Abnormal Combustion in H_2 Engines

SOUTHWEST RESEARCH INSTITUTE®

Abdullah Bajwa

04/16/2026

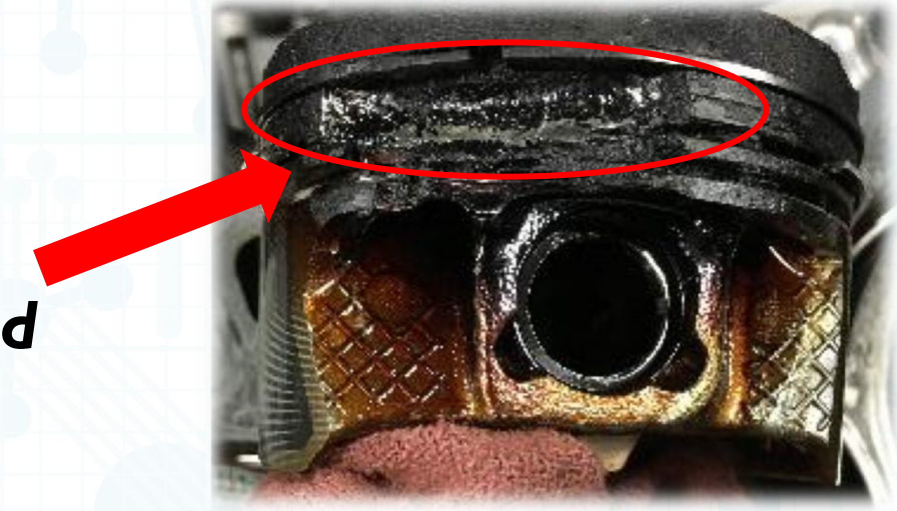
44th API Automotive/Petroleum Industry Forum

Agenda

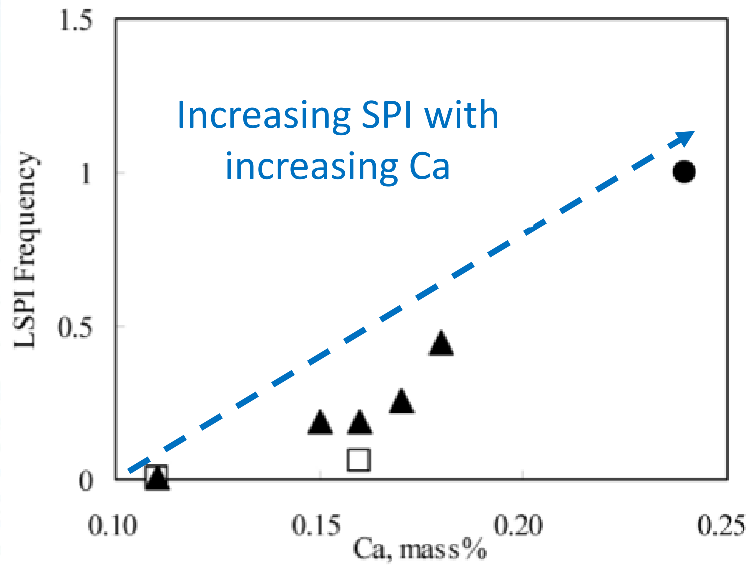
- SPI in gasoline engines
- SwRI's SPI research experience
- SPI in H_2 engines

SPI in Gasoline Engines

- **SPI = Stochastic Pre-Ignition**
- Observed in turbocharged, gasoline direct injection (TGDI) engines, ***resulted in many field failures***
- Fundamental work traced propensity of SPI to ***engine oil properties***
  - Largest driver was identified as ***calcium content*** (commonly used detergent additive)
- Industry responded with development of ASTM Sequence IX engine test to measure SPI propensity of an engine oil
  - Included for light duty engine oil categories, API SN Plus and SP
  - Aged oil SPI test added for API SQ category



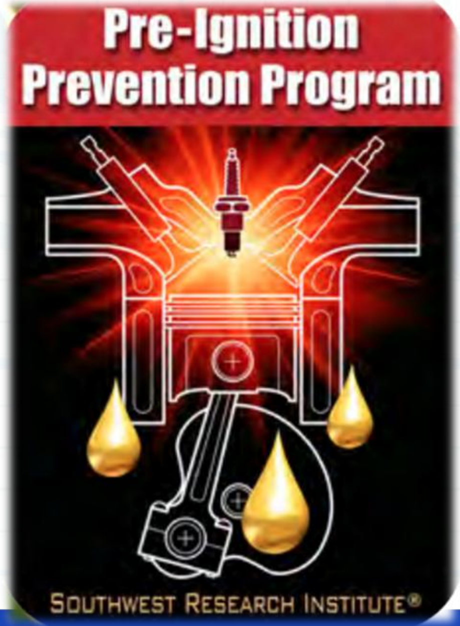
SAE 2018-01-1676



SAE 2013-01-2569

SwRI SPI Testing Experience

- SwRI led multi-year projects on SPI in boosted gasoline engines, developing SPI methods and contributing to the ASTM Sequence IX SPI test.



DAQ System
Developed DAQ system for continuous crank-synchronous in-cylinder pressure measurement.

Post-Processing Tools
Developed post-processing tools to determine SPI events.

Piston Crevice Material
Extraction of piston crevice material to understand lubricant state.

Transient Vehicle Test
Developed a transient vehicle-based SPI test and associated data processing tool chain.

Statistical Test
Developed a test to statistically differentiate SPI activity for variable test conditions.

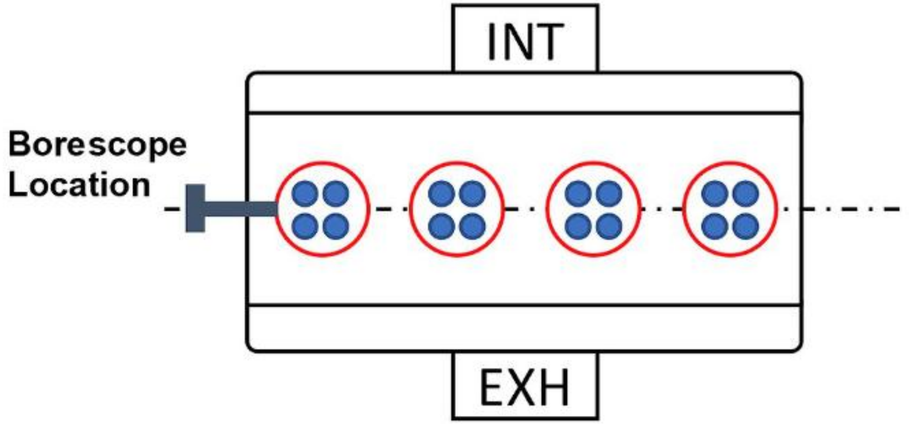
Optical Investigation
Research projects involved optical SPI investigation.

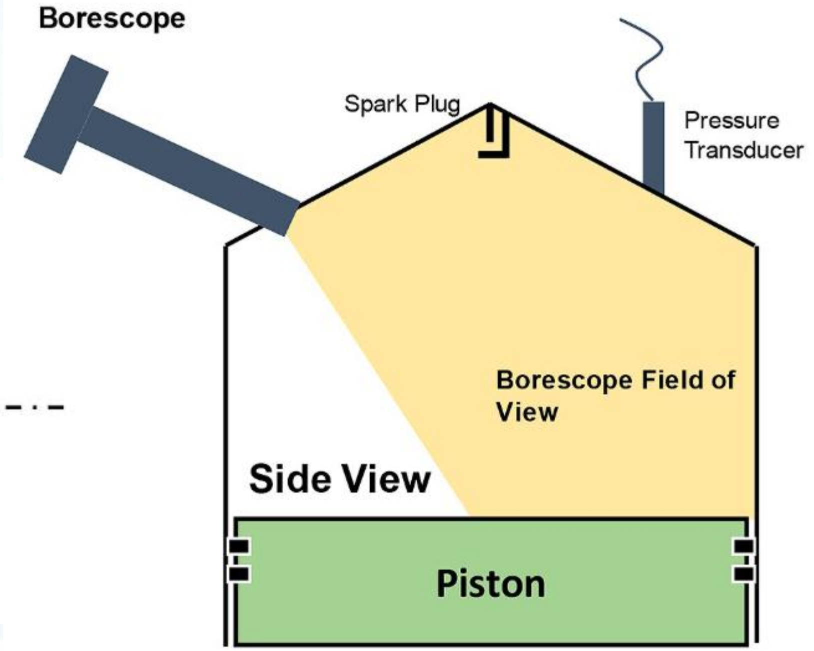
Seq IX Test
Developed Seq IX test for lubricant certification for SPI.

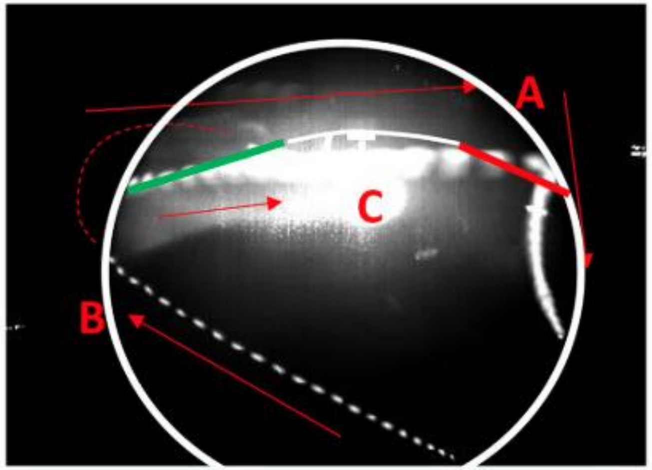
SwRI operates numerous ASTM Sequence IX and development SPI test stands

Optical Visualization of SPI – SwRI

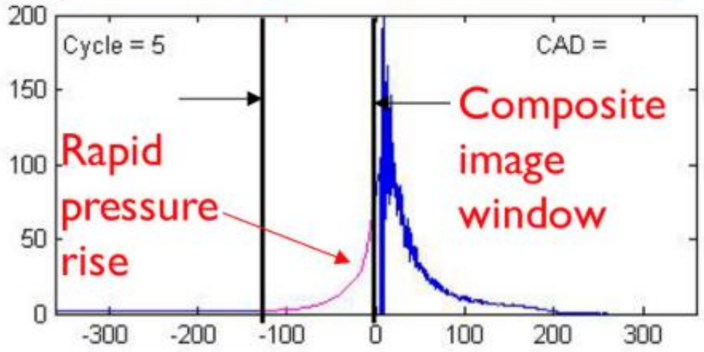
- SwRI developed an optical borescope that could be mounted on a production engine head to image the pre-SPI-event visible light activity in the combustion chamber







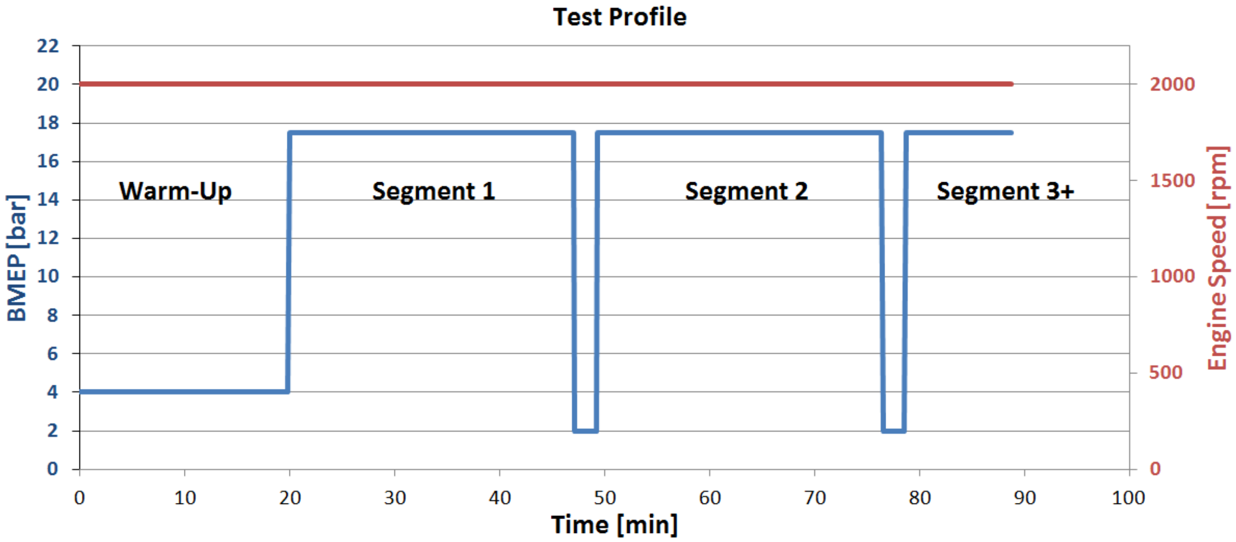
Composite image for the integrated window



https://doi.org/10.4271/2021-01-0486.

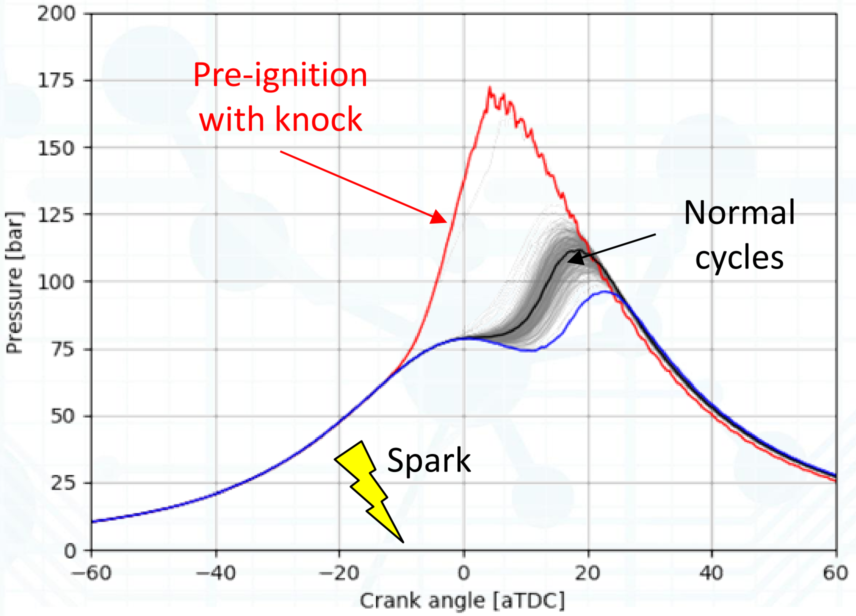
SPI Test Methodology → Gasoline

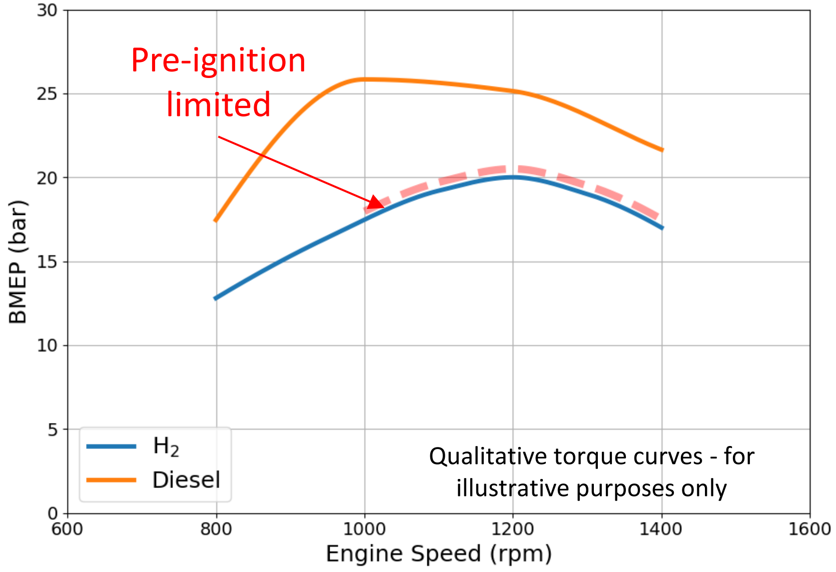
- A typical SPI cycle is implemented for gasoline SPI testing is shown
- This includes
  - Warmup phase
  - Followed by a high load test segment(s) run for n number of cycles with continuous data acquisition
  - Typical test length is of the order of 600,000 engine cycles, with segment lengths varying from 25,000 cycles to 170,000 cycles
- A similar approach is currently used to study SPI in H_2 ICEs



SPI in H_2 Engines

- OK, SPI is a problem in gasoline engine, so what?
  - It also has been ***observed in H_2 engines*** & effectively ***limits maximum load***
- Unlike gasoline engine SPI, H_2 SPI is still not very well understood
- SwRI is investigating H_2 SPI to
  - Understand mechanisms
  - Developing tests and evaluating impact of oil properties
  - Developing statistical / machine learning based characterization methods

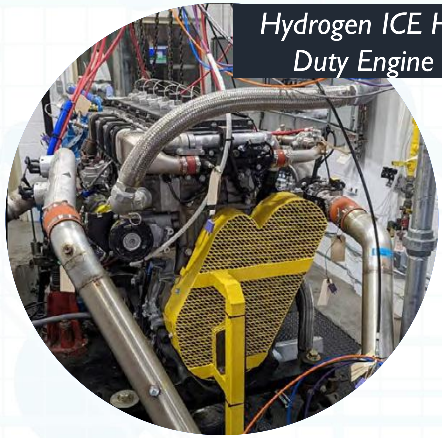




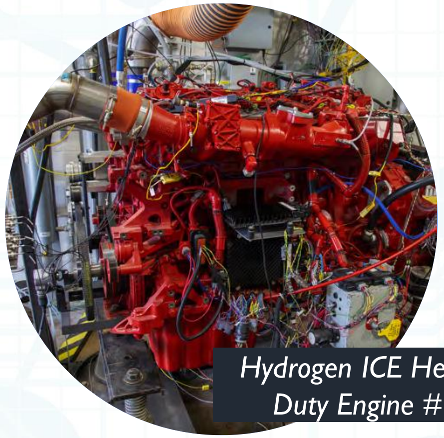
Qualitative torque curves - for illustrative purposes only

Powertrains for Alternative Fuel Research

From single-cylinder research engines (SCE) development to class 8 demonstrator

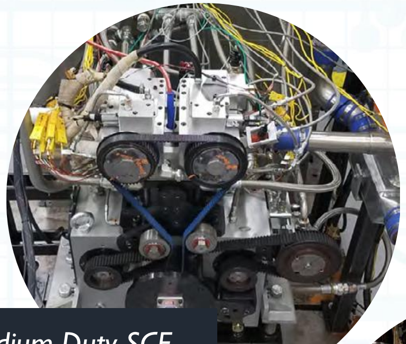


Hydrogen ICE Heavy-Duty Engine #2



Hydrogen ICE Heavy-Duty Engine #1

Light-Duty SCE



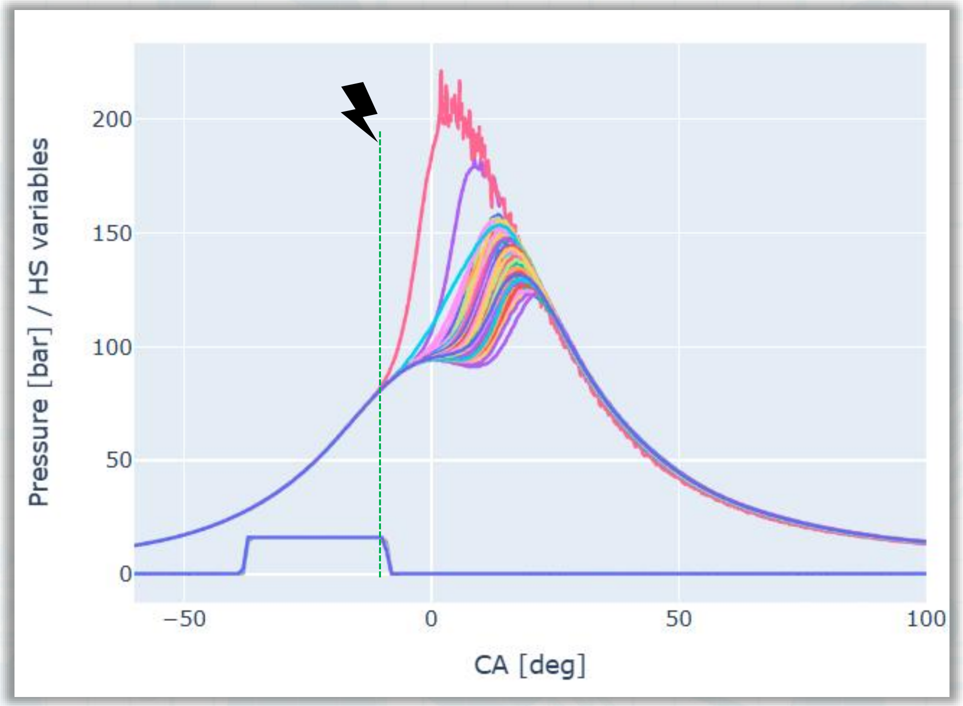
Medium-Duty SCE

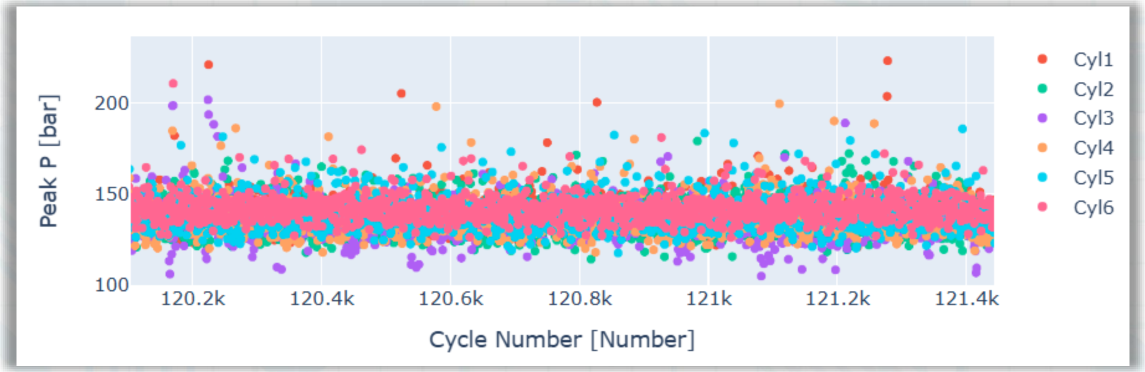
Heavy-Duty SCE

SwRI Hydrogen ICE Class 8 Demonstrator

SPI Event Example from SwRI H_2 ICE

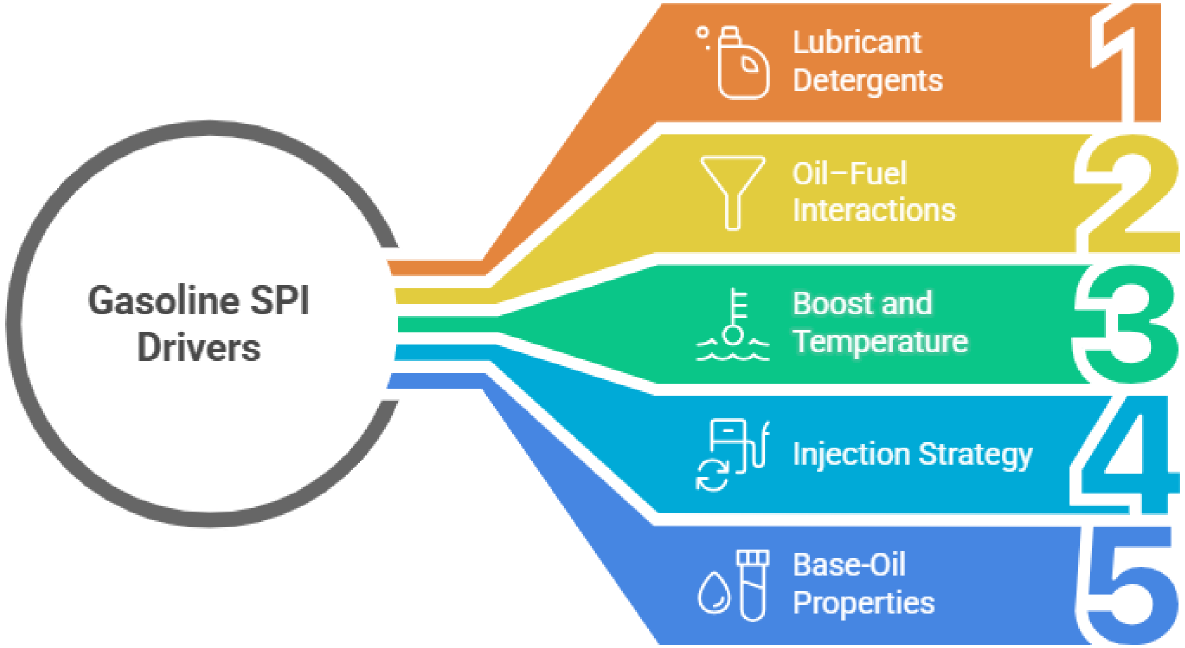
- H_2 SPI **frequency is higher**, albeit most events are **mild compared to gasoline SPI** superknock
- Moreover, HD engines employing H_2 have stronger cylinders and higher PcP limits compared to light-duty gasoline engines.
- Nonetheless, there are opportunities to optimize H_2 ICE combustion chamber design to mitigate or eliminate hot spot SPI, for instance
- SwRI is currently working to understand the lubricant impacts on SPI





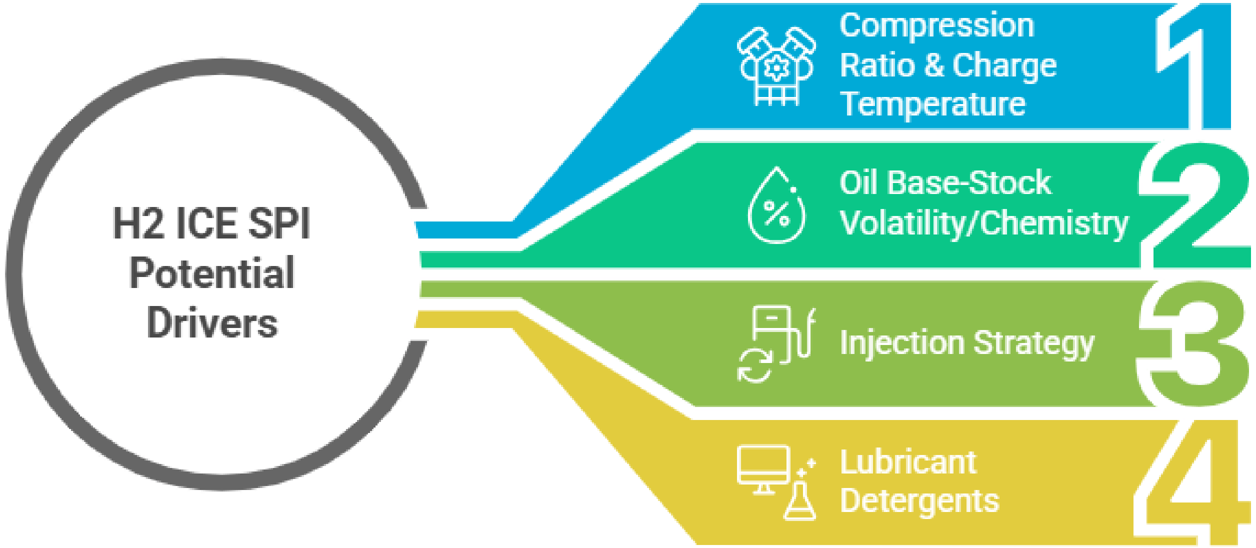
Is SPI Different In H_2 vs Gasoline ICEs?

- Limited literature studies have demonstrated that oil volatility and compression ratio may influence H_2 SPI more, while additive chemistry dominates gasoline SPI.



Gasoline SPI Drivers

1. Lubricant Detergents
2. Oil–Fuel Interactions
3. Boost and Temperature
4. Injection Strategy
5. Base-Oil Properties



H2 ICE SPI Potential Drivers

1. Compression Ratio & Charge Temperature
2. Oil Base-Stock Volatility/Chemistry
3. Injection Strategy
4. Lubricant Detergents

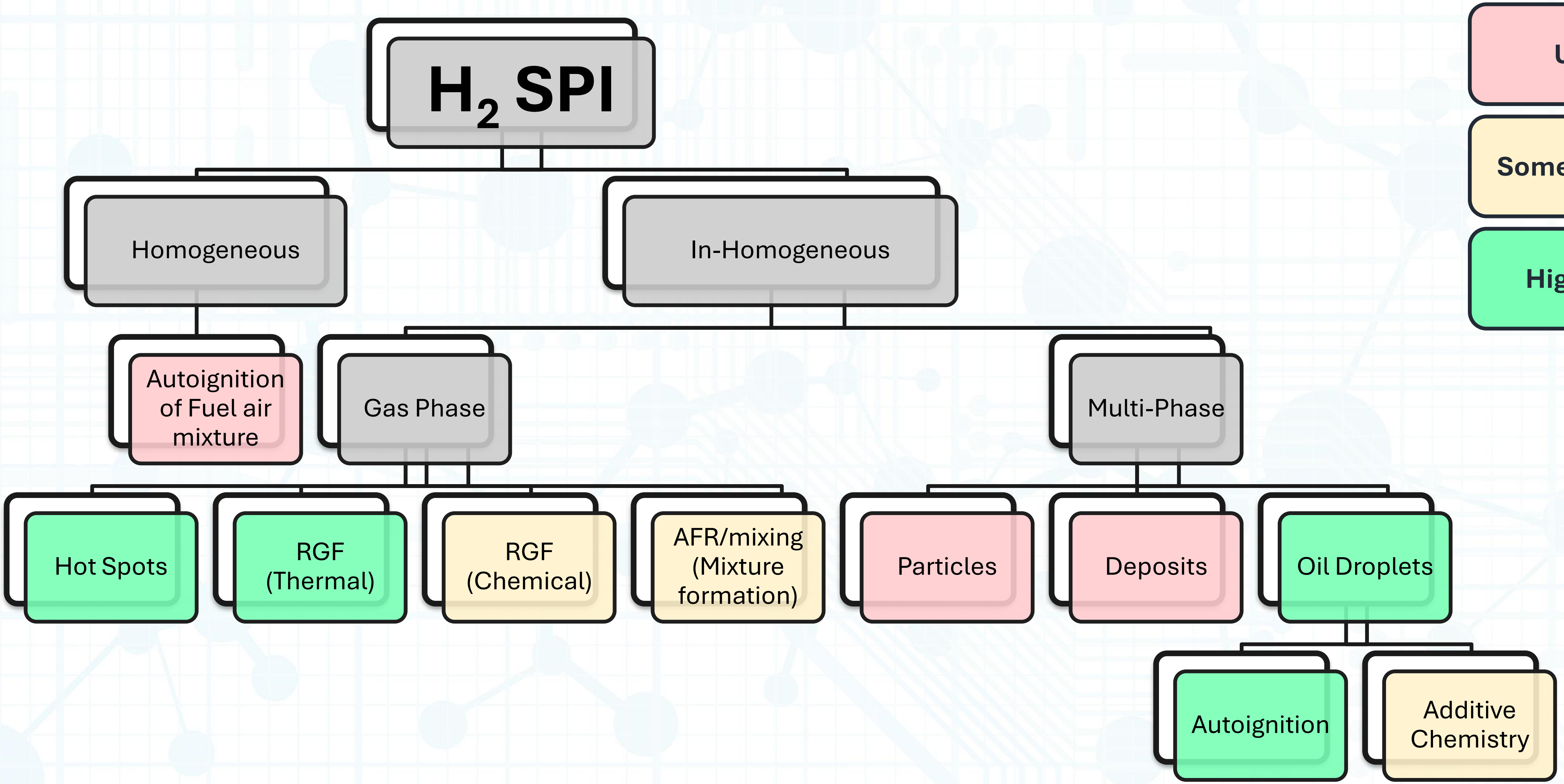
Note that SPI is only a challenge for lean premixed SI H_2 ICEs. Other H_2 combustion strategies, such as H_2 HPDI combustion, are not susceptible to it

Potential/Likely SPI Mechanism(s) in H_2 ICEs

Unlikely

Somewhat Likely

Highly Likely



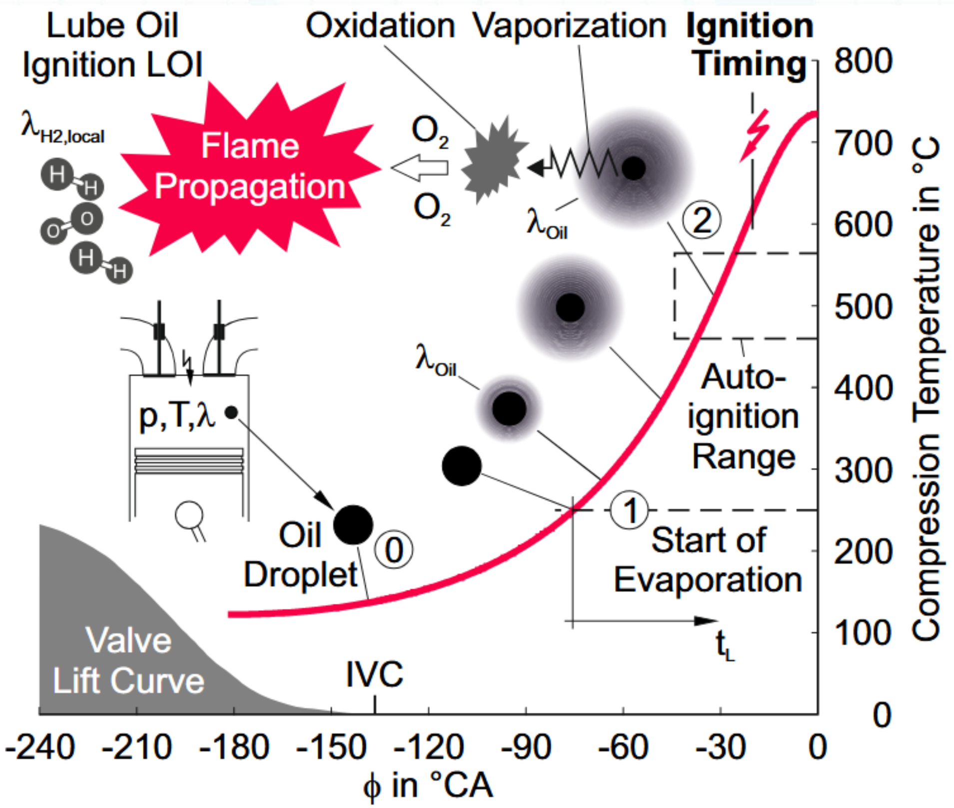
- H_2 SPI
  - Homogeneous
    - Autoignition of Fuel air mixture
  - In-Homogeneous
    - Gas Phase
      - Hot Spots
      - RGF (Thermal)
      - RGF (Chemical)
      - AFR/mixing (Mixture formation)
    - Multi-Phase
      - Particles
      - Deposits
      - Oil Droplets
        - Autoignition
        - Additive Chemistry

Oil Induced H_2 SPI Mechanism

Hypothesis

Relative to gasoline engines, lean H_2 engines have higher compression pressure and temperature due to higher mixture λ, compression ratio, and γ, whereby any lubricant droplets ejected into the combustion chamber will auto-ignite with little sensitivity to the oil additive chemistry

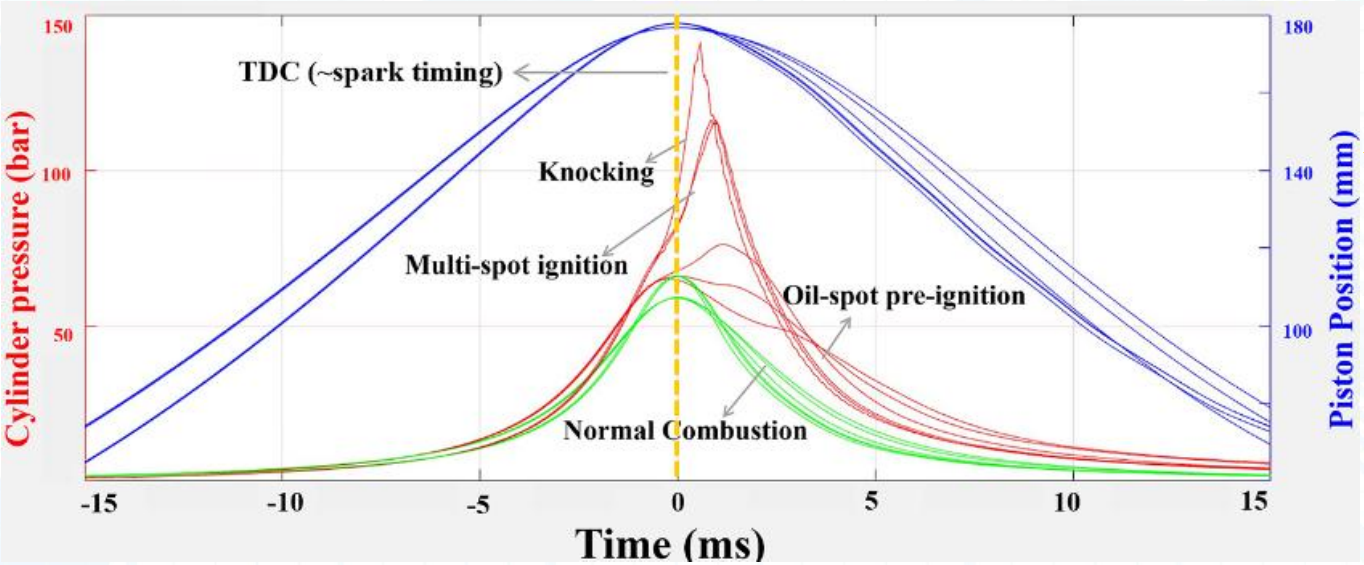
- Explored via:
  - Literature review
  - 0D chemical kinetics modeling
  - Engine testing

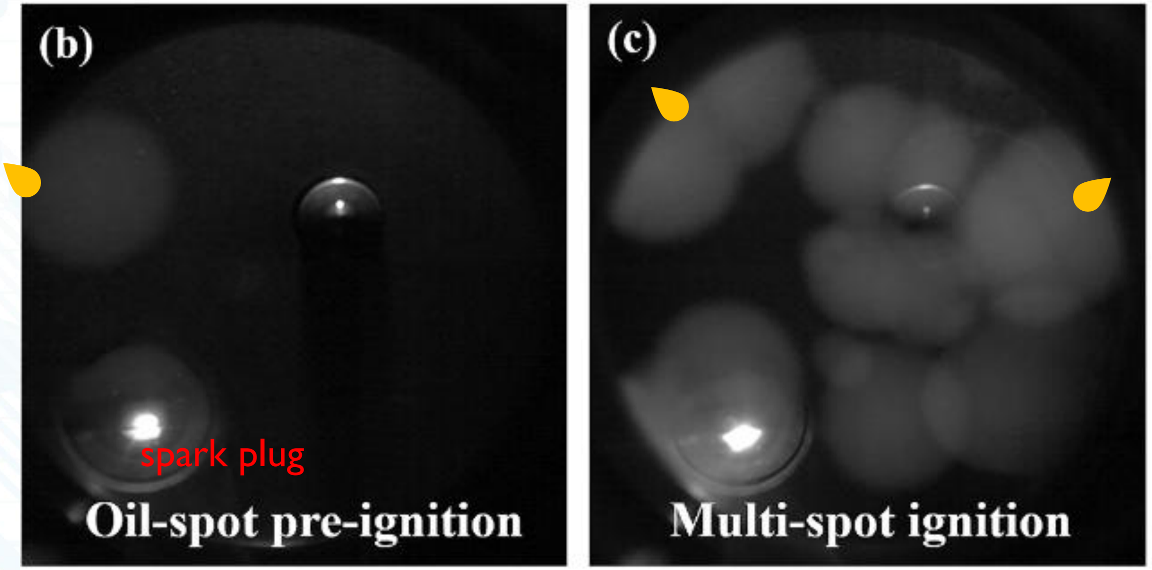


https://doi.org/10.1007/s41104-024-00141-7

Yeganeh, Maryam, et al. "Experimental investigations of hydrogen pre-ignition phenomenon induced by two different lubricating oils in a rapid compression expansion machine." *PCI (2024)*

- Oil sprayed on liner before compression
- **Oil spot PI**: one AI flame from an oil droplet
- **Multi-spot PI**: multiple AI flames from oil droplets / hot pockets
- Oil AI did not occur at CR < 12:1 (λ: 2 - 3)
- Oil AI occurred at lower CRs at higher λ

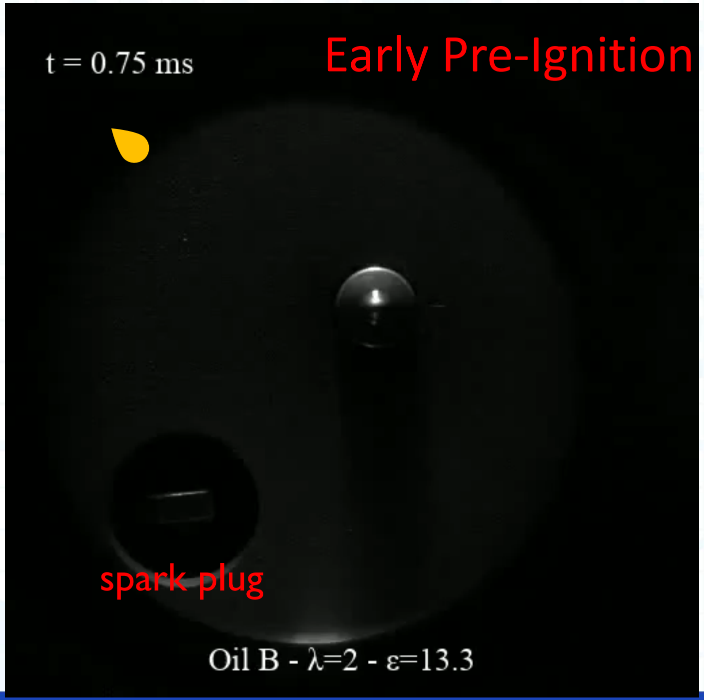


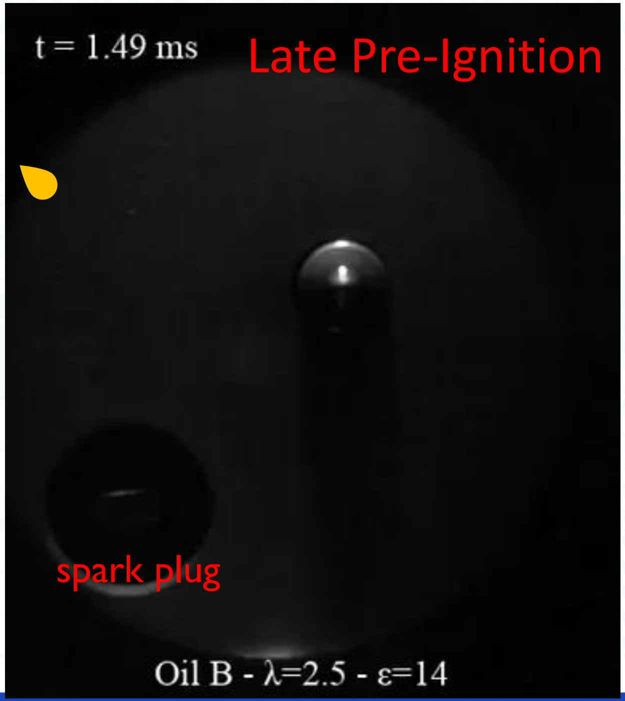


Yeganeh, Maryam, et al. "Experimental investigations of hydrogen pre-ignition phenomenon induced by two different lubricating oils in a rapid compression expansion machine." *PCI (2024)*

- Compared 2 different oils
  - Oil A, Gr. II with Ca
  - Oil B, Gr.V with Ca & Mg
- Oil B resulted in "early" pre-ignitions

Gr. II (n-Hexadecane) is more reactive than Gr. V (methyl decanoate or glycol)





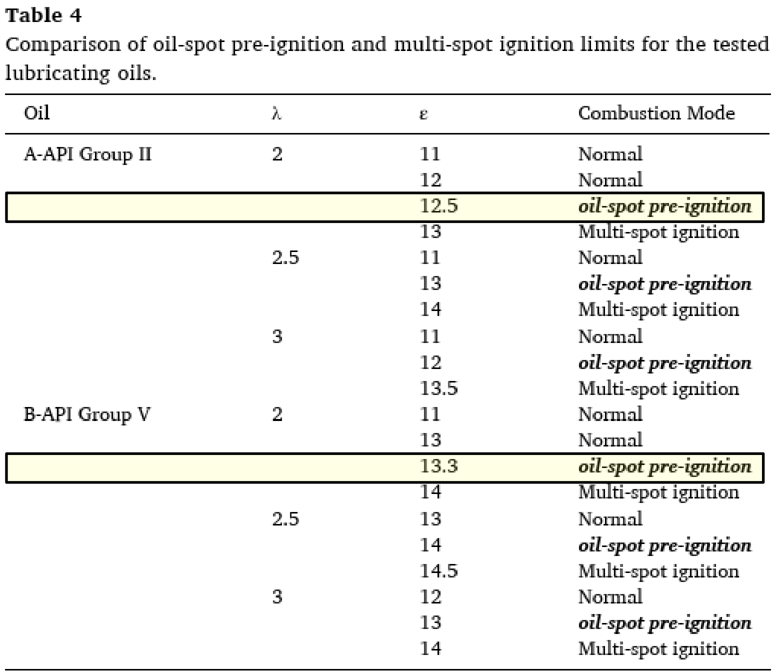


Table 4
Comparison of oil-spot pre-ignition and multi-spot ignition limits for the tested lubricating oils.

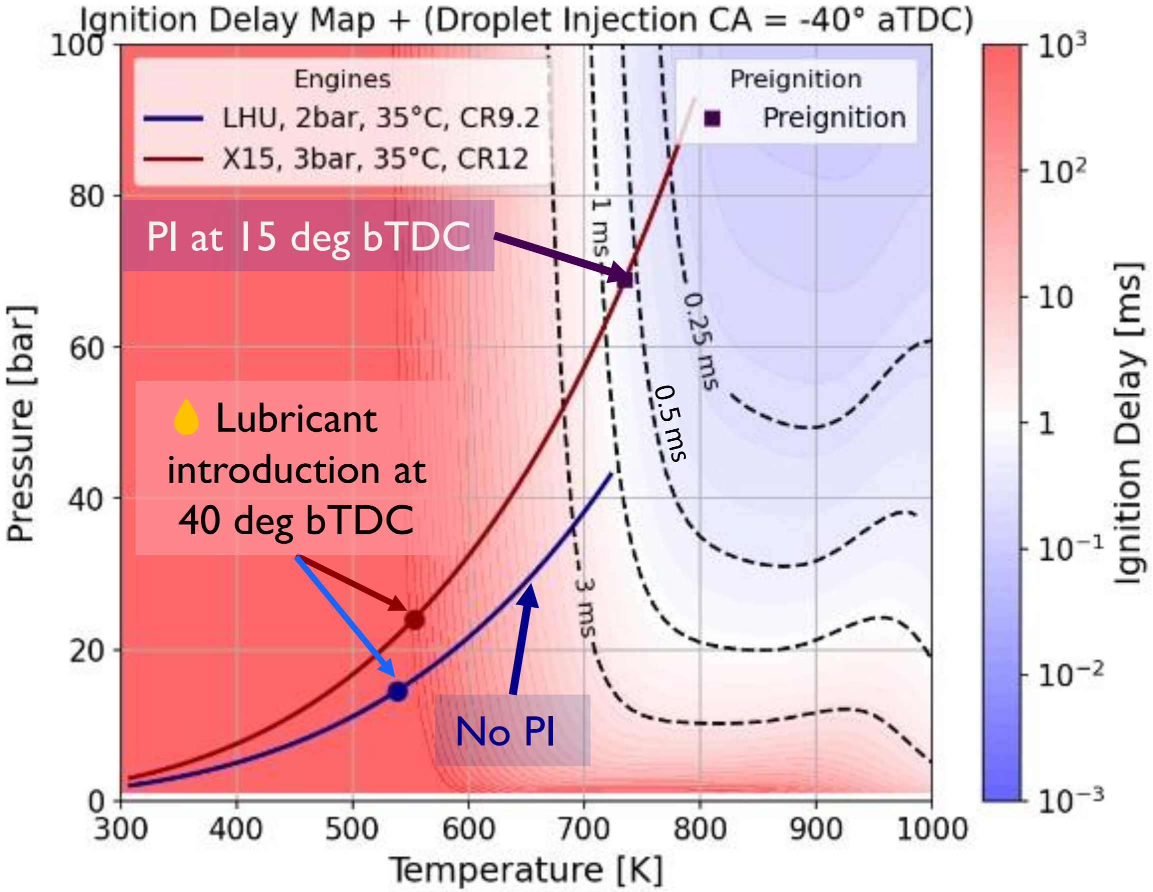
Oil	λ	ε	Combustion Mode
A-API Group II	2	11	Normal
		12	Normal
		12.5	***oil-spot pre-ignition***
		13	Multi-spot ignition
	2.5	11	Normal
		13	***oil-spot pre-ignition***
		14	Multi-spot ignition
	3	11	Normal
		12	***oil-spot pre-ignition***
		13.5	Multi-spot ignition
B-API Group V	2	11	Normal
		13	Normal
		13.3	***oil-spot pre-ignition***
		14	Multi-spot ignition
	2.5	13	Normal
		14	***oil-spot pre-ignition***
		14.5	Multi-spot ignition
	3	12	Normal
		13	***oil-spot pre-ignition***
		14	Multi-spot ignition

SPI occurs at higher CR for Oil B

0-D Preignition Modeling

- Motoring curves were generated for representative gasoline and H_2 engines using 0-D engine models swept from BDC to TDC, and
- Preignition likelihood was estimated based on lubricant droplet auto-ignition

Parameter	LHU (Gasoline)	SwRI H_2 X15
Bore [mm]	85	135
Stroke [mm]	85	169
CR [-]	**9.2**	**12**
Lambda [-]	**1**	**2.2**
RPM	1800	1200
P_{int} [bar]	**2**	**3**
T_{int} [°C]	35	35



PI at 15 deg bTDC

Lubricant introduction at 40 deg bTDC

No PI

Oil droplet introduction at 40 ° $aTDC_f$ resulted in oil autoignition at 15 °$bTDC_f$ in the H_2 ICE case

H2 SPI Testing - Test Engine

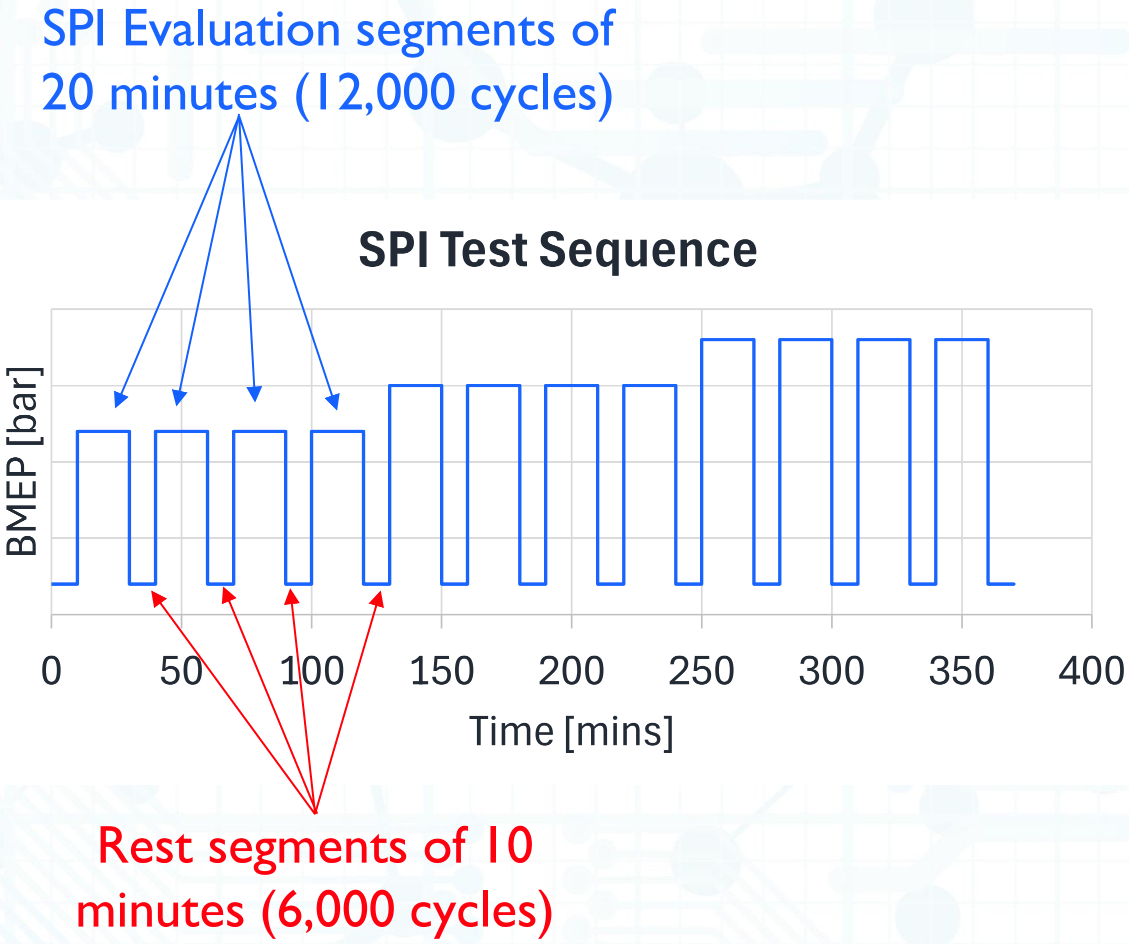
- Cummins X15N engine converted to run on H_2 ICE
- Twin engine to the one used in the SwRI H_2 ICE Truck demonstrator
- At the time this work, the engine was limited to 370 hp
  - Turbo has now been upgraded: capability of 440 HP, ~ 20 bar BMEP @ 1200 rpm

SwRI X15H	
Displacement (L)	15
Configuration	Inline, 6 cylinders
Bore (mm)	135
Stroke (mm)	169
Compression ratio	12:1
Fuel admission	Port fuel injection (10-15 bar)
Ignition type	Spark ignition

Zero Impact Engines: A Demonstration of H2-ICE Technologies for Zero-CO2 and Near-Zero NOX in the North American Class 8 Heavy-Duty Truck Market. 45th International Vienna Motor Symposium 2024. *https://doi.org/10.62626/ws3g-faaf*

H_2 ICE SPI Testing Procedure

- Test architecture was similar to the gasoline engine SPI test
- Four repeats at each of the three test conditions
- Speed of 1200 RPM
- Temperatures:
  - Oil Gallery: 100 °C *(controlled by coolant temperature)*
  - Coolant Out*: 90 °C



* *Coolant temperature as low as 70 °C was tested and yielded lower SPI rates. Not discussed today*

H_2 ICE SPI Test Oil Matrix

- Oil matrix chosen to evaluate impact of additive chemistry, primarily Ca versus Mg content
- 2 Commercially available
  - Shell Rotella T4 (API CK-4, traditional HD engine oil)
  - Valvoline Premium Blue One Solution (API CK-4, SP, Cummins CES 20092)
- 2 Experimental (volatility & detergent type)

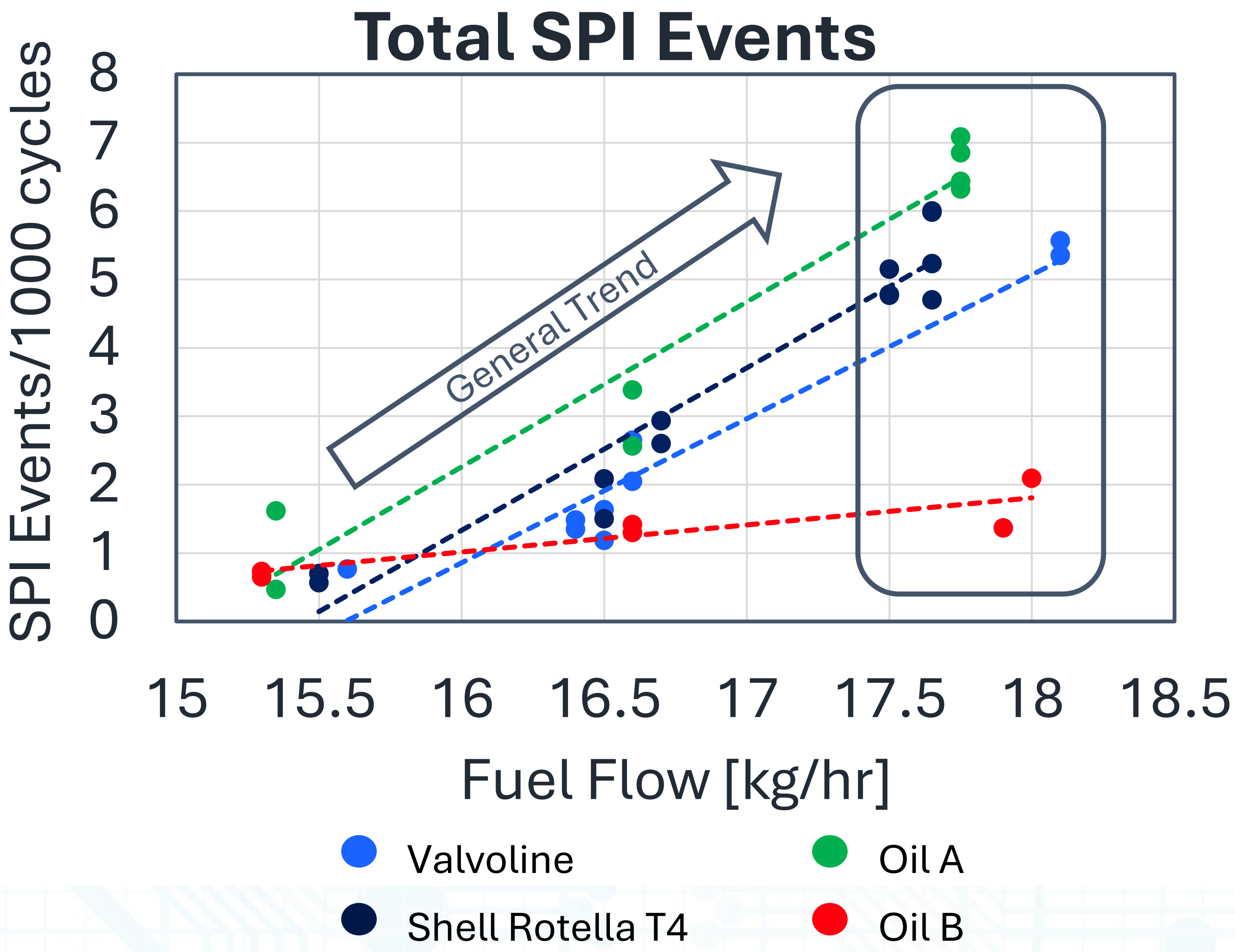
Method	Property	Units	Valvoline Premium Blue	Shell Rotella T4	Oil A	Oil B
D445	KV at 100°C	(cSt)	15.1	14.81	11.28	10.59
D5185	Ca	(ppm)	1184	2261	10	677
D5185	Mg	(ppm)	746	14	938	349
D5185	P	(ppm)	768	1106	873	807
D5185S	S	(ppm)	2243	3414	2213	2254
D5800	Volatility	(%)	12.2	11.7	12.6	27

Difference in additive metals

Difference in base oils

H_2 ICE SPI Testing → Example Results

- Results demonstrated oil-to-oil SPI differences
- Higher volatility experimental Oil B exhibited lower SPI – surprising result – further work ongoing
- Further internal and external client-funded work is ongoing to understand SPI in H_2 ICEs



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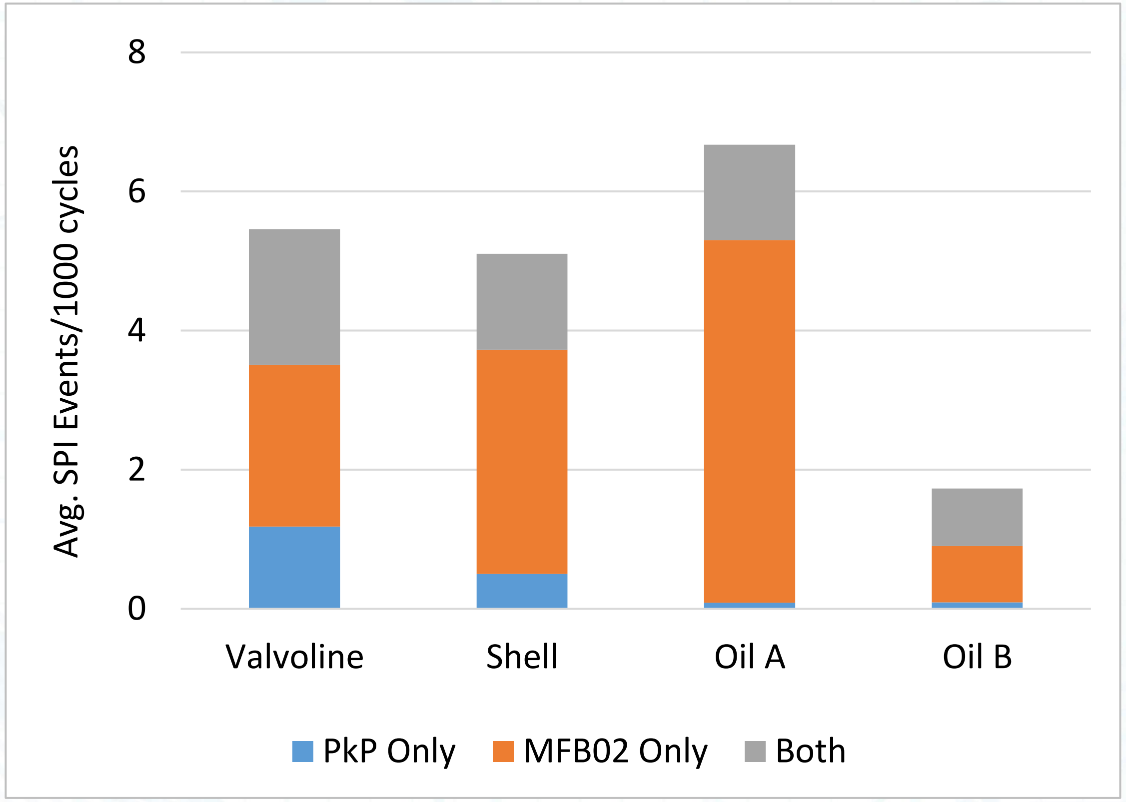

Commercial oils had similar SPI
Surprisingly, the ***high volatility*** oil gave the ***lowest*** SPI

Concluding Remarks and Next Steps

- A repeatable SPI test procedure was demonstrated on the multi-cylinder H_2 ICE
  - H_2 ICE SPI activity was investigated for four oils in a limited capacity
- Conclusions: Base oil properties seemed to impact the SPI rates, with higher volatility oil demonstrating the lowest SPI rates, contrary to the expected trend under high-load operation
  - 0D modeling suggested that lubricant may autoignite on its own in H_2 ICE high load operating conditions subsequently causing late-cycle H_2 SPI
  - Lubricant additives, especially calcium, did not seem to correlate with H_2 SPI
- Lubricants with varying volatilities and boiling points are being investigated for SPI in H_2 ICE
- This established test procedure is available to evaluate different oils or hardware designs for SPI mitigation

Questions?

Dr. Vickey Kalaskar
Lead Engineer, Engine Systems, Research & Innovation
Powertrain Systems Engineering
+1-210-522-5342
Vickey.kalaskar@swri.org

LinkedIn profile

Dr. Abdullah Bajwa
Research Engineer, Engine Systems, Research & Innovation
Powertrain Systems Engineering
+1-210-522-2782
Abdullah.bjawa@swri.org

LinkedIn profile

Alex Michlberger
Lead Engineer, Engine Systems, Research & Innovation
Powertrain Systems Engineering
+1-210-522-6097
Alexander.michlberger@swri.org

Relevant SwRI SPI Publications

- Kristian Rönn, Andre Swarts, Vickey Kalaskar, Terry Alger, Rupali Tripathi, Juha Keskiväli, Ossi Kaario, Annukka Santasalo-Aarnio, Rolf Reitz, Martti Larmi, Low-speed pre-ignition and super-knock in boosted spark-ignition engines: A review, Progress in Energy and Combustion Science, Volume 95, 2023, 101064, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2022.101064
- Kalaskar, V., Swarts, A., and Alger, T., "Impact of Engine Age and Engine Hardware on Low-Speed Pre-Ignition," SAE Technical Paper 2018-01-1663, 2018, https://doi.org/10.4271/2018-01-1663
- Swarts, A. and Kalaskar, V., "Market Fuel Effects on Low Speed Pre-Ignition," SAE Int. J. Adv. & Curr. Prac. in Mobility 3(5):2473-2483, 2021, https://doi.org/10.4271/2021-01-0487
- Kalaskar, V., Moore, T., and Swarts, A., "On Optical Semi-Quantitative Spectral Study of Low-Speed Pre-Ignition Sources in Spark Ignition Engines," SAE Int. J. Adv. & Curr. Prac. in Mobility 3(5):2581-2593, 2021, https://doi.org/10.4271/2021-01-0486
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Relevant SwRI SPI Publications (2)

- Mounce, F., "Development of a Standardized Test to Evaluate the Effect of Gasoline Engine Oil on the Occurrence of Low Speed Pre-Ignition - The Sequence IX Test," SAE Technical Paper 2018-01-1808, 2018, https://doi.org/10.4271/2018-01-1808
- Amann, M. and Alger, T., "Lubricant Reactivity Effects on Gasoline Spark Ignition Engine Knock," SAE Int. J. Fuels Lubr. 5(2):760-771, 2012, https://doi.org/10.4271/2012-01-1140
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- Michlberger, A., Sutton, M., Kocsis, M., Anderson, G. et al., "On-Road Monitoring of Low Speed Pre-Ignition," SAE Technical Paper 2018-01-1676, 2018, https://doi.org/10.4271/2018-01-1676