2020 CRC STOCHASTIC PRE-IGNITION WORKSHOP

Summary

July 2021

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

AGENDA

2020 CRC Stochastic Pre-Ignition Workshop

Workshop Organizers

Elana Chapman, Co-Chair, General Motors
Vince Costanzo, Co-Chair, Aramco Americas
Jim Anderson, Ford Motor Co.
Allen Aradi, Shell
John Cruz, Daimler
Andrew Ickes, Chevron
Asim Iqbal, FCA US, LLC.
Greg Lilik, ExxonMobil Research & Engineering Co.
Steve McConnell, Marathon Petroleum Co.
Bob McCormick, National Renewable Energy Laboratory
Scott Sluder, Oak Ridge National Laboratory
Matthew Thornton, National Renewable Energy Laboratory

WebEx Event
September 28-29, 2020

Monday, September 28, 2020		*U.S Eastern time (UTC-4)
* 7:00 AM	CRC Introduction and Logistics by Chris Tennant, Executive Director	
7:15 AM	Workshop Introduction to Stochastic Preignition by Co-Chairs Elana Chapman, (GM), and Vince Costanzo (Aramco)	
7:30 AM	Hardware/Operating Conditions	Andre Swarts (SwRI)
7:50 AM	**Q & A**	**Rick Davis (retired GM), Vickey Kalaskar (SwRI)**
8:00 AM	Test Methodology	Vickey Kalaskar (SwRI)
8:20 AM	**Q & A**	**Roger Cracknell (Shell), Brad VanDerWege (Ford)**
8:30 AM	Statistics	Doyle Boese (Infineum)
8:50 AM	**Q & A**	**Balki Chinta (GM), Ati Tolou (FEV)**
9:00 AM	Final thoughts and Wrap up for Day 1	Elana Chapman, (GM), Vince Costanzo (Aramco)
9:10 AM	**END OF DAY 1 TECHNICAL PROGRAM**	
Tuesday, September 29, 2020		
7:00 AM	Oil	Ashu Gupta (Afton)
7:20 AM	**Q & A**	**Andy Ritchie (Infineum), Alex Michlberger (SwRI)**
7:30 AM	Fuel	Allen Aradi, (Shell)
7:50 AM	**Q & A**	**Paul Loeper (Chevron), Derek Splitter (ORNL)**
8:00 AM	*Break*	
8:10 AM	***Panel Discussion (All Speakers and additional panelists)***	**Elana Chapman, (GM), Vince Costanzo (Aramco), Andre Boehman (UM), Balki Chinta (GM), Frank Cooney (GM), Roger Cracknell (Shell), Rick Davis (retired GM), Andrew Huisjen (FCA), Eric Kalberer (Shell), Masaharu Kassai (Nissan), Leandro Menezes (Mahle), Andrew Ritchie (Infineum), Ron Romano (Ford), Derek Splitter (ORNL), Andrea Strzelec (WISC), Ati Tolou (FEV)**
8:50 AM	Final thoughts and Wrap up for Day 2	Elana Chapman, (GM), and Vince Costanzo (Aramco)
9:00 AM	**END OF DAY 2 TECHNICAL PROGRAM, END OF WORKSHOP**	

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Introduction to Stochastic Preignition

Presenter: Elana Chapman (GM), Vince Costanzo (Aramco)

Summary:

Elana Chapman provided a brief introduction defining what Stochastic Preignition (SPI) is, describing the effect of SPI, and reviewing past history on the causes of SPI both in the far past and current experimental findings in the literature. The Introduction was meant to serve as the means to kick off the series of topics from the panelists into specific areas that are identified aspects of the causes of SPI in Gasoline Turbocharged DI engines.

Presentation Notes:

Slide 1: Introduction to Stochastic Preignition

- Materials presented predominately sourced from:
    - SAE paper SAE 2015-01-1869
    - JSAE 20159129
    - Oral presentation at the 2016 SAE World Congress in Detroit

Slide 2: What is SPI-Stochastic Preignition?

- Early pressure rise in the cylinder, prior to a normal average cycle ignition, which can exhibit damaging high peak cylinder pressures and engine knock
    - Can occur with and without knock, and before or after the spark point, and with pressure occurring in advance of the normal cycle
    - Damaging cycles are those with peak knock pressures above the engine design limits
        - Sometimes referred to as “Superknock” or “Megaknock”
- Important to note that while pressure rise prior to the ignition point is a clear indication of SPI not all SPI cycles exhibit this behavior.
    - It is possible to have SPI that occurs coincident or after the main spark event

Slide 3: Significance of Stochastic Pre-Ignition Issue

- OEMS are introducing turbocharged engines for improved fuel economy
    - These applications are designed to operate at low engine speeds and high loads for fuel economy
    - Production volumes are increasing making SPI an even more important issue
- SPI failures have been found in Turbocharged engines
    - Cracked pistons
    - Broken piston skirts, lands, and rings
    - Occasional connecting rod and crank damage

Slide 4: What History Tells Us

Slide 5: A Literature Review of Abnormal Ignition by Fuel AND Lubricant Derivatives

- Detailed literature review for the 2015 SAE paper
- Goal was to see if anything similar to SPI had occurred in the past and, if so, how did the industry handle it
  - A key finding was that the industry worked together to accelerate learnings and develop solutions

Slide 6: Rumble – key points

- 1940's through 1960's
- Low pitched noise in the ~800 to 1400 Hz range
  - Due to bending vibration of the crankshaft, caused by abnormally high pressure rise rates
- Distinctly different than end-gas autoignition / knock!
  - Isooctane: RON = 100, very resistant to rumble
  - Benzene: RON ~ 103, very prone to rumble

Slide 7: Rumble – sample data

- Not knock / autoignition
  - Rather it was very fast late-phase combustion leading to high pressure rise rates exciting the crank structure

Slide 8: Rumble – cause

- Cause attributed to hot, "flaked" combustion chamber deposits
  - Extended operation at light duty schedules tended to produce deposits
  - Operation at high load / speed would then result in abnormal ignition from these deposits

Slide 9: Wild Ping – key points

- Appears to be much more closely related to the current SPI issue
  - "One or more erratic sharp cracks"
  - Short-lived nature: particles either burn up or are exhausted
  - Seemingly erratic occurrence over "short" time periods

Slide 10: Summary – Past Observations of Abnormal Ignition

- Rumble: not similar to SPI/LSPI
- Wild Ping: very similar to SPI/LSPI
- HOWEVER, <u>past investigators saw very similar trends with regards to abnormal ignition for both rumble and wild ping</u>
  - Similar trends regarding fuel, hardware, and lubricants
  - BOTH related to deposits in the combustion chamber

Slide 11: SUMMARY – Historical Effects

- Summary table of trends and effects – many similarities to today's SPI findings
  - Metallic additives
  - High aromatic content in fuel

    - Operating conditions leading to high in-cylinder pressures and temperatures

Slide 12: Recent Understanding

Slide 13: A Sequence of Events, Not a Singular Phenomenon

- Engine failure due to SPI is the net result of a sequence of necessary, but not sufficient, steps
- Each step is affected by engine hardware, operating parameters, fuel properties, and lubricant properties
- SPI, in this context, is defined as the steps leading up to the actual pre-ignition event – regardless of whether or not it results in high knock amplitudes

Slide 14: Initiation Mechanisms

- Background information from Toyota research:
    - Abnormal preignition can initiate from:
        - Deposit particles
        - Oil droplets
        - Top land fluids

Slide 15: Comparison to Historical Effects

- It is not clear that the modern SPI phenomenon is exactly the same as past phenomena.
    - HOWEVER, It is clear that many of the trends observed in recent history are very similar to those observed in the past
    - Many of the current findings of SPI sensitivities seem to align with historical findings:
        - Base fuel:
            - Higher boiling fraction components
        - Oil additives:
            - Metallic detergent content - calcium had the strongest impact
            - Phosphorus and sulfur content
            - Presence of zinc inhibitors
            - Total sulfated ash content does not correlate
        - Operating conditions:
            - Factors that promote combustion (higher temperatures and higher oxygen partial pressures)
            - Soot production (due to specific operating conditions)
        - Deposit properties:
            - Size of particles
    - Others may be similar but there is not enough data available to make connection

Slide 16: What's Missing?

- Based on a literature review of the previous 10 years of research (prior to 2016)

Slide 17: Suggested Areas of Further Investigation

- Suggestions made in 2016 SAE World Congress Oral Presentation *(see presentation for details)*

- One of the goals of this CRC SPI Workshop is to determine what work has been done in the interim to address these issues and identify those that need further understanding

Slide 18: What's next?

Slide 19: Goal of this event

- Technical exchange focused on role of the following on stochastic preignition and associated engine hardware failures:
    - Hardware
    - Operating conditions / operating pattern
    - Fuel
    - Lubricant
    - Statistics
- Identify next steps and opportunities for possible collaborative studies

Hardware/Operating Conditions

Presenter: Andre Swarts (SWRI)

Summary:

Andre Swarts from Southwest Research Institute provided a high-level overview of the LSPI phenomenon followed by a discussion of the influence of engine hardware and operating conditions on LSPI tendencies. It was noted that the crevice fluid hypothesis of LSPI initiation remains the best supported description, with solid particle initiation seen to have a complementary impact. With a focus on the low speed, high load operating conditions, the influences of the following engine operating parameters were considered, including potential implementations of LSPI mitigation techniques based on the observations:

- Calibration factors:
  - Engine coolant temperature (reduced temperature promotes LSPI)
  - Air-fuel ratio (leaner mixtures promote LSPI)
  - EGR fraction (increased EGR rates reduce LSPI)
  - Injection timing and pressure (wall wetting increases LSPI)
- Design parameters:
  - Injection spray targeting (wall wetting promotes LSPI while piston wetting decreases LSPI)
  - Injector location – Side vs. Central (Central DI worsens LSPI compared to side DI)
  - Piston chamfer (reduces crevice volume and, consequently, crevice fluid loading)
  - Top land height (can similarly reduce crevice volume)
  - Ring tension and gaps (High tension or gapless rings can reduce oil exchange between rings, reducing the ejection of crevice fluid)
  - Piston strength (does nothing to affect LSPI rates, but may avoid damage)
- Other considerations:
  - Engine age (LSPI rates drop as engine ages – due to piston ring wearing into liner)
  - Fugitive oil (small increases in oil increase LSPI, very large increases in oil may reduce LSPI)
  - Engine deposits (not a primary effect)
  - Transient effects (has not yet been systematically studied)

Following the main presentation, Andre provided answers to a number of questions. The questions and answers are summarized in the notes.

Presentation Notes:

Slide 2

- Preamble
- Trying to cover everything else

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- Refers to LSPI throughout presentation
- Might not be exhaustive, any omissions are not intentional
- Presenting a general view, even if some observations are contradictory
- Accept, for now, that steady-sate is a reasonable representative of what happens in real-world transient work

Slide 3

- Contents

Slide 4

- Working hypothesis
- Crevice fluid as likely cause of LSPI
    - Mixture of fuel and oil at right proportion under right T and P conditions
- Soot/particles have a contributing or complementary impact
    - Soot/deposits

Slide 5

- Speed/load demands
- Typically at lowest end of engine speed range (unlike high speed spark knock we're used to)
- High load with high intake air pressure are most prone
- Only started seeing this once forced induction DI engines came into production
- High load, low speed with really retarded spark (a lot of time for pre-ignition to take place)
- Movement of crevice fluids are important

Slide 6

Calibration

- Engine coolant temperature
    - Reduction in coolant temp increases LSPI activity
    - Contrary to general view of autoignition (where temperature makes it worse)
    - This is engine-specific, some engines display contrary response
    - Good correlation between wall temperatures and fuel characteristics that contribute to LSPI tendencies

Slide 7

Air-fuel ratio

- Lean, LSPI gets worse
    - Direct (fueling) indirect (cam timing, etc.)
    - Not sure what the mechanism is for why lean mixtures make things worse (apart from oxygen availability)
- Rich, LSPI rates drop
    - Good lever used in industry for mitigation/avoidance of LSIP
    - Used for protection in real life calibration

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Slide 8

EGR

- Increasing EGR reduces LSPI activity
- Not necessarily production-feasible, but a factor that can be considered
- Same benefit on spark knock

Slide 9

Injection timing and pressure

- Mechanism – comes down to fuel impingement on wall
- Very early or very late – more wall wetting – higher LSPI activity
- Have to consider emissions and performance, so it might not represent a production-ready control mechanism for LSPI
- Similar for pressure – tradeoff between atomization and penetration

Slide 10

Injection targeting

- Could change the targeting (liner vs. piston impinging injector)
- Hitting the piston results in a drop in LSPI
- Correlation between LSPI and hydrocarbon emissions

Slide 11

Injector location

- Central DI and PFI worsens LSPI compared to side DI (due to increased wall wetting)
- With gaseous fuels, LSPI is almost non-existent
- In HD, there's still an SPI phenomenon that is attributed to oil consumption
- Engine specific, but gives some indication of phenomena at play

Slide 12

Design – Piston chamfer

- Tying to reduce crevice volume
- Added a chamfer to the piston crown results in lower LSPI (reduced volume, less fluid to be ejected into chamber)
- Maybe not production appropriate (emissions, robustness, etc.)

Slide 13

Top land height

- Reducing top land height reduces crevice volume, also reduces LSIP
- Have less initiators to get things going

Slide 14

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Ring tension and gaps

- High tension or gapless rings can reduce oil exchange between rings
    - Upsets composition of oil and amount in crevice region
    - Reduces amount available to initiate LSP
- Have to balance benefit of LSPI reduction with other impacts (emissions, friction, etc.)

Slide 15

Piston strength

- Damage is very different than what we see with spark knock
- Design solution is very different
- May want to reinforce piston in weak areas (Mahle is working on particularly robust piston designs)
- Does nothing about LSPI rates, but minimizes consequences

Slide 16

Engine condition – age

- Generally reduces LSPI rate with engine age
- All new oil fills for measurements as engine ages
- Cylinders seal up better, reducing oil flow into crevice
- RE-honing or anything else to restore oil exchange will allow LSPI rate to recover

Slide 17

Fugitive oil

- Increased LSPI due to increased blowby by design or due to engine wear, etc.
- Extra oil consumption just makes things worse
- "Goldilocks" response
    - Small increase in oil leads to a small increase in LSPI
    - Large increase decreases LSPI

Slide 18

Deposits

- Not a primary effect – plays a complementary role

Slide 19

Transient LSPI

- No systematic study of transient LSPI response
- LSPI can occur at much higher engine speeds than we've been studying

Slide 20 – Conclusions

- Data points to crevice fluid as impacting LSPI

- Engine parameters are Agnostic to fluid changes

Slide 21

Recommendations

- Not only frequency but severity is also important
    - Not many studies of severity

Question & Answer

Questions in black, responses in blue

- Are higher engine speed events more or less problematic from an engine hardware damage perspective? In general engine component temperatures (i.e. pistons) are higher at high engine speeds lowering material strength.
    - Nothing in the academic domain
    - OEMs are monitoring LSPI in the market, but no systematic study of severity or impact on hardware

- why do crevice fluid, oil droplets or combustion particles act as igniters? What imparts the pyrophoric-like character to these aerosolized solid/liquid phases
    - As far as fuel and oil are concerned, it is autoignition as traditionally understood
    - If the temperature rises enough, it will ignite
    - For solid particles, need a lot of time to heat it to a high enough temperature
        - If there are volatile components on the particle, this seems more likely to be the source of ignition
- Is autoignition of an ejected droplet directly causing SPI still a supported theory? There seems to be evidence that droplets are ignited by the main combustion and retained in the cylinder to initiate SPI on the following cycle which fits with the typical alternating cycle pattern.
    - We still believe that the first cycle in a series is fluid-ignited, shockwaves from knock may release deposits, which then have sufficient residence time to survive next cycle if not exhausted and may be the source of ignition for subsequent events
- Alternating cycles – any comment on length of sequence on durability?
    - Not aware of any study in the public domain
    - Fatigue design question, not aware of anything systematic
    - Is it difficult to generate these LSPI cycles
    - More difficult to generate a specific type of sequence
    - Similar behavior with very early spark
    - **Related questions:**
    - Could you provide the percentage of chain events as the fraction of total events in Sequence IX?
    - It is mentioned that "other statistical analyses can be performed to test the tendency towards chain events." Could you provide details on these analyses?
    - Is there any other statistical approach to correct for data distribution normality, in case of inequalities failure of Sequence IX?

- Has any information been published on the impact of "follow-on" events on engine hardware damage? Specifically, when counting SPI events are X individual events more or less damaging than a single SPI event with X alternating cycle "hits" of similar magnitude? (edited)
- How important is SPI at higher engine speeds? Most early studies linked SPI with low engine speeds and most test procedures focus on the lower engine speeds. But several newer publications have noted high speed SPI events. Are these stand-alone events or "follow-on" events during an acceleration?

- Rich operation is becoming a non-viable option (due to emissions impacts). How significant is this change on our ability to control LSPI?
  - Rich operation has been the means to control this
  - Our ability to do this really depends on how/when we may be able to use rich excursions
  - If rich excursions are not allowed at all, then we would have to resort to the other possibilities discussed, but ti would be hard
- Does EGR reduce the rate of SPI events or just the propensity of those events to generate high knock amplitudes?
  - Everything he's commented on is an effect on frequency, though, intuitively, it may also affect severity, but he doesn't have any data to point to in that regard.

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Test Methodology

Presenter: Vickey Kalaskar

Question and Answer

1. Is the engine controlled differently when running an oil evaluation test vs a fuel evaluation test?
   The test cycle is the same. The oil is fixed to study the effect of fuel on SPI. The fuel is fixed to investigate the effect of oil on SPI events.
2. How make apples to apples comparison for the oil or fuel with test conditions/ operating conditions?
   For different engine stands with the same engine make: The baseline SPI test with fixed oil and fuel every 3-4 candidate tests on different stands can help adjust the severity of the candidate SPI tests concerning engine normalized and hour corrected baseline SPI activity.
   For different engine stands with different engine platforms: The same procedure as above can be followed to make apples to apples comparisons.
3. In the data analysis, are pre-igniting cycles without knock being counted as LSPI events? Are non-knocking cycles predictive of imminent knocking cycles?
   Pre-ignition is stochastic in nature. The non-knocking events could have knocked under the "right" conditions. They should be counted since it is probable for such events to knock in the future if the same test is repeated and the "right" condition is met in the combustion chamber.

4. Is the engine aging normalization a consistent approach across all engines, or specific to a OEMs particular engine?
   The trend is consistent across all the GM LHU engines tested using the SwRIs research AEF test cycle and it is observed that the overall engine activity declines with an increasing number of tests again emphasizing on baseline testing for SPI activity severity adjustment.
5. Is the engine aging normalization process public information?
   It is public information. It can be found in a publication by SwRI on the subject.
6. How representative is steady-state LSPI testing for real-world behavior? Are we controlling and measuring the right things in steady-state testing?
   The dynamics of oil droplets in LSPI tests can be different from real-world behavior due to the choice of engine operating conditions. LSPI tests run at high-load operation for extended durations. The resultant oil dilution can change oil film characteristics. Also, the extra fuel in oil will find its way to the combustion chamber and can polish the liner. It seems like that the effect of hardware aging and the drift in SPI counts over time due to liner polishing will be stronger in LSPI tests. Moreover, due to excessive fuel dilution and operation under high-load conditions, the combustion chamber deposits in some instances can be lower than what one may observe in an engine operating under real-world conditions. Hence the impact of deposits on SPI seems to be diluted during steady-state testing.
7. In your opinion, do we *need* a transient LSPI/SPI test? Why?
   Despite the challenges with transient SPI tests including repeatability and statistical significance, we need to move toward more realistic operating conditions reflecting real-world operations. A

transient test might be difficult to realize as a standardized test, however, such a test may be used to understand the deposit and engine perturbation impact on SPI which would make the test more realistic.

Related Questions that were left unanswered during the discussion but notes from the presenter:

1. Stated that the LSPI "rate" was lower in the Lubrizol On-Road tests. Is this based on "all" engine cycles or just those in the low-speed, high-load regime.
   No matter how the data is dissected, the number of events in particular speed and MAP bin in the Lubrizol test is significantly lower than the number of total cycles for that given bin.

2. Is the "field observed" fuel dilution in the oil a result of volatile evaporation of fuel in the oil?
   In the real-world, the engine is operated mostly at lower loads during urban driving which also includes starts and stops with periods of engine idle. During this low-load operation, the total fuel injected in the cylinder is much lower and often does not impinge on the cylinder walls for extended durations. A net effect of this is reduced overall dilution. The fuel dilution will also be a function of the controlled oil temperature in the test. Having said that, both the SPI test stand and the real world engines allow for fuel evaporation through the sump, the only difference being that the fuel vapors are often not rerouted back into the intake for SPI testing

3. What's the typical fuel dilution measured in the transient SPI testing?
   Real world DI engines: 3-5%
   Sequence IX testing target for fuel dilution: 8-10%
   SwRI Cycle fuel dilution: 10-15%

4. How does the performance of the oil in the 12 ramp transient test compare to the steady state performance of the same oil?
   Not enough data with transient testing to be able to comment on this.

5. What role might decel fuel shut off in abrupt transient operation play in generating events on following accelerations?
   Fuel decel shutoff typically should not directly affect the SPI events. However, there could be secondary indirect effects of fuel shut off such as not enough fuel impinging on the liner to create the right conditions as well as viscosity in the crevice region for the droplets to eject and cause preignition in the following accelerations. This is just a conjecture and no direct evidence is available as per my knowledge to support this.

6. What is the advantage of a long slow RPM ramp compared to many rapidly repeated RPM ramps in transient testing? Is it just repeatability?
   The long slow ramp was a limitation of our engine dynamometer during testing. Ideally, the real transient operation would have much faster ramps. No matter what the ramp rate is repeatability of the ramps should be given particular attention while implementing a transient test cycle. Despite that as Doyle mentioned, it will be challenging to statistically filter out the preignition cycles under transience.

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Statistical Aspects Relating to SPI Test Data to Evaluate Fuel and Lubricant Effects

Presenter: Doyle Boese (Infineum)

Presentation Notes:

- An outline of Sequence IX test procedure including statistical concepts, best test practice for the baseline, DOE considerations were presented.
- Sequence IX primarily focused on Low speed and high load SPI (LSPI). It is a rigorous, repeatable, and controlled test procedure. It uses 4 segments of 175K cycle each. The test is monitored by Lubricant Test Monitoring System (LMTS) and adjusted for severity differences and engine ageing drift.
- Design of a test depends on many variables such as
  - Engine
  - Test conditions including duration and severity
  - Fuel and oil
  - Steady state or transient
- After eliminating obvious poor data points from the collected data, outliers are removed first by using Grubbs test for PP and MFB. Grubbs criterion includes 5 sigma distance from the mean. Grubbs method is based on normal distribution. If it is not normal, the criterion for outliers needs to be adjusted.
- Skew and Kurtosis measure deviations of a distribution from the standard normal distribution. Skew measures the symmetry and Kurtosis measures flatness or peak of a distribution. These two attributes need to be considered to eliminate false positives and negatives.
- Chain (follow on) SPI events are rear is Sequence IX test procedure conditions.
- Transient tests are complicated as they include acceleration and deceleration (ramp up and down) conditions in the drive cycles. New statistical measures need to be developed to identify outliers and SPI events.
- Sequence IX test is a steady state test and uses a medium severity oil for testing – 5 events per segment. Engine median life is 470 hours and it roughly corresponds to 19 tests.

Question and Answers

Q1: on first and follow on events

A: Follow on events do not include run-away conditions. If there are one or two follow-on events after the first, they may not be considered as follow-on. After the first LSPI detection, PCM calls for fuel enrichment to mitigate follow-on SPI events.

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Q2: Steady state and Transients:

A: Steady state tests are conducted at the same test conditions for a long time and so it is easy to determine statistical constants such as mean and sigma. This helps easy determination of an SPI event and an outlier.

In transient tests, drive conditions include acceleration and deceleration, and are repeated in segments over a length of period. There could be some variability within test conditions themselves. As rpm and load are being changed (unlike in a steady state test), statistical measures become variables (not constants as in steady state) and they need to be regressed with load and rpm. Then, observed data can be transformed by applying regression results to determine an SPI event or an outlier.

Q3: SPI mechanisms:

If you make assumptions on an SPI mechanism beyond statistics, then learnings at one load and rpm condition can be applied at other conditions by using physics of the mechanism.

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Engine Oil Impacts on SPI

Presenter: Ashu Gupta (Afton)

Question and Answer

1. The first slide you presented showed a difference in LSPI with base oil, do we understand this phenomenon?

   Generally better-quality base oils reduce LSPI.

2. What is the balance of fuel economy loss for a no-calcium oil versus the increase in engine efficiency that OEMs could deliver if SPI was eliminated?

   Difficult to quantify what this would be with so many factors to consider. Additionally, the optimal balance will likely be different depending on hardware, calibration, and evaluation technique.

3. Is SPI an engine specific problem? GM LHU engine is not the current state of the art and has been updated. Do fuel quality differences play a role too?

   Different engines have different propensities to LSPI and respond differently to fuel quality.

4. Will LSPI events always be a combination of the Fuel and Lube issues?

   Yes, both fuel and lubricant quality and composition have large impacts on LSPI.

5. Do we understand what about an aged oil makes the SPI rate increase over time?

   This represents an area which is not completely understood yet, however multiple factors such as additive depletion and deposit build up are two possibilities influences

6. We haven't seen a lot of studies on SPI and commercial fuel+lube effects from certain geographical markets (e.g., Europe). Is SPI not as big a deal there? Why?

   There are some studies which confirm regional differences related to different fuel qualities. Differences in driving patterns and vehicle calibrations likely also has an impact.

7. If OEMs are able to live with a no-Ca oil and take the FE hit, are their other technical issues to be considered with an all-MG oil?

   It is difficult to answer that with the many factors which would need to be considered in such a determination. This is a question for the OEMs.

8. Does a low-ASH or no-ASH oil help to reduce or eliminate the SPI issue?

   It depends on the type of ash. For example, ZDDP has a strong SPI mitigating effect, whereas Ca detergents tend to increase SPI, both additives are considered ‘ash’.

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Fuel Effects

Presenter: Allen Aradi (Shell)

Presentation Notes:

Using the term SPI reflects the fact that PI can occur at a range of engine speeds.

SPI is a problem with downsized boosted engines

<u>Summary: Key fuel: factors</u>

1. PMI (Honda Index) <1.80 to limit PMPM
2. Deposit control additives (DCAs) for clean injectors to control PMPN
3. RON>96 to facilitate high compression ratio, aiming for BTE>45%

<u>PMPN -SPI</u>. Cited paper s by Kar et al (SAE 2020-01-0610), Tanaka (2017-01-1002) and Wiese et al at 39th Vienna Symposium.

Tests used a high Ca lubricant.

Fuel A (PMI=0.49) gave no LSPI
Fuel B (PMI=1.36) gave 228 #epm
Fuel C (PMI=2.83) gave 1450 #epm

Fuel B and Fuel C had same aromatic level. It is the heavier aromatics (C10+) which are responsible. Using Fuel C with a reformulated lubricant can bring SPI down.

Wiese at al paper showed upward PN drift, which stabilises at various points.

Plateau PN levels reflect PMI of fuel Upward drift associated with injector coking

<u>Solutions</u>

Paper of Conifer et al (SAE 2017-01-0808.) Fuels without DCA showed rapid upward drift. This can recover when subsequently using a fuel with a high level of DCA.

Fuels with a higher level of DCA are better able to eliminate upward drift better than fuels with a lower level of DCA.

<u>Other points</u>

Not calling for change in Fuel specs

PM Index which requires a detailed hydrocarbon analysis is better than other indices (PN index, Moriya index)

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Nucleation mode particles (~10nm diameter). Can TWC deal with these?

Question & Answer

Q What effect does ethanol have on SPI, bearing in mind that it can inhibit vaporisation
A Needs more work – see activities of Rothamer in Wisconsin

Q IS SPI link on PMI causation or correlation?
A Causation

Q What are implications of possible Euro 7 regs to measure PM down to 10nm
A Expect TWC can deal with these. Shell encourages studies on this topic.

Q What other fuel properties (e.g. physical properties, flame speed have you considered?)
A Flame speed not considered in recent studies. Heavy aromatics are correlated with high final boiling point.

Q What fuels specs would you propose?
A Not for specs. Might need to get cars using available higher octane grades.

SPI Panel Discussion

29 September 2020

Panel discussion comprised of 3 of the 4 questions presented below being covered during the discussion. Question 3 was not asked and covered during the discussion.

1. **Where should efforts be focused, and what is "noise"?**
    a. **Transient tests**
    b. **Aged oil**
    c. **(*others areas?)***
    d. **<u>Related question</u>: where can academia contribute?**
2. **As powertrains evolve, how important is SPI?**
    a. **Can control/operating strategies <u>at least</u> protect against SPI failure?**
    b. **How does hybridization (mild and full) affect SPI?**
3. **What is the right way to make comparisons between oil, fuel, and operating conditions?**
4. **Do the panelists have any comments on commonly-reported observations related to SPI that they feel are misconceptions or misinterpretations?**

Notes from Panel Discussions – CRC SPI Workshop, Tuesday Sept 29, 2020

Below are 2 sets of notes from two separate note takers, each with their own style.

Note Set 1:

- **Where should efforts be focused, and what is "noise"?**
    - Transient tests
    - Aged oil
    - (*other areas?)*
    - <u>Related question</u>: where can academia contribute?

A1: Despite very different physical phenomena – the trends for fuel and oil are the same – focus on steady-state testing, with more fresh oils. There are too many tangential lines of study (transient testing) Academics can contribute by investigating the hardware failure mechanisms to prevent these failures.

A2: For the past 10 years, the focus has been on steady-state testing – yet it has not reduced the occurrence of SPI in the field, so we are not solving the right problems. Forensic analysis of real-world failures would be helpful.

A3: Academic involvement would be beneficial at the fundamental level – for example, with ignition. There are a lot of confounded effects – makes it difficult to isolate specific issues with fuels and lubricants. Understanding the ignition processes with fuels (minimum ignition energies) may help shed light on fuel effects. CFD and fundamental kinetics of the fuel droplets and ignition sources. Current materials may not be able to solve hardware (piston) failure issues.

A4: One thing that we need to sort out (re: Andre Swartz's presentation) – what causes SPI may be subtly different than what causes mega-knock. Important to understand when an SPI event might cause engine damage. Problem can be approached from both the test development standpoint as well as the forensic analysis of field parts. Is it the max pressure that causes the damage? Or is it the pressure oscillations? What can we do to prevent mega-knock? is octane important? Is it effectively an early ignition issue? Similar to an early spark? That might be mitigated with high octane? Fundamental combustion aspects are a good target for academics.

A5: Dibble's work with SPI sensors shows that there is something going on before MEGA-knock. Sensor detects ions that are responsible for this phenomena. Perhaps a sensor could be used to move quickly away from catastrophic failure?

A6: Very interested in if/how transient mechanism would be different than steady state? If the mechanisms are in fact different, then I think it is important to explore transient testing– however, if there is no difference in mechanism, then focus on steady state for statistical ease.

A7: Dibble's work was carry-over from an HCCI sensor, was an ion probe – questionable if it would be enough to catch things early enough (in a prior cycle) or early in the cycle to mitigate. Also – it is interesting to think about how CFD could be used – since things are occurring on such a diverse range of scales (particle deposits, non-uniformity of mixture, lube droplets ejected from crevice volume, but also P buildup/F transfer) – are there ideas on what could specifically be targeted with CFD? Could the SACI work be leveraged?

A8: We don't have a strong grasp on what the ignition sources are – compositionally, or chemically, or thermally. The events occur very early, 10-20 BTDC for the extreme events – the initial conditions, when we can measure the bulk P rise phenomenon indicative of a SPI event, means the ignition source has a significant impact on the charge air-fuel mixture. This ignition source must be very strong. How is this being ignited? This is a big part of what we don't understand well. Might be a good target for academics.

A9: Regarding the transient issue – we have developed some transient testing – and have a test now as part of the dexos spec - transient perturbations can contribute to both the physical and chemical factors of SPI – therefore, we think there is a role for transient testing (for both fuels and lubes), and we are moving forward with this testing and have standardized the tests.

A10: Academic contribution: this panel's multidisciplinary makeup shows the need for a broad range of input and talent. Academic can contribute by leading collaborative research.

A11: I'm interested in learning what is happening in these transient tests – the kind of pre-ignition occurring at 3000 rpm is likely to be mechanistically different – interested in transient analysis

A12: Interested in transient phenomena or perturbations in the cylinder that you would not capture in a steady-state test – instantaneous oil consumption, fluctuations in air flow, fuel flow, etc – features that are seen in vehicles, that are important.

Observation: a lot of comments in support of continuing transient work

What about oil aging? Is aged oil important?

A1: Some oils are robust, while others are not. In well controlled testing, aging does seem to affect SPI performance. Does OEM field data agree with this?

A2: Data shows consistent increase in LSPI activity with oil aging. It is a small, but consistent increase (not a runaway effect) – we know oils generate more sludge with age and create deposits. Since it is not a large effect - perhaps we need to ask more of the fresh oil, since it is known that oil aging will be an issue.

A3: Going back about 5 years – we developed steady-state SPI testing to be used to optimize fuels and lubes – and now we are at v2.0 (for transients or aged oil) because these tests are not necessarily representative of real-world performance- we need testing to corollate to real-world/field results.

A4: Seems like we think transient mechanisms will be different – and that these should be based on accel/decel – to come up with an informative cycle, where should we focus?

- **As powertrains evolve, how important is SPI?**
    - Can control/operating strategies at least protect against SPI failure?
    - How does hybridization (mild and full) affect SPI?

A1: Hybridization will help with torque, boost – and preventing SPI at the low speed, high load region – but this isn't the only region that matters. As we continue to improve efficiency, we'll need to push the engine harder – so SPI will always be an issue - expect to still see this problem with hybridization, don't anticipate being able to just handle SPI with a controller operating strategy.

A2: With hybrids – you can just go to medium or high load directly with a cold engine – therefore oil dilution problems might be worse – with more impingement. Therefore, you may end up with more problems with hybridization.

A3: Cold operation is a potential source of emissions and increased SPI rate.

A4: Classic conditions for PI are low speed, high load. We tend to see SPI events during this low efficiency operation. Hybrids may allow you to avoid the areas of the map where this occurs. In addition, more and more engines are incorporating EGR – if we get to EGR at full load that may help. If we disallow enrichment on cycle, we'll have to shift around to find new ways to achieve full power.

A5: Downsizing in response to emissions is what got us to this situation – real-world driving and increasing FE requirements will require hybridization – have an opportunity to redesign/re-spec the engine. Broadly speaking, we are moving away from the risky zones – allows you to avoid the less efficient areas of the engine map where SPI may occur.

A6: We seem to be past peak-downsizing – real world drive cycles have a preference for larger displacement.

A7: I don't think you can get away from the SPI challenge with hybridization – high speed, high torque or low speed, low torque engine operation – you will still be running the engine at max efficiency. We see SPI across all speeds – so you will catch it one way or another – even if you hybridize.

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Q: As the energy companies address sustainability and introduce more alternative fuels into the system –

Is there potential for the fuel work in concert with powertrain to reduce SPI?

A1: E companies have forecasting models for the mosaic of fuels as we approach 2050 – we anticipate liquid fuels persisting, with the addition of gaseous fuels – optimizing based on economics and C footprint. Regular quality gasoline in the US will not have a market – it is anticipated that it will be displaced by BEVS. Premium sectors of the market will persist to at least 2050, since these fuels, with their higher octane, enable higher CRs and allow for greater efficiencies. They key factors are efficiency and carbon intensity/footprint. For SI, octane has to be there. For CI, maybe regular grades are fine. The investment that OEMS are putting into their platforms seems to be 80/20 SI/CI for passenger vehicles – this tells us where the fuels need to go.

A2: For alternative fuels – you just may end up with different kinds of PI problems – for example H_2 may have a hot spot PI problem instead. We may solve one problem but find another. Same is likely for methanol.

(skip to last question)

- **Do the panelists have any comments on commonly-reported observations related to SPI that they feel are misconceptions or misinterpretations?**

A1: Two points (1) when people talk about SPI, it is as a solvable problem and not a limit…. However, we should acknowledge that SPI is a limit, not a problem that we will solve. (2) correlation between SPI and PMI is ONLY a correlation, not causation. Both phenomena likely come from the same sources (*e.g.* wall-wetting)

A2: Keep the focus on the real issue with SPI from OEM perspective is the hardware failure – need to keep this perspective – need to figure out what is causing the hardware failures. Is it the low speed stochastic single events? Is it the run-on multi-cycle events? Is it the high-speed events? May be different issues that come into play at low/high speed or for single/multi-cycle events.

A3: In general, there is a misconception that the ignition source droplets are oil (base oil from the sump) –it is definitely not what is in the sump, the droplets may be coming from the top ring zone of the piston, which has completely different chemistry.

A4: In the ring zone – between the piston and the liner– you are blending fuel with oil from the liner – to get a completely different chemistry.

A5: SPI is likely not just one mechanism – we have already identified liquid droplets and deposits/particles – but there may be other mechanisms as well, that vary.

A6: I believe that there are multiple mechanisms – different operating conditions likely have different (dominant) mechanisms.

A7: Crevice fluid (Andre's work which isn't public yet) – it is not only the composition, but the state of it as well. You need the mixture to be pre-conditioned – also, octane does not correlate/cause pre-ignition. Octane does not correlate – it has a role in the severity of the PI/super knock – there can be a lube oil autoignition phenomenon in natural gas engines. (some poor audio quality issues here)

A8: Clarification: the octane enables the engine to move into the T,P operating regimes where catastrophic failure is likely. Engines will be going toward those operating conditions – will need something to mitigate LSPI. We don't think octane correlates with LSPI, just enables the conditions where it can occur.

- **What is the right way to make comparisons between oil, fuel, and operating conditions?**

Not addressed explicitly during the panel.

Note Set 2:

Where should efforts be focused?

- Trends are the same across the test cycles, steady-state vs transient, impacts of fresh/aged lubricant, etc. So, we should focus testing on steady-state since such tests are more readily performed and interpreted.
- Role for academia could be to explore where and how does hardware break, using CFD and mechanical simulation, to help drive more durable designs without sacrificing fuel economy or increasing pollutant emsisions.
- Need to figure out real-world event causation
  - Tracking and diagnosis of failures to better understand causation
  - Such an effort needs OEM involvement
- Role of academia could be elementary studies of ignition, parsing out fuel and lubricant impacts, such as measuring ignition energies. This could include CFD and kinetics studies and other approaches to get at the fundamental understanding.

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- Overcoming SPI can be addressed via new test cycles and testing approaches and improved diagnosis of failures, and by developing a better understanding of the patterns of the transition to detonation.
- Sensors that directly detect pre-ignition to give time to mitigate SPI actively could help. Prof. R. Dibble had been developing such a sensor. (Notetaker notes: earlier work by Dibble involved HCCI control via an ion sensing probe, perhaps that is what the panelist was referring to.)
- Need to better understand the underlying differences in transient versus steady-state test procedures and how that affects SPI frequency.
- Need to determine what to target in CFD simulations, to implement modeling to address SPI.
- We don't understand the ignition sources very well, or the initial conditions that lead to building up such a strong ignition source.
- Transient test methods continue to be developed. Transient testing has been added to the dexos specification. Transients effect the chemical and physical origins of SPI.
- The multidisciplinary attendance at this CRC SPI Workshop reflects the need for broad talents to be brought to bear to overcome SPI. A communal activity is called for, perhaps by forming an SPI Consortium?
- In transient tests, at higher speeds such as 3000 rpm, what is the SPI mechanism and how is it different from that at low engine speeds?
- Does lubricant ageing relate to transients and if so how? Aged lubricants are known to increase the frequency of SPI, but its not a runaway effect. Can we ask more from fresh oil, to suppress SPI?

As powertrains evolve, how important will SPI be?

- Under hybridization, you will still visit SPI-propne regions and will push the engine harder. No powertrain controller alone will mitigate SPI.
- With hybrids, you can go to medium load in a cold engine, and then oil dilution will be worse with a hybrid.
- Cold operation is an area of current study.
- To make drive cycles more efficient, you can avoid SPI-prone zones with transmission and hybridization and thereby avoid high load points. EGR at high load is coming, and you may not need such high load demands in future powertrains with the right hybridization of the powertrain.
- Downsizing has created the SPI problem. Hyrbidization is going to increase, so you can do more to avoid low efficiency and SPI-prone portions of the engine map. This is going in the right direction with respect to powertrain design, and we may be past the peak in the downsizing trend.
- With regard to hybridization and SPI, you can't avoid SPI necessarily in either high or low speeds with high torque. To get maximum efficiency, you will operate at high torque. So hybridization won't fully avoid SPI.
- Will future fuels influence SPI tendency?
- Liquid fuels will remain in the mix, although we may shift to gaseous fuels. Regular quality gasoline will not be needed, since smaller passenger cars will be replaced by BEVs. But premum fuels will be needed out beyond 2050 for high compression ratio engines to achieve lower

carbon intensity by further dramatic increases in fuel economy. So high octane fuels will be needed for the SI engines that remain in the marketplace.
- There could be different types of autoignition problems with future alternative fuels, wherein we may exchange one problem for another.

Are there SPI misconceptions

- It is a matter of perception, whether SPI is a problem to solve or a limit that needs to be acknowledged.
- Correlation observed between SPI and PM/PN is a correlation, not causation. (Notetaker notes: corrects an earlier comment during the Q/A for one of the presentations)
- The key this for OEMs is the hardware failure; that is the most important issue. Whether they are single low speed events or multiple high speed events, we need to identify the key contributions to hardware failure.
- A misconception is that droplets of oil from the sump contribute to SPI. This is not true. What is ejected from the top ring zone remains incompletely understood. The composition and chemistry of what is ejected from the ring groove is some complex mixture of fuel distillate and lubricant from the liner.
- Multiple mechanisms are happening at different operating conditions.
- The state and composition of what is ejected from the top ring zone is important, being affected by the ratio of fuel and oil and the amount of preconditioning.
- Octane number is not necessarily correlated with SPI, although it affects ignition severity.
- Octane number enables high compression ratio, which gets you into SPI-prone regions. So, you need to mitigate SPI in concert with efforts to increase fuel economy, for example increasing octane number as you go to higher compression ratio.
- With regard to alternative fuels, SPI goes away with gaseous fuels, but in CNG engines there is an observation of lubricant ignition, which remains a challenge.

Wrap Up – Final Comments and Questions

- We need a consortium effort.
- SPI event severity is a function of location, conditions, and event “chain length”, but this is a stochastic phenomenon. So, there is sensitivity to initial conditions. How do fuel and lubricant formulation affect the initial conditions and then link to severity.
- If there is interest in hardware damage mitigation strategies, Mahle is interested in a discussion and with sharing information.