SPI Test Methodology

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Introduction

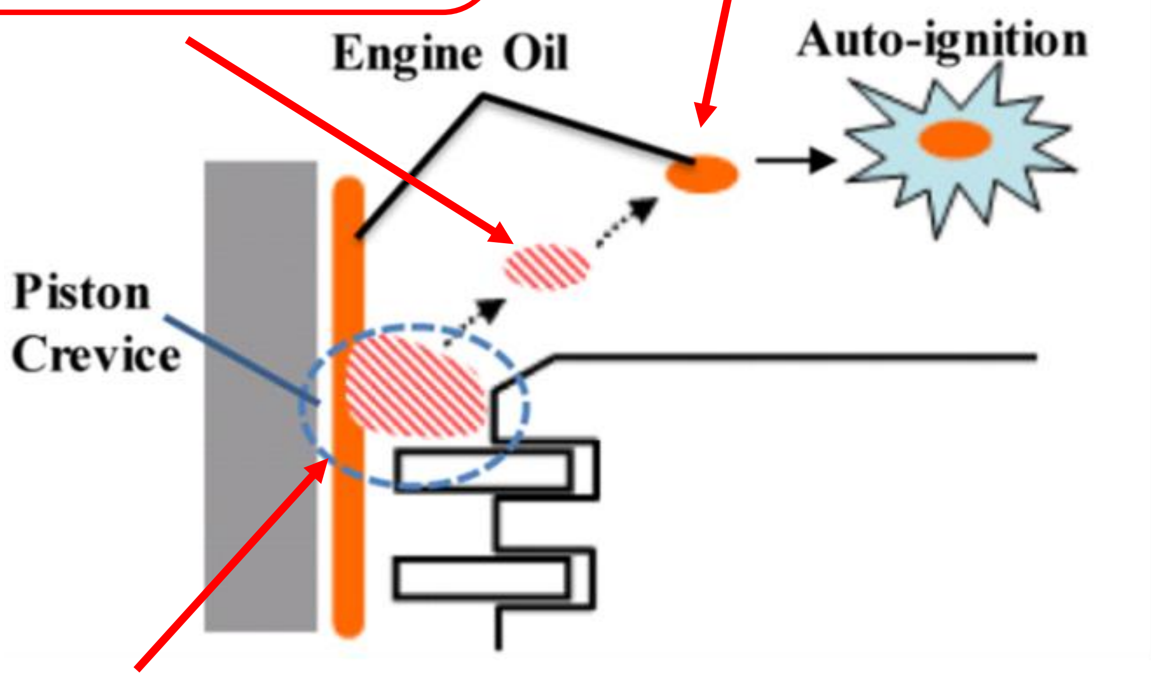
- A general overview of the steady-state low speed preignition (LSPI) test methodology is presented
  - Discussion of statistics associated with SPI event determination is avoided in this presentation as there is a separate presentation topic dedicated for statistics
- The presentation discusses
  - Operating regimes for steady-state LSPI testing
  - The advantages and possible shortcomings of steady-state LSPI testing
  - Repeatability of LSPI testing
  - Oil aging impacts on LSPI
  - A case for transient stochastic preignition (SPI) testing

Mechanisms for SPI

Droplet Induced SPI

Droplet ejection and Initial loss of mass by evaporation and droplet breakup

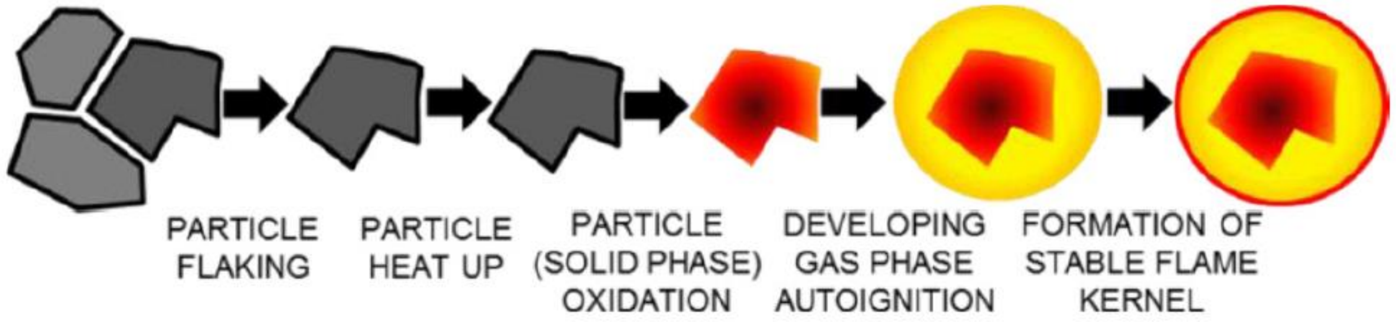
Stable droplet leading to pre-ignition



Crevice fuel-oil-additive mixture

SAE 2014-01–2785

Deposit Induced SPI

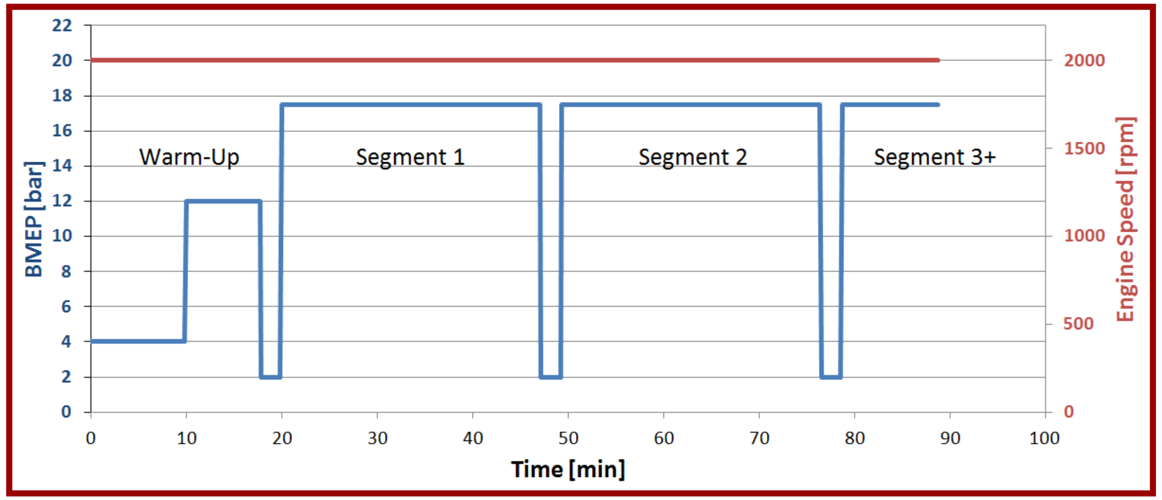


Parameter	Effect on Preignition			
(increase in parameter)	Experiments/ Engine Tests	Ref.	Present Study	Proposed Mechanism
Particle Temperature	↑	13	↑	Increase in thermal inertia of particle
Particle Size	↑	13, 14	↑	Increase in thermal inertia of particle
Intake Air Pressure	↑	5	↑	Increase in rate of heat release due to increase in rate of particle oxidation
Air-Fuel Ratio	↑	5	↑	Increase in rate of heat release due to increase in rate of particle oxidation
EGR/ Residuals	↓	4	↓	Decrease in rate of heat release due to decrease in rate of particle oxidation

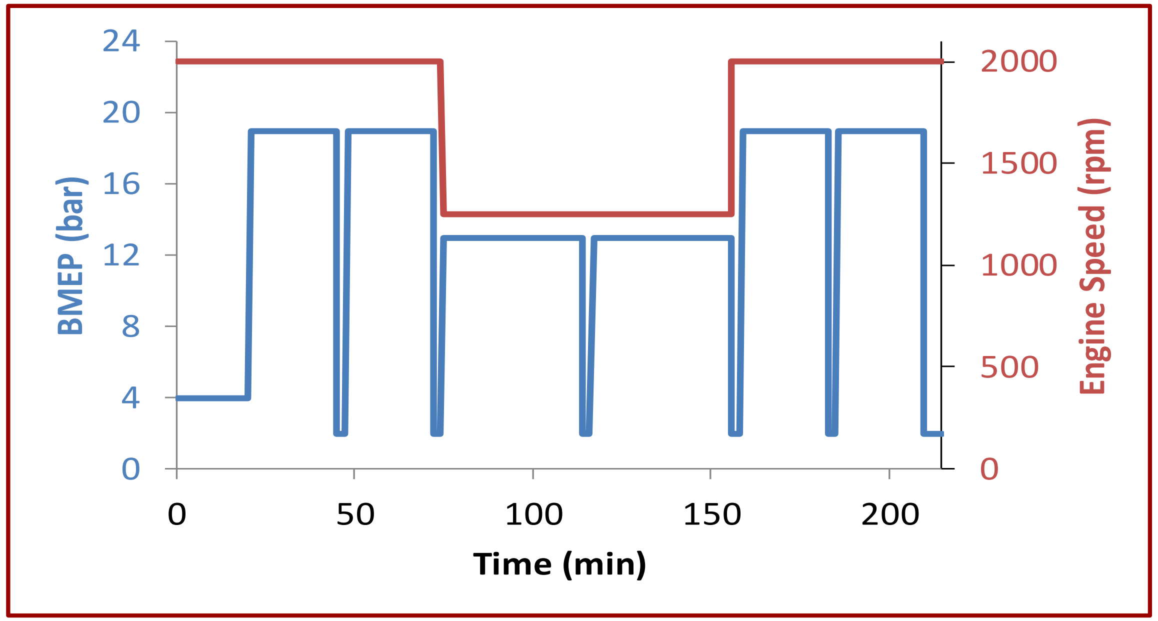
SAE 2017-01–2345

Steady-State LSPI Testing - I

SwRI Current LSPI Test Cycle



SwRI P3 LSPI Test Cycle



- Repetitive testing allows for acquiring sufficient data for statistical differentiation between fluids LSPI response
- Testing is usually automated and controlled with minimal operator interaction
- Continuous logging of the combustion data is a necessity → ensures application of desired statistics to carefully filter the "abnormal" combustion cycles

Steady-State LSPI Testing - II

- Steady-state tests are aimed at evaluating fluid LSPI responses and they are good at it
- There are however differences when it comes to engine operation in the vehicle with factory calibration compared to the industry accepted steady-state LSPI tests
- To highlight a few
  - A specific fuel is used for a test and the intake air quality controlled
  - Blowby system is often disabled
  - A few ECM parameters are externally controlled and held constant
    - Retarded spark timing and disabling of the knock mitigation
    - Controlled equivalence ratio
    - Oil, coolant, intake manifold temperatures
    - Intake boost and exhaust backpressure
    - Cam timings

Comparison of LSPI Tests

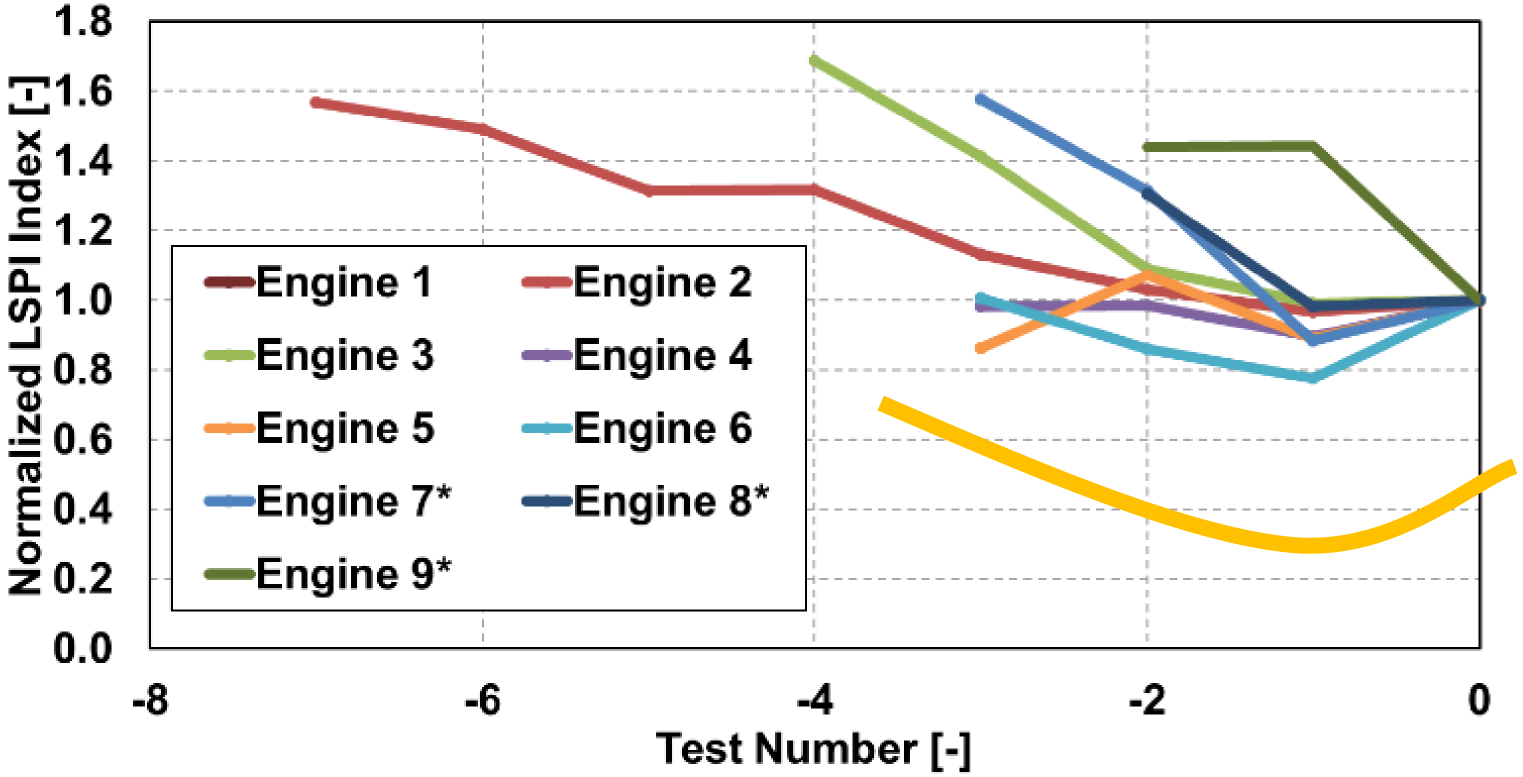
		Certification		3rd Party			OEM Proprietary
Parameter	**Unit**	**ASTM Seq. IX**	**Dexos1**	**SwRI**		**SwRI**	**Toyota**
OEM		**Ford**	**GM**	**GM**		**GM**	**Toyota**
Engine		**Ecoboost**	**Ecotec**	**Ecotec**		**Ecotec**	**Research**
Configuration		**I4**	**I4**	**I4**		**I4**	**I4**
Number of Cycles		**175,000**	**135,000**	**100,000**	**50,000**	**150,000**	**?**
Speed	RPM	1750	2000	2000	1500	2000	1800
Torque	Nm	267	350	290	274	290	?
Load (BMEP)	bar	17	22	18	17	18	22
Oil Sump Temperature	deg C	95	100	100	100	100	90
Coolant-out Temperature	deg C	95	95	70	70	70	90
Intake Manifold Temperature	deg C	43	32	35	35	35	45
Intake Dew Point	deg C	16.1		15.5	13	15.5	?
Equivalence ratio	Lambda	1	1	1.11	1.11	1.11	1
Cycles per Segment	cycles	175,000	15,000	25,000	25,000	25,000	?
Segments per Iteration	#	1	9	4	2	6	?
Iterations per Test	#	4	5	4	4	4	?

What is Being Evaluated in a Steady-State LSPI Test

- Constant low-speed and high-load operation can result in significant fuel dilution in GDI engines
  - ~10-20% for an LSPI test
  - ~3-5% for actual engine operation
- An overall effect is a relatively cleaner engine operation for LSPI tests compared to on road vehicle operation
  - This indicates that the impact of "deposits" on LSPI is often not evaluated in these steady-state tests

Is a repeatable LSPI test market relevant?
OR
Is a more realistic and market relevant transient test a necessity moving forward?

Engine Stabilization



- Engine LSPI behavior shows significant variation initially
  - For a new engine, the LSPI activity can start relatively high and reach a stabilized level also identified as a point where the LSPI activity slightly increases post the initial decrease

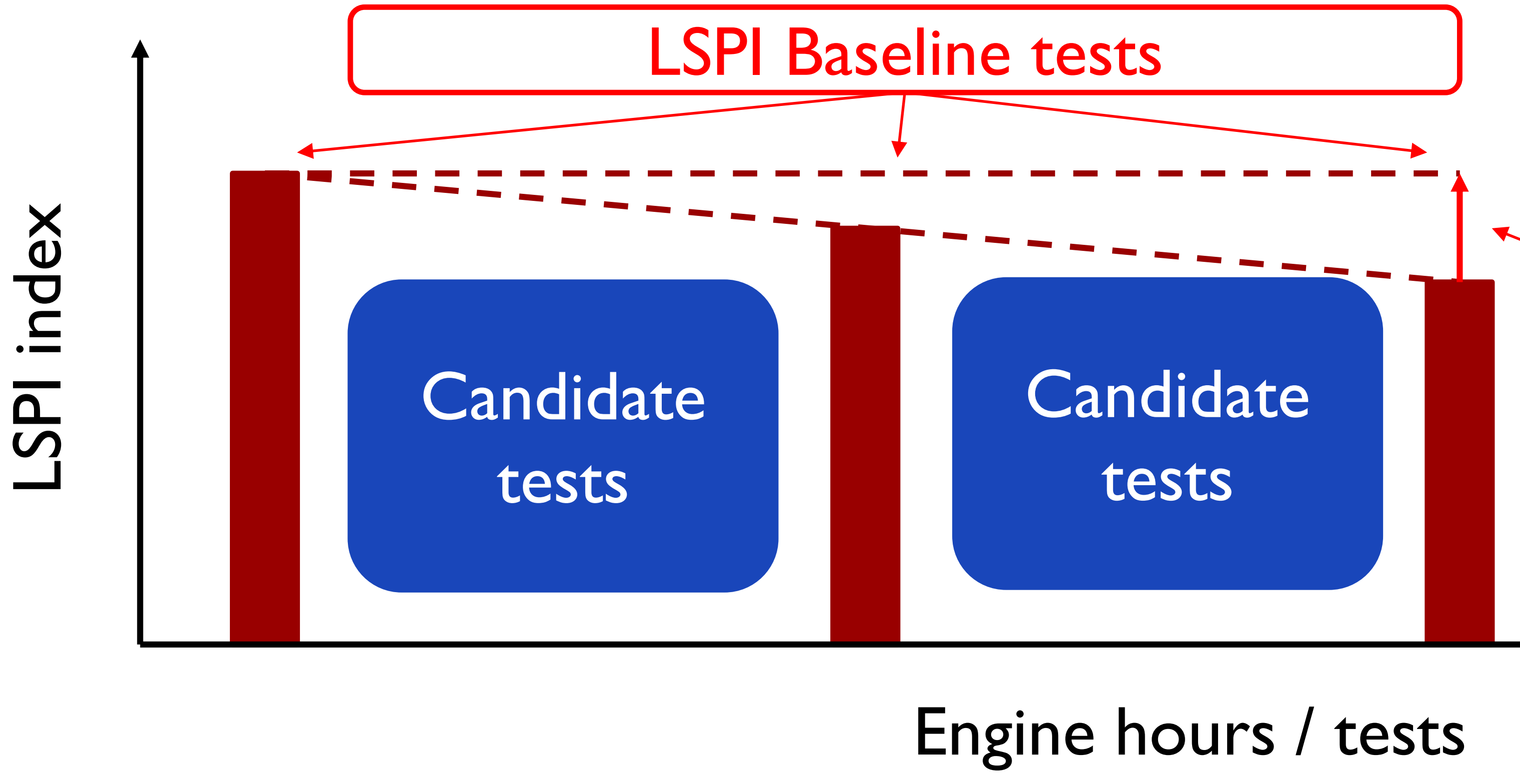
The initial activity can drop by half for most of the engines before they are stabilized
Engine to engine absolute LSPI activity also can be significantly different

SAE 2018-01-1663

*Normalized LSPI indexes for multiple GM LHU installations at SwRI are shown

Accounting for Engine Hours

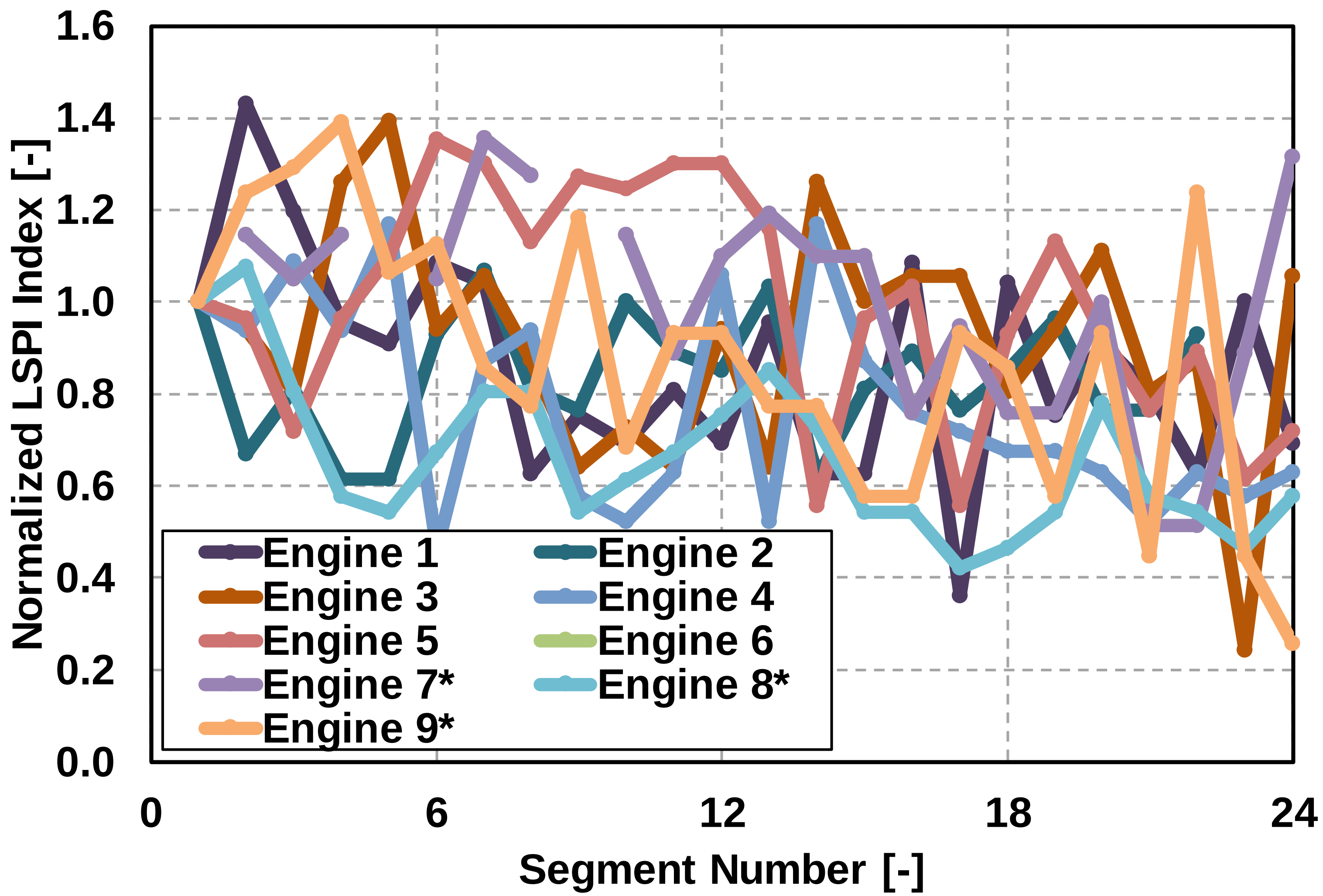
- Differences in initial stabilized engine LSPI activity need to accounted for
- Declining engine activity over time must also be accounted for
- A known baseline every few candidate tests can help normalize the engine LSPI activity over time



Engine hour corrections can be applied based on intermediate baseline testing
Typically, a baseline is run after every 4 candidate tests to monitor the engine health

Eventually, the engine activity will drop to a point where it may not distinguish between fluids anymore - LHU engines typically last for 20 – 30 good LSPI tests
Approach shown for the SwRI research LSPI test. Similar approach followed for the Sequence IX test

LSPI Activity as a Function of Segment Number



- Segment – segment differences in LSPI activity may not indicate a trend
- A general downward trend for overall "LSPI test" is observed

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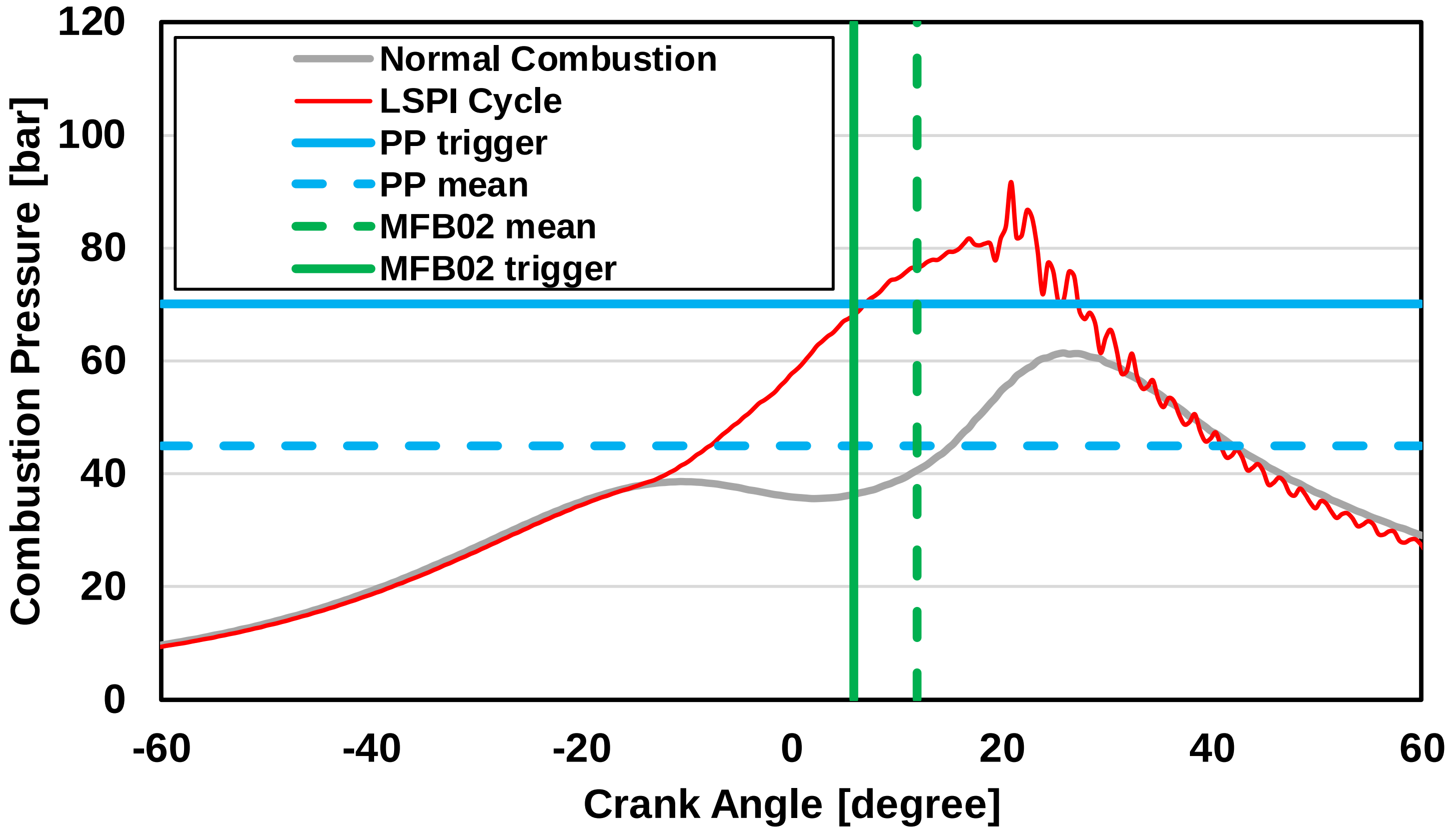
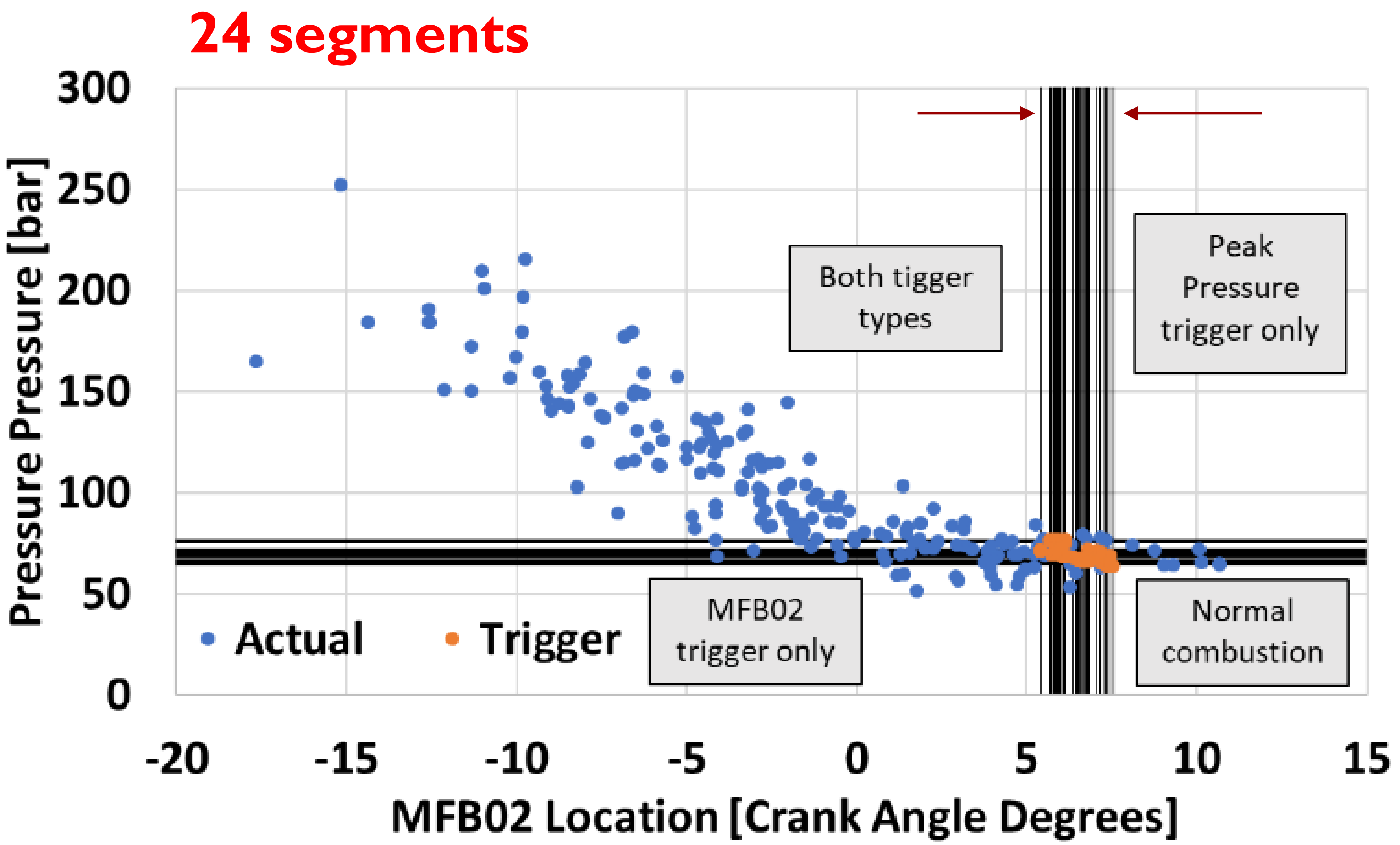
Example shown for multiple GM LHU installations at SwRI

LSPI Trigger Visualization





- LSPI trigger distribution helps visualize the difference between normal combustion and LSPI combustion cycles
- Peak pressures as low as 65-70 bar can be binned as LSPI test cycle following this test methodology

Two fluids with similar LSPI index can have significantly different peak pressure distribution for the recorded LSPI events

Aged Oil LSPI Response

Aged Oil Testing

- While approximately three dozen papers have been published on this topic since ~2010, nearly all research has focused on the performance of fresh oils
  - Since base oil properties and chemical additives change during use, and contamination occurs through the development of wear debris, it is logical to expect some change in SPI propensity over a normal oil drain interval
- To date, **only five papers** which evaluate the impact of oil aging have been published
  - SAE 2013-01-2569 & 2014-01-2785 (Toyota & Idemitsu)
  - SAE 03-11-01-0002, 2018-01-0934, & 2018-01-1676 (Lubrizol & SwRI)

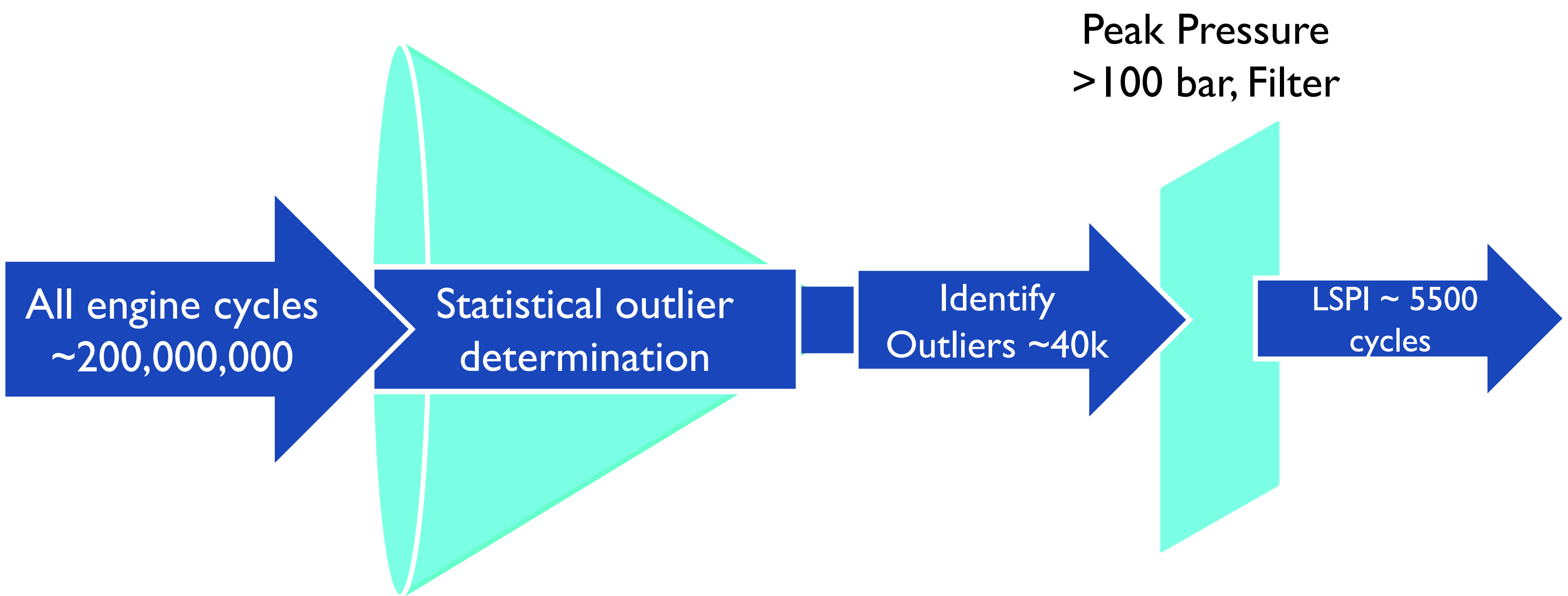
Summary of Oil Aging Literature

- Toyota demonstrated that addition of wear metals can increase the LSPI activity
- In addition, the LSPI activity will also depend on wear metals in the aged oils
  - High amounts of Fe and Cu in the aged oil corresponded to higher LSPI for the aged oil
- Mixed results were observed for low LSPI aged oils
  - In some cases the LSPI activity increased after aging and in some the activity stayed similar as compared with the fresh oils
- Magnesium seemed to inhibit the LSPI activity increase in aged oils while calcium promoted this behavior - Lubrizol (LZ) study

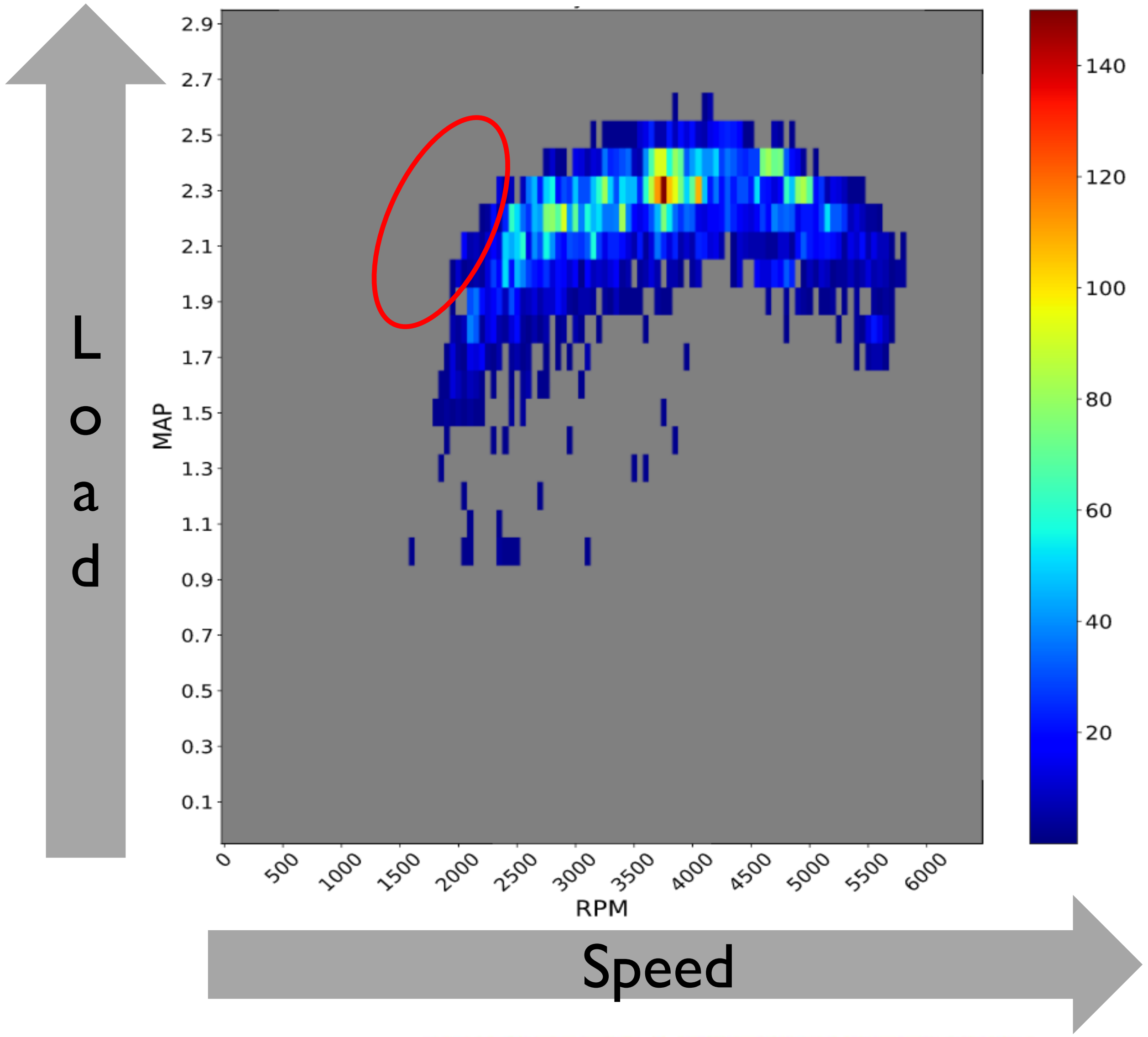
Transient SPI Testing

Lubrizol – On-road SPI Evaluation

- Collect all engine cycles and partition all cycles based on 50 rpm and 0.1 bar MAP ‘bins’
- Analyzed the data using ‘Funnel and Filter’ approach



SPI Cycles



The data from this paper revealed

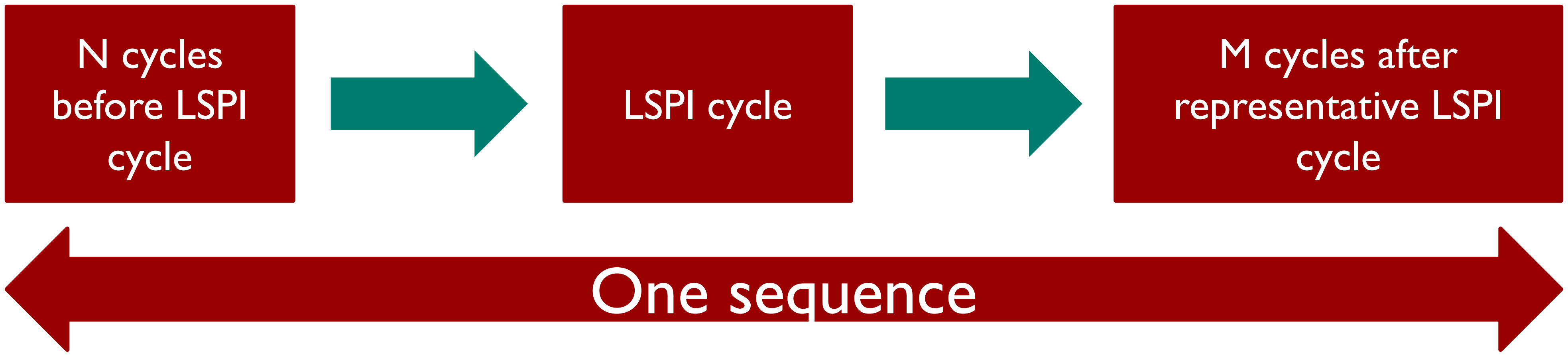
- SPI can occur at higher engine speeds and moderate to high loads
- The relative SPI frequency was much lower compared to an LSPI test as a function of total number of engine cycles

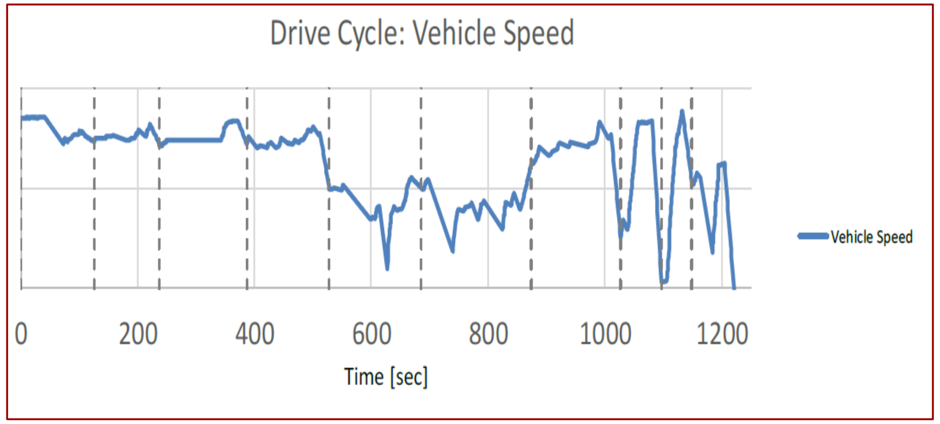
Transient SPI Testing

- We built a case suggesting that steady-state LSPI evaluation is good for distinguishing the LSPI performance between different fluids (lubricants and fuels) and this test is repeatable
- Is LSPI response evaluated at 1700 – 2000 rpm high load boosted condition valid when discussing the engine operation in a vehicle under realistic conditions?
- What additional information can we learn from a transient test?

SwRI Transient SPI Testing – Attempt 1

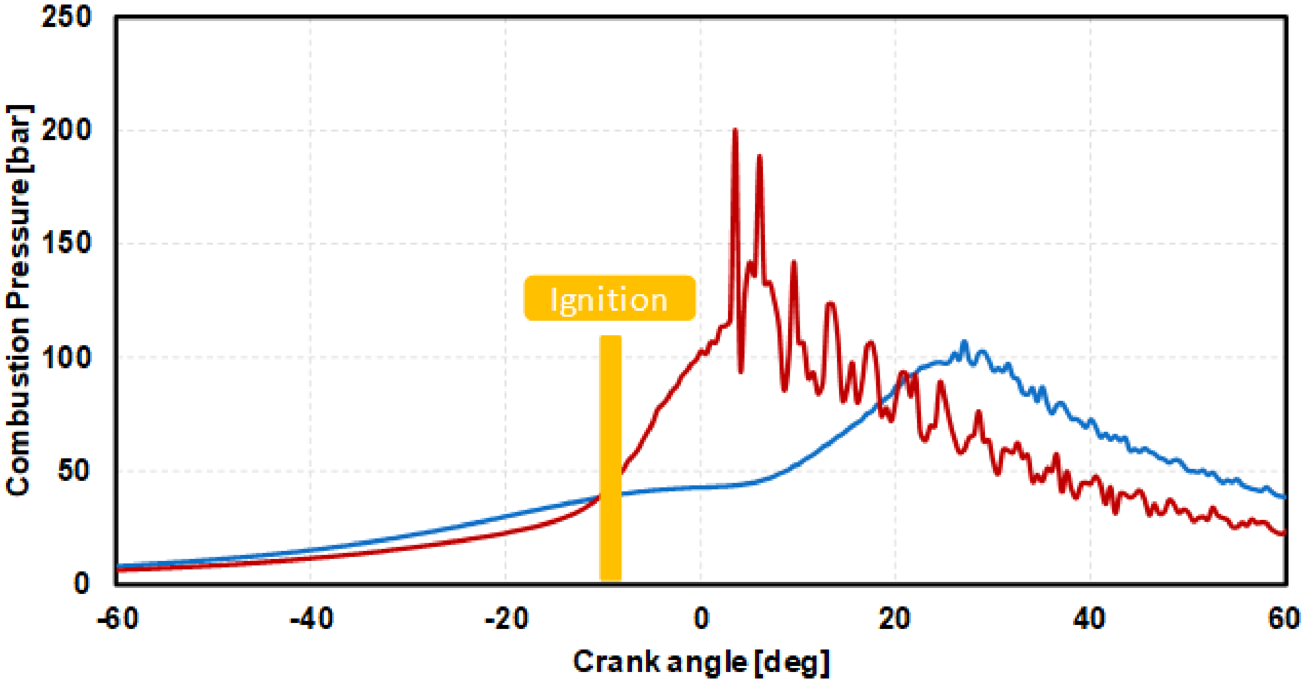
- Use 'Big Data' analysis to construct a drive cycle based on the data mined from the LZ vehicle study **(SAE 2018-01-1676)**
  - Found the most probable engine cycle sequence which led to LSPI
  - Used multiple such sequences to produce a chassis dyno-based drive cycle
  - A fully instrumented Buick Regal (GM 2.0L LHU engine) was run on chassis dyno using this drive cycle





SwRI Transient Testing Results

- The aim of the first attempt of transient testing was to demonstrate SPI under transient conditions that occurred at similar conditions as shown in the LZ vehicle study
- With a Gen 1 Dexos 1 oil we were able to observe a few SPI events

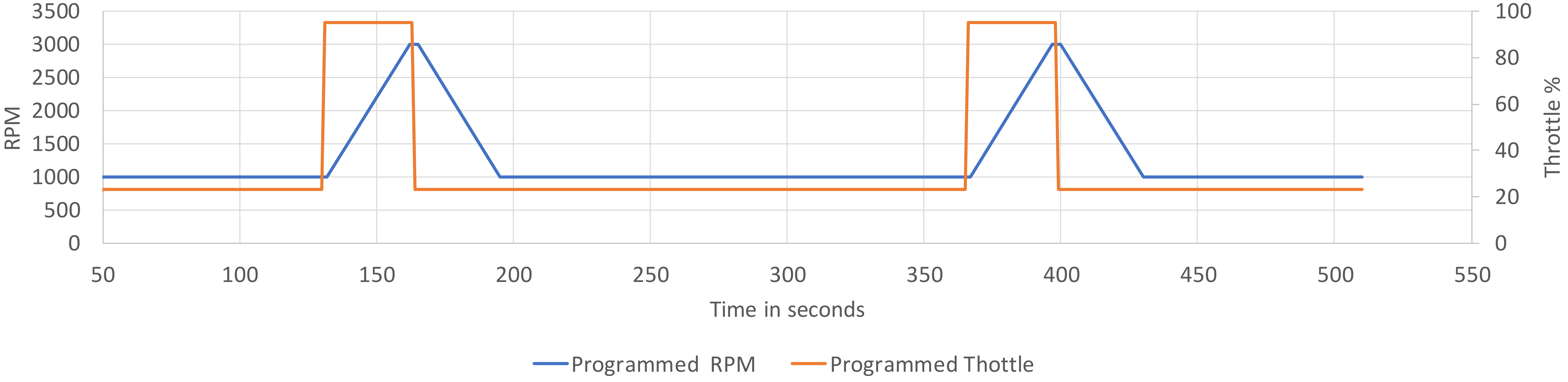


- An example of and SPI cycle is shown that occurred at 3800 rpm high-load condition
- A mildly knocking cycle at similar engine condition is also shown for comparison

SwRI Transient Testing – Current Effort

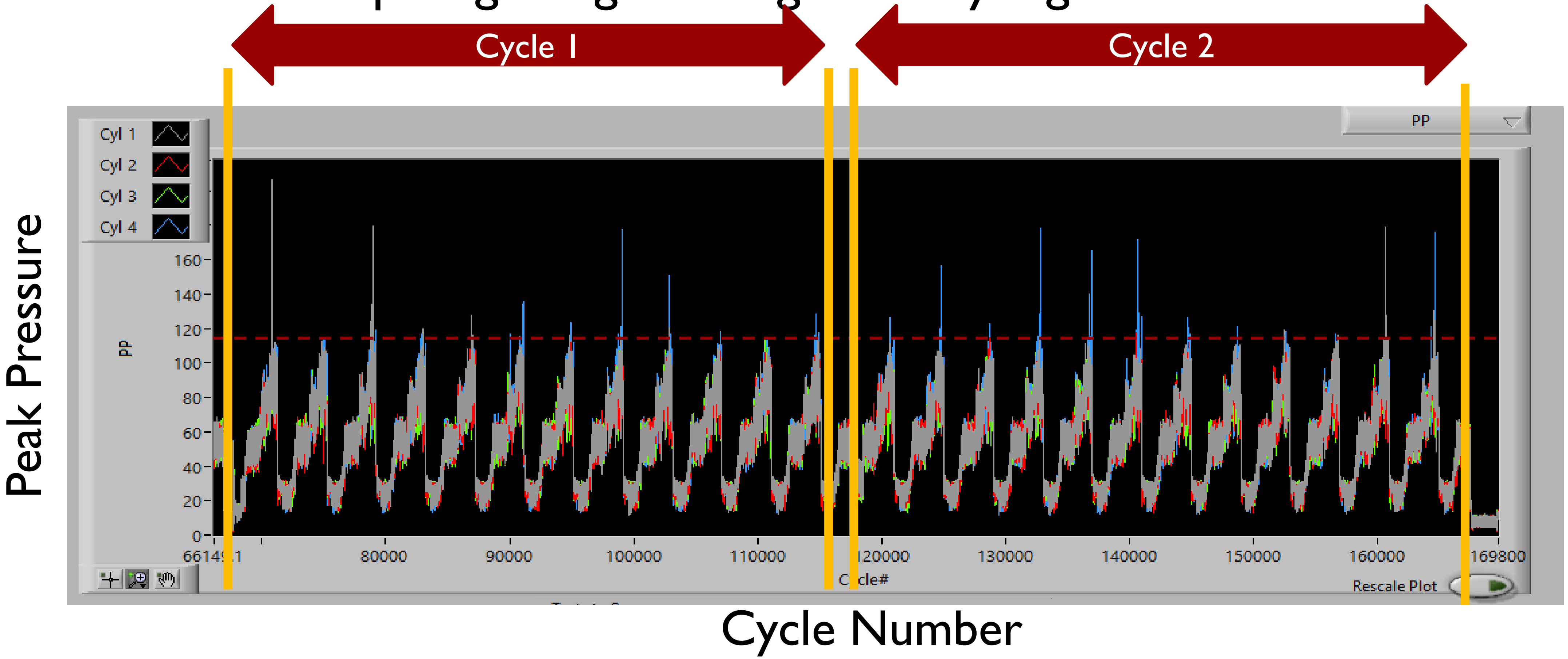
- In the current approach we are looking at simpler step transients on both engine and chassis dynamometer tests
- The aim here is to see if we can increase the SPI frequency such that suitable statistics could be applied

Each ramp was repeated 12 times with set duration of idle in between



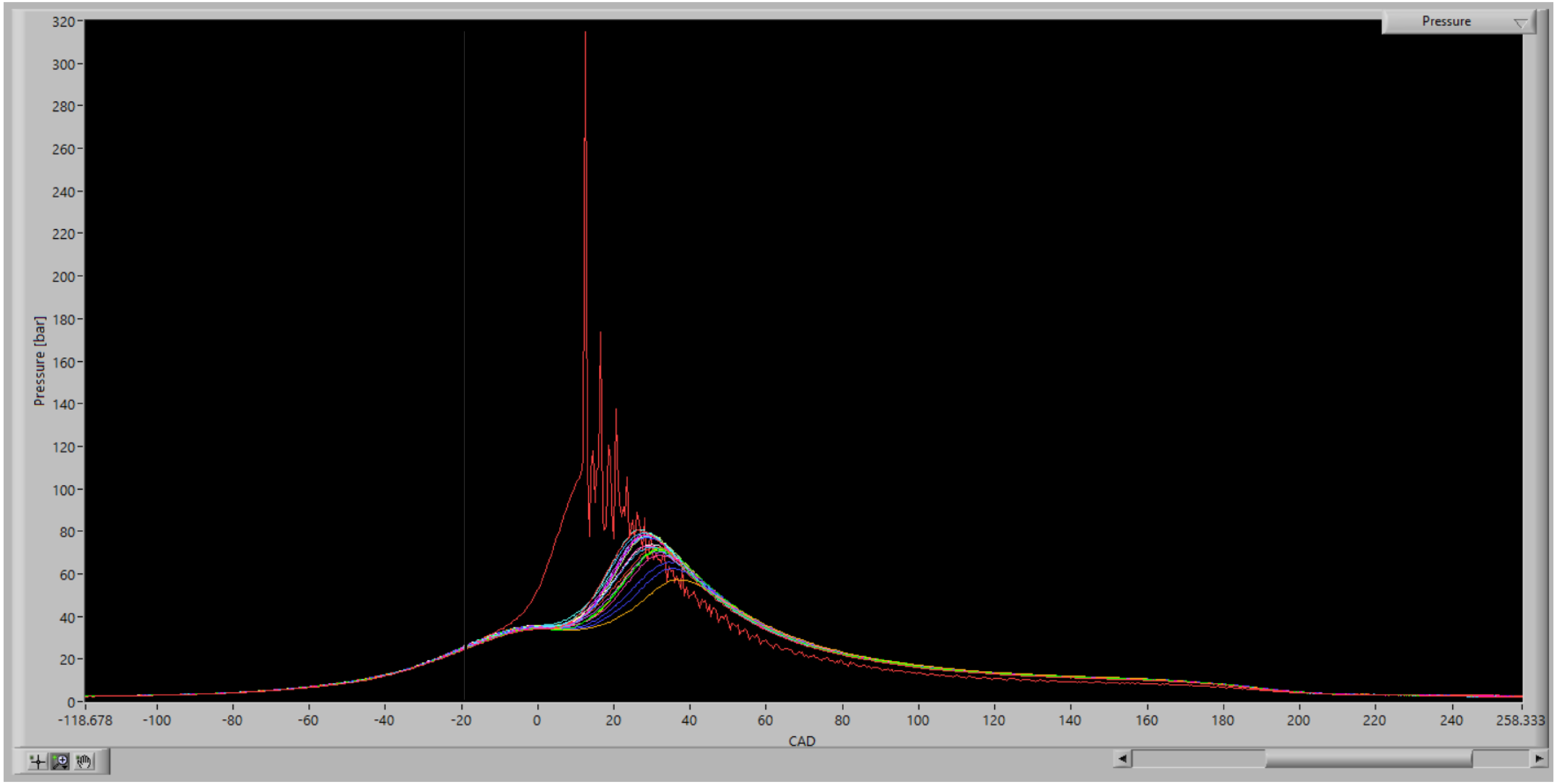
SwRI Transient Testing – Current Effort

- An example of two cycles of 12 ramps are shown in the figure below
- There were a several events that were captured above 100 bar PcP and many of them were confirmed to be pre-igniting with significantly higher PcP



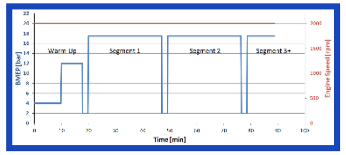
Example data from engine dynamometer testing shown – high activity oil
Engine ramp: 1000 rpm moderate load to 5000 rpm WOT

Example Transient SPI Cycle ~ 4000 RPM



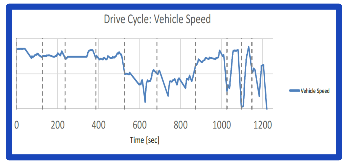
Steady-State vs Transient Testing Platforms

Current | **>>>>>>** | **Future Possibility**

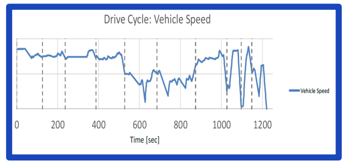
Steady-state LSPI testing on an engine dynamometer

- Pros→
  - Established test
  - Good for distinction between fluids
  - Engine health tracking
- Cons →
  - Does not represent "real-world" driving conditions
  - Failure in the field despite the usage of oils determined to be "good" using this test

Transient engine SPI testing on an engine dynamometer

- Pros→
  - Better control of conditions
  - Engine health tracking
  - Realistic
  - Good platform for developing/ tweaking the transient vehicle-based test cycle
- Cons →
  - Doesn't look at the whole system
  - It is not market relevant

Transient vehicle-based SPI testing on a chassis dynamometer

- Pros→
  - Realistic
  - Market relevant
  - Uses OEM ECU without modifications
  - Evaluates the powertrain as a whole and not only the engine
- Cons →
  - Instrumentation and engine health tracking is a challenge
  - A single drive cycle solution may not be applicable to different vehicles with varying powertrain configurations

Transient SPI Wrap-up

- The mechanism for transient SPI is not well understood currently
  - The steady-state test is good for evaluating the impact of lubricant and fuels on LSPI
  - However under realistic and transient conditions the deposit impact on SPI may play a bigger role especially at higher engine speeds
    - *Glowing deposits can impact next cycle combustion if retained within the cylinder from previous cycle – based on historical optical evidence at SwRI and literature*

Overall Conclusions

- The steady-state LSPI tests are mature and do a good job of distinguishing the LSPI response of different fluids
- The engine operating conditions in a steady-state test may differ from typical engine operating conditions in a vehicle
- The steady-state is more likely to assess the fluids performance on LSPI
  - This, however, may not present a complete picture in terms of how the LSPI unfolds during typical vehicle operation due to differences in engine cleanliness
- Oil aging LSPI investigation may require careful consideration moving forwards
  - How the oil is aged, where it is aged and under what conditions etc. needs to be determined
- Moving to a transient test platform can:
  - provide an opportunity to test the SPI in more depth
  - allow for investigating the SPI phenomenon for not just the engine but for the complete powertrain setup which will also include the transmission response
  - create challenges in terms of repeatability and sufficient SPI activity
  - provide solutions to curb SPI under realistic operating conditions

Thank You

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STOCHASTIC PRE-IGNITION IN TRANSIENT ENVIRONMENTS

A Consortium of SwRI