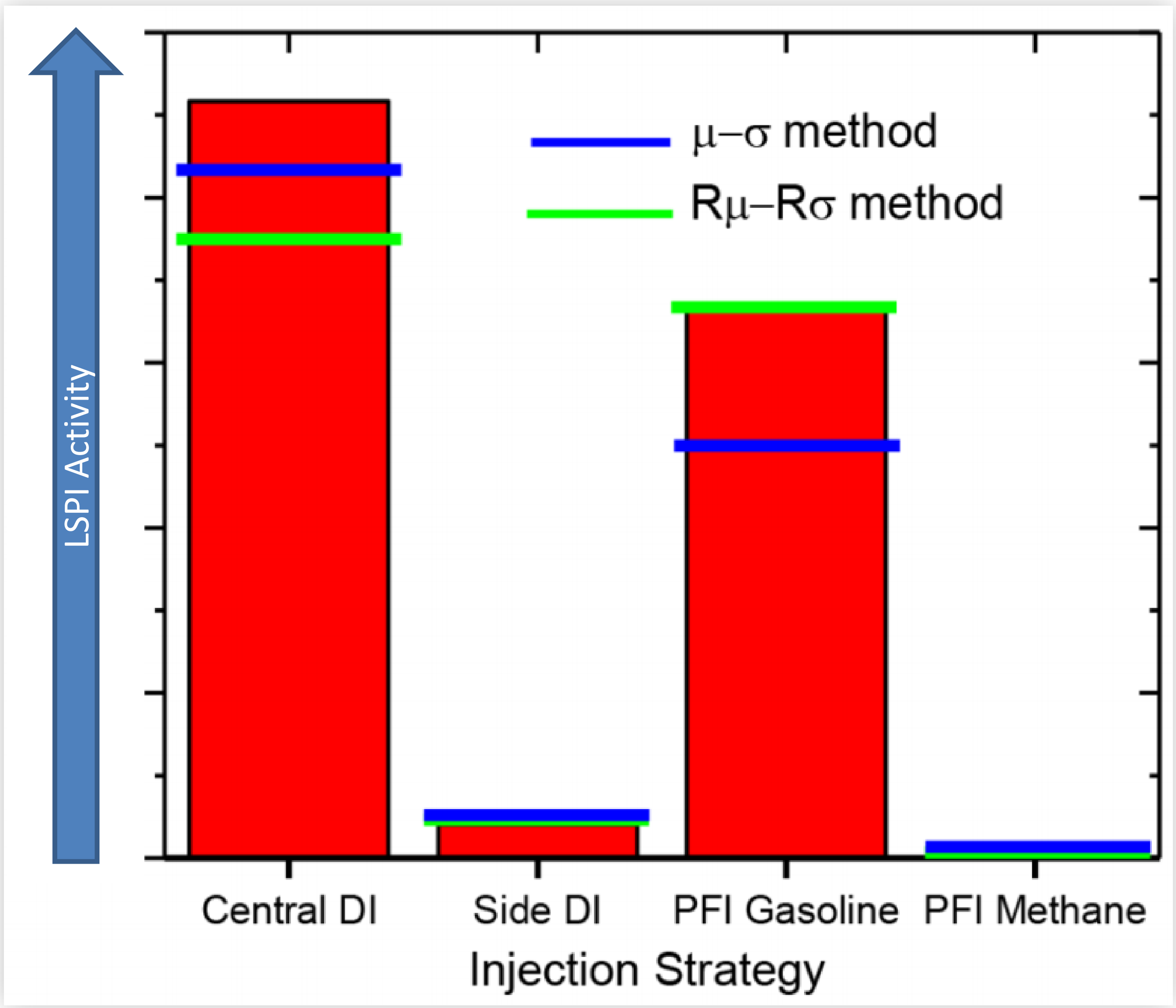

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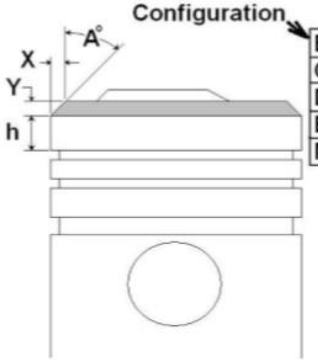
Design - Piston Chamfer

- Chamfered piston crown decreases LSPI frequency
  - Likely leads to reduced crevice fluid accumulation and impacts composition
- Design may not be production appropriate due to emissions, costs or robustness

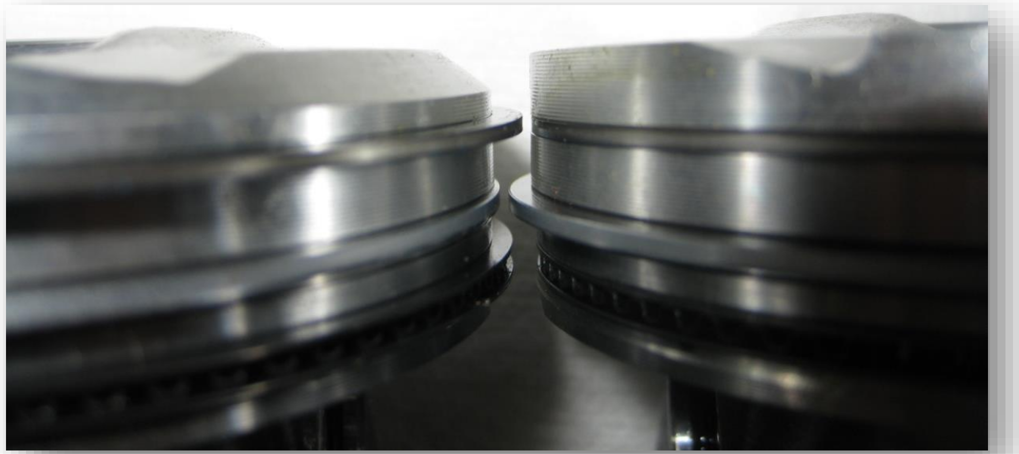


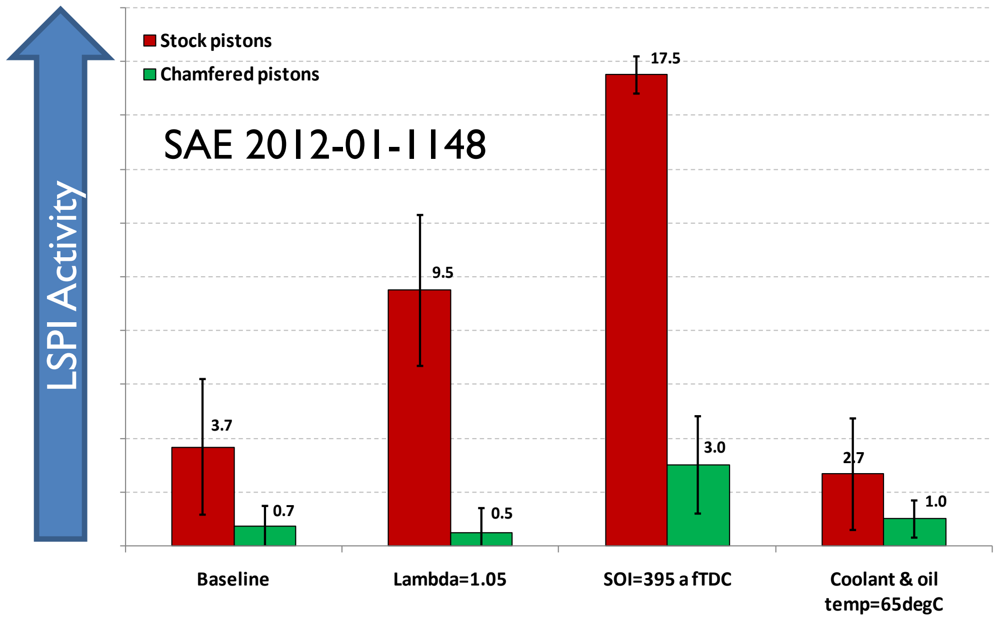
Configuration

Configuration	X	Y	h	A, deg
B	3.8	3.7	1.54	45.8
C	4.3	3.24	2.0	53.0
D	5.2	2.74	2.5	62.2
E	6.5	2.24	3.0	71.0
M	2.9	4.74	0.5	31.5

Removed volume kept constant at 1.95cc for all configurations

Figure 14. Chamfered Piston Crown - Second Iteration





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Design – Top Land Height

- Strong correlation between piston top land height and LSPI frequency
  - Reduces crevice volume
- May not be production feasible due to strength and robustness considerations

Coolant temp.	◎
Inj. start timing	◎
Fuel pressure	○
Ig. timing	×
A/F (Exhaust)	×
Blow-by gas	△
Deposit	○
Top ring gap location	◎
Low oil cetane number (and w/o Ca)	◎
Oil w/ & w/o Ca	◎

◎: Strong effect
○: effect
△: weak effect
×: no effect

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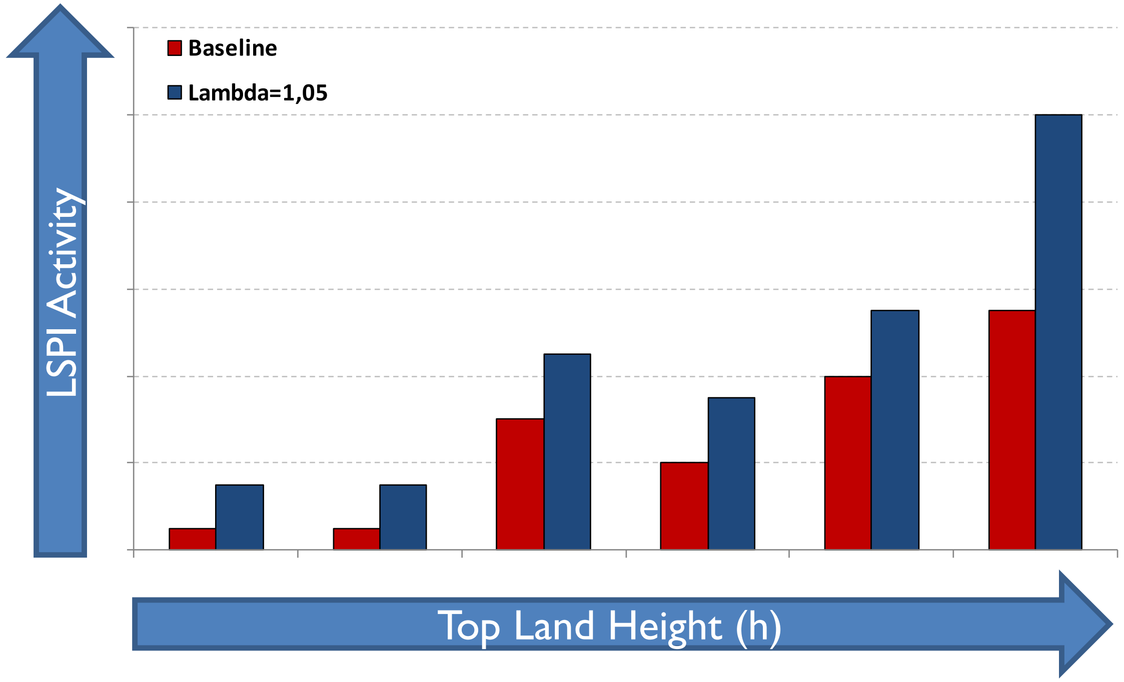

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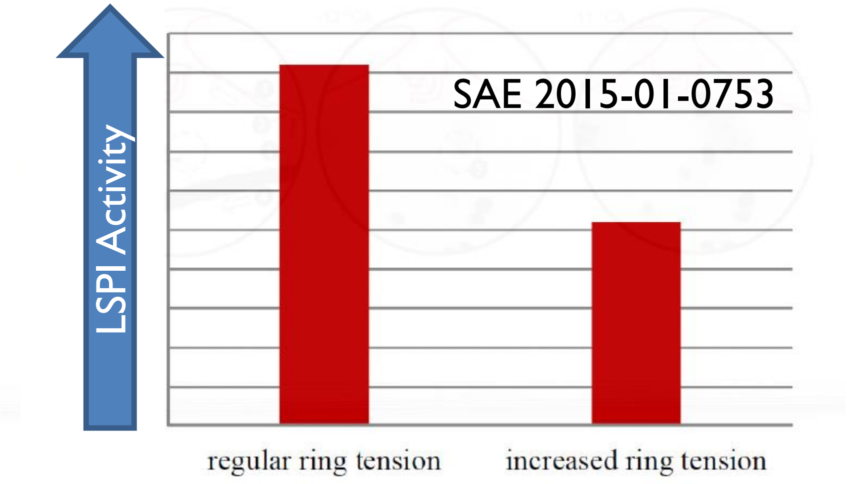
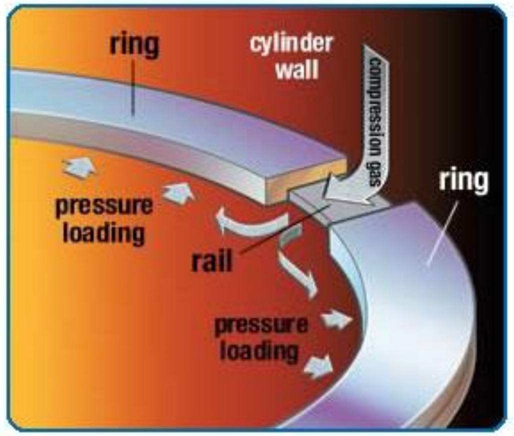
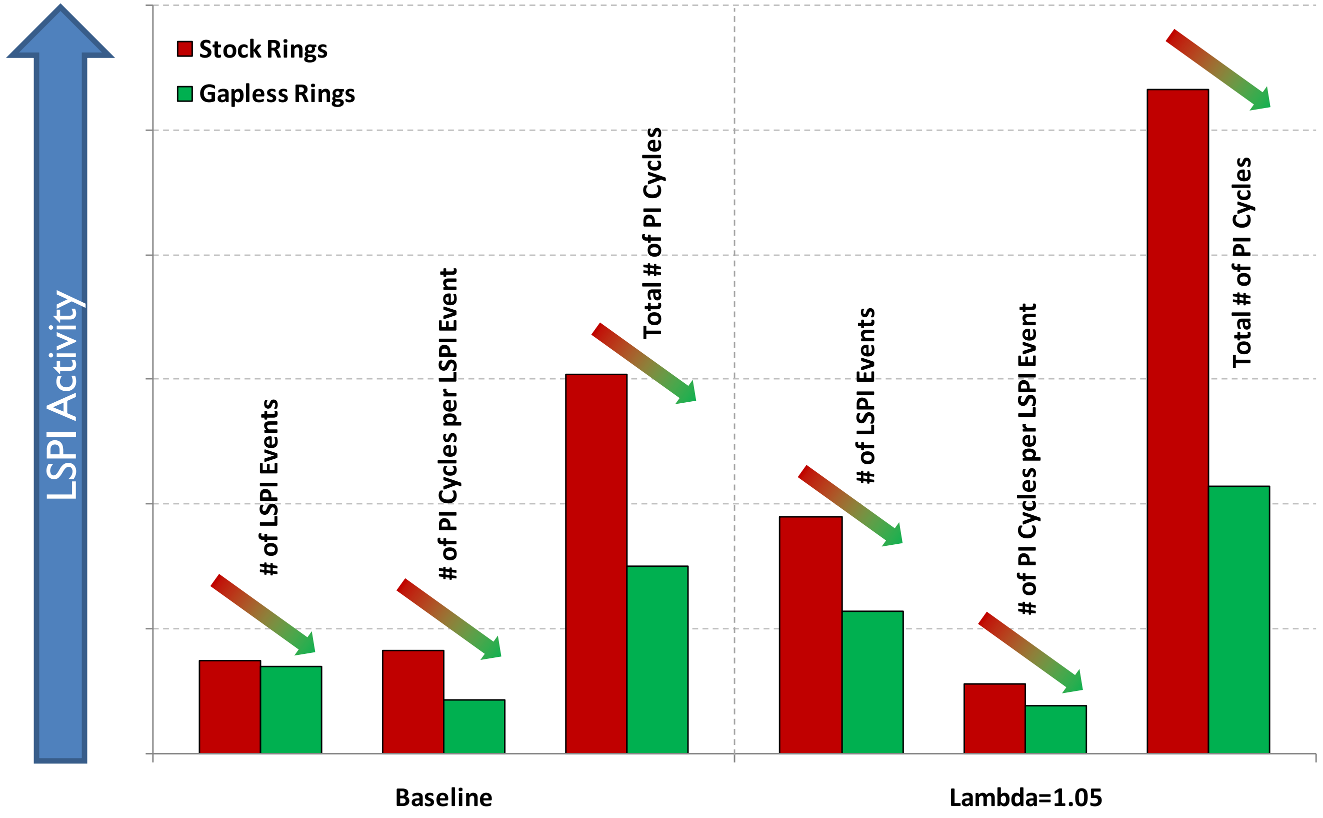
Design - Ring Tension and Gaps

- Higher ring tension and gapless rings reduce LSPI tendency
- Both impact the oil transfer to the crevice region
- Need to balance LSPI benefits with friction and durability





www.totalseal.com



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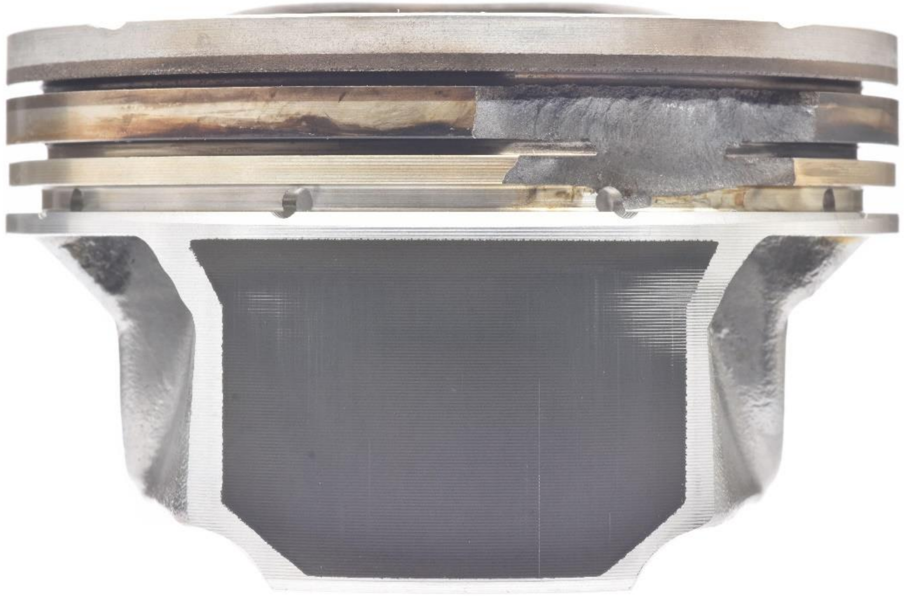
Design – Piston Strength

https://www.sae.org/news/2017/06/mahle-tests-for-mega-knock-in-downsized-boosted-engines

- LSPI typically manifests in piston ring land and skirt damage
  - Less commonly spark plug, valves or conrod damage
- Improved piston design and material choices can enhance strength and improve durability
  - LSPI damage is unlike that caused by spark-knock and may require different solutions
- Ultimately a cost-benefit trade-off



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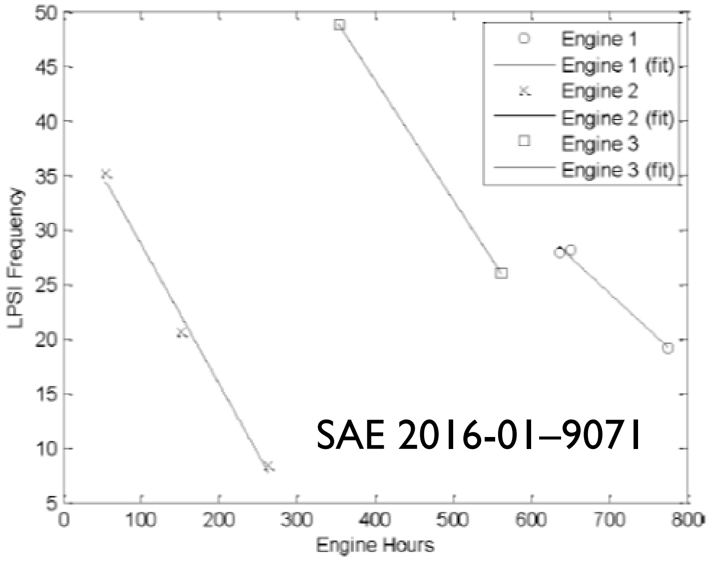
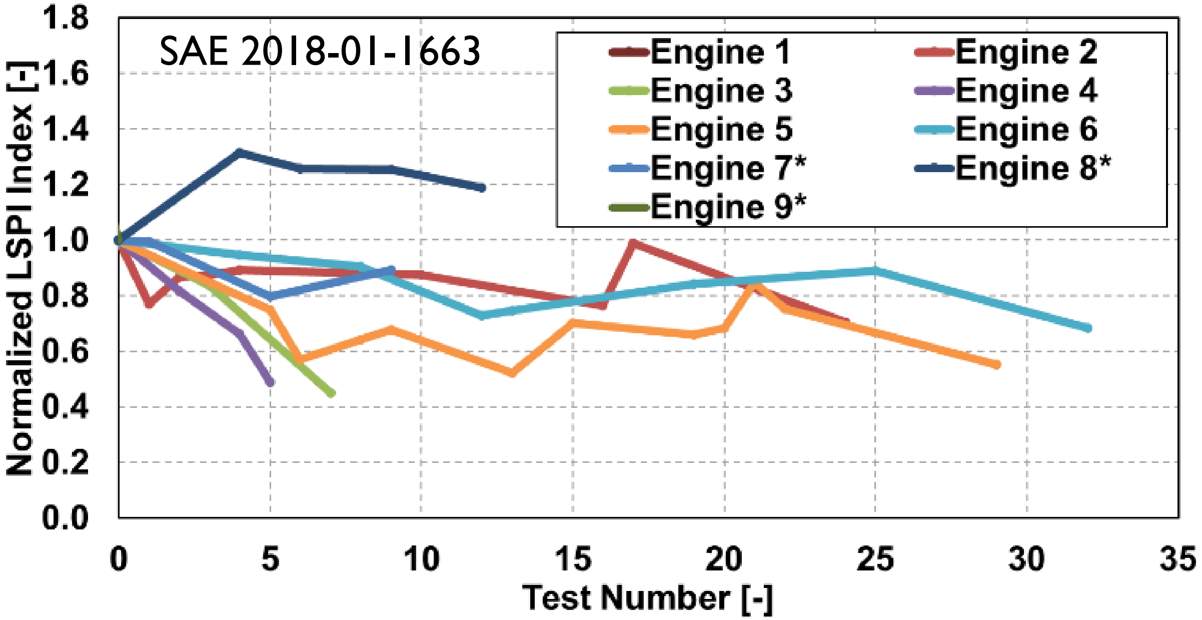
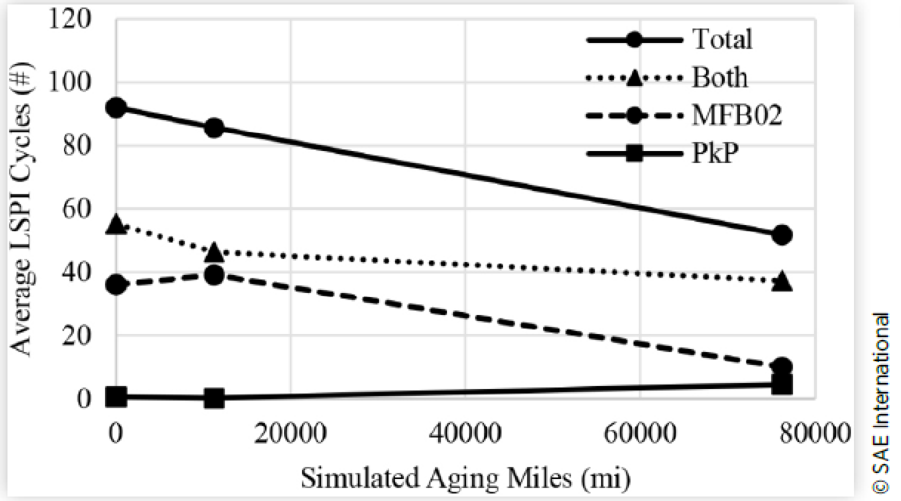
Engine Condition - Age

- New oil LSPI activity generally reduces with engine age
  - Test bed (left and middle) and on-road (right) aged engine LSPI activity
- Attributed to engine wear and changes in flow past ring pack and into crevice
  - Countered by re-honing and bore damage *(not shown)*



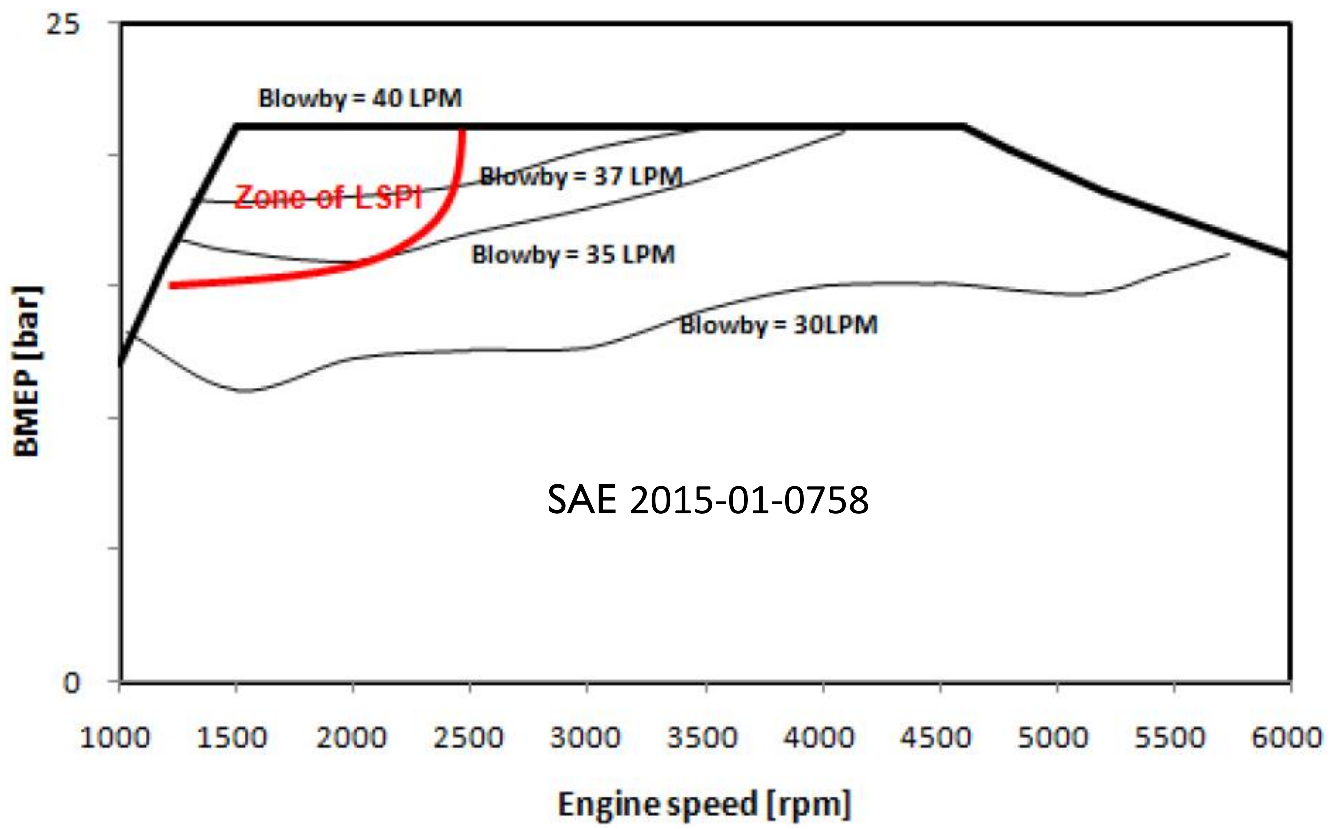




https://doi.org/10.4271/03-11-01-0002

Engine Condition – Fugitive Oil

- Increased LSPI due to increased blow-by either due to design, maintenance or engine wear
- Similar observations with PCV and turbo-seal leakage
- Goldilocks response
  - A small increase increases LSPI
  - A large increase decreases LSPI



SAE 2015-01-0758

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Engine Condition - Deposits

- Deposits liberated during first LSPI cycle of a multi-cycle event
  - May not heat up sufficiently within a single engine cycle to cause preignition *(top)*
  - Volatile components incorporated into deposits required for ignition
- Dynamics of real-life deposits nearly impossible to measure / replicate repeatably in an engine
  - "Dirty-up" pre-conditioning in some LSPI bench tests aimed at consistency
- Rebuilding and cleaning of engine does not affect LSPI activity *(bottom)*

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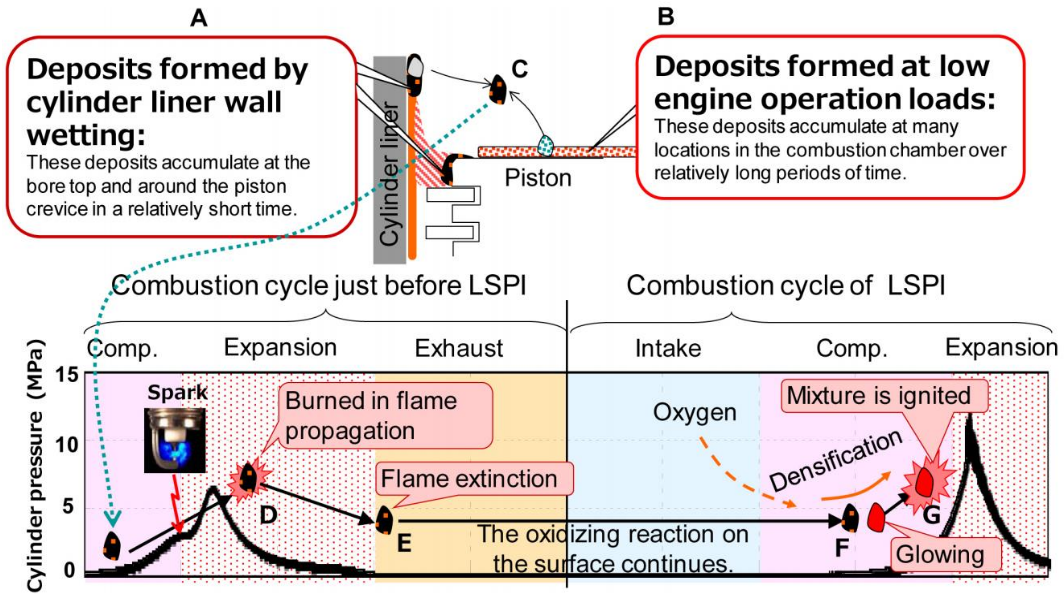
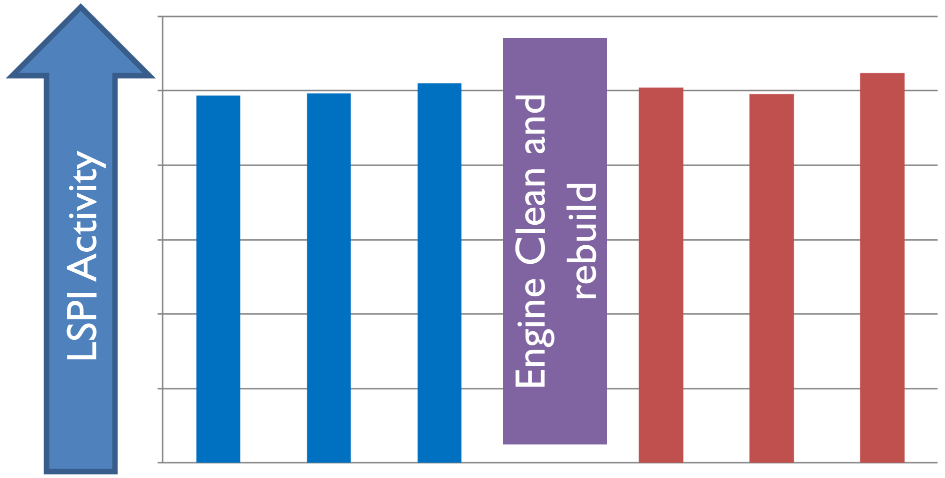


Figure 15. Schematic of new LSPI mechanism.



SAE 2018-01-1663

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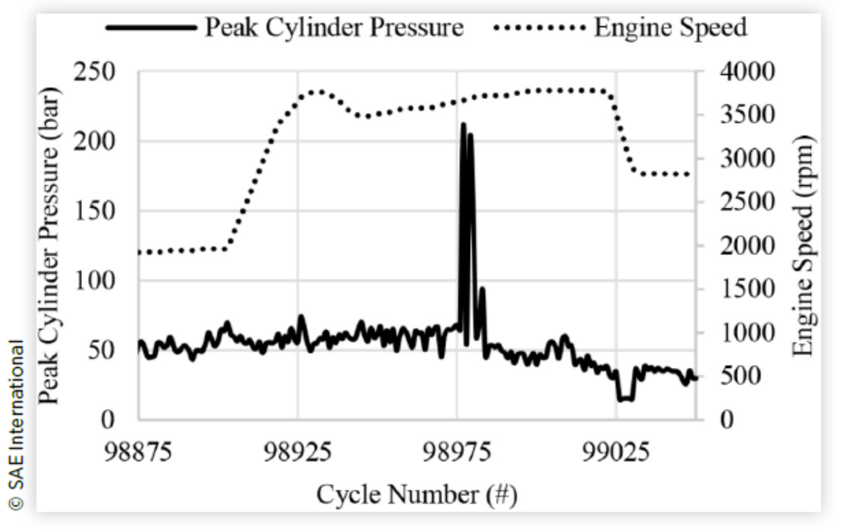
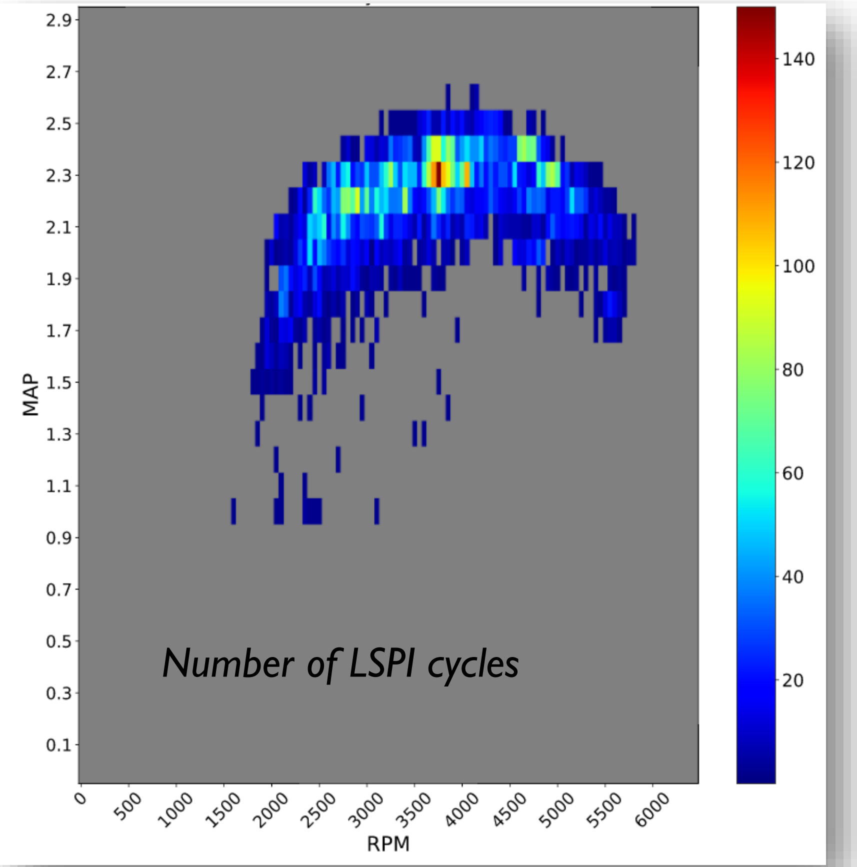
Transient LSPI

- Real-life LSPI is truly a transient phenomenon during which the factors above may reinforce or detract from each other due to dynamics
  - No known systematic study
- On-road LSPI encountered at higher engine speeds (>3,000 rpm) and with "real" deposits
  - Rare event (~5,000/200 million cycles)

FIGURE 17 Peak cylinder pressure and engine speed.





https://doi.org/10.4271/03-11-01-0002

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Conclusions

- Factors that impact the amount or composition of the crevice fluid appears to impact LSPI
  - Not all design, operation or calibration adjustments are attainable due to emissions / performance / durability / cost considerations
- Operational and hardware factors are agnostic to fluid changes
- Little evidence of the impact of engine deposits, although it is thought to be complementary
- Quantification of transient or real-life LSPI response still open
  - OEM proprietary flagging and mitigation are already in use

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Recommendations

- LSPI observed during steady-state testing transients may be mined for additional insight
- Determine how "steady state factors" may manifest during transient testing
  - Acceleration /deceleration
  - Tip-in / tip-out
  - Warm-up / cool down
- Determine the impact on LSPI severity, not only frequency
- Understanding the impact of "real" deposits
- Cost-benefit analyses of design and calibration mitigation versus fluid solutions
  - Likely not in the research realm

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Thank You

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