CRC Report No. CM-137-17-1

REVIEW OF LOW-SPEED PRE-IGNITION LITERATURE

June 2019

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5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Review of Low-Speed Pre-Ignition Literature

Final Report

CRC Project No. CM-137-17-1

Author: Patrick Haenel

FEV Europe GmbH • Neuenhofstr.181 • D-52078 Aachen • Telefon +49 241 5689-0 • Fax +49 241 5689-119

Executive Summary

Project: Review of Low-Speed Pre-Ignition Literature			
Project for:	CRC	***Project No.:***	CM-137-17-1
Project Manager:	Patrick Haenel	***Date:***	June, 2019

Objectives:

The scope of the project was to investigate the existing literature on the abnormal combustion phenomena Low-Speed Pre-Ignition (LSPI). The following objectives have been specifically included:

1. Outline the factors that have been shown to induce / produce LSPI
2. Outline the factors that have been shown to affect the severity of LSPI
3. Identify how the factors produce the required chemical kinetics and physical system that promote LSPI events, and how they impact the severity of the events
4. Identify gaps in the understanding of LSPI
5. Propose and prioritize technical questions that could be addressed through projects around LSPI that would help to further elucidate the causes and enable development of solutions

Methodology:

The chosen approach to attempt to answer these questions was a systematic review of the available body of literature on LSPI. The literature review included information published by interested parties such as vehicle manufacturers (OEM), Tier 1 and Tier 2 suppliers, government labs, independent contractors, consortia, and academia. The materials fall into various categories as outlined below:

1. The open and published literature from 1990 forward
2. To the extent permissible, materials from symposia which publish their own materials
3. Suppliers, OEMs, and Government Organizations that are currently performing work that is not published or is not in the open literature, including planned work
4. Unattributed materials from FEV projects that were shared with CRC with consent of the owners

Summary:

Low Speed Pre-Ignition (LSPI) is a complex problem that combines interacting factors from the fuel side, oil formulation and characteristics, engine hardware and calibration, engine boundary conditions, and engine operating history (e.g. deposits). One single LSPI initiation mechanism can therefore not be derived from the performed study. While more research to identify the detailed mechanism behind LSPI is encouraged, the reason for this ambiguity may be that modern highly boosted Gasoline Turbo Direct Injection (GTDI) engines operate close enough to auto-ignition limits that various LSPI initiation mechanisms may come into play depending on the exact design and boundary conditions in a specific engine. Therefore deposit, oil/fuel droplet, and surface initiated pre-ignition events have been reported. Across different engine platforms, this literature search could however identify some aspects that have been repeatedly shown to reduce

the incidence of LSPI in engines, even though the utilized measurement equipment, research methodologies, hardware and even definitions of what constitutes pre-ignition vary significantly between studies. Some general outcomes and main research gaps are outlined on the following pages.

It can be generally stated that an improved oil formulation and reduced oil ignitability as well as a design that leads to reduced oil intrusion from the crankcase ventilation system or past the piston rings is of benefit. Oil properties that have been consistently linked to low LSPI counts in the past are low calcium and high zinc dialkyldithiophosphate (ZnDTP) or molybdenum dialkyldithiocarbamate (MoDTC) formulations. Individual studies showed other additives and base stocks also to have an impact. Therefore, it can be stated that individual formulation details can still have significant impact on LSPI occurrence beyond these three additives, and thus a more holistic look is needed to develop a final guideline. On the fuel side, high fuel volatility and proper mixture formation by either fuel formulation, high charge motion or optimized injection hardware, or calibration (e.g. targeting or split injection) avoids increased wall wetting, local fuel dilution and deposits. This affects both the deposit as well as the droplet initiation path. Higher engine block operating temperatures can additionally reduce some of the negative impact of fuel impingement onto cylinder walls or the piston surface. Fuel properties that reduce the amount of accumulated fuel in the top ring land such as the final boiling point or the integrated, non-evaporated fuel mass above a threshold temperature and fuels with low aromatics content are also linked to better LSPI performance. While high octane fuels do not necessarily suppress LSPI occurrence, an increase in knock resistance can help to mitigate the effect of subsequent damaging mega knock. In addition, calibration measures that can suppress LSPI are measures that reduce the reactivity and temperature of the mixture towards the end of compression. These measures can include e.g. cooled low pressure exhaust gas recirculation (LP-EGR), fuel enrichment or improved scavenging of the residual gas. Finally, an overall engine design that reduces the formation of deposits (injector, combustion chamber, and intake valve) is recommended.

Recommendations:

Even though the existing body of research is already extensive, numerous open questions and research gaps can be identified based on the performed literature search. First, it would be generally helpful to define Pre-Ignition, Mega Knock, and LSPI events as well as establish a standard how to count and detect LSPI events. Currently, no common methodology is used or established which significantly diminishes the comparability of the existing literature. Additionally, a few topics stand out as the most pressing research gaps:

- Numerous articles have been published on how (fresh) oil formulation impacts LSPI. However, an LSPI oil benchmarking performed by FEV in 2017 revealed that oils in the market still show a massive variation in LSPI occurrence. Even though the body of literature on this topic is substantial, this topic can still be further investigated, specifically, the question of how additives interact in different formulations.

- Reaction mechanisms which include lubricants and additives are not available. This limits opportunities to simulate effect interactions.
- The leading LSPI mechanism in lubricants is currently not well understood. Understanding the impact of lubricant formulation on local deposit formation and deposit ignition likelihood, as well as the ignition of liquid or gaseous oil/fuel mixtures could help. How does this effect differ for first and following LSPI events, single, burst, or intermittent LSPI burst events?
- The impact of oil ageing on LSPI behavior is not well understood at this point. This has the potential to lead to significant field issues. This includes e.g. the impact of additive consumption, base oil degradation, engine wear or fuel dilution on LSPI over one oil change interval.
- Another topic of interest that has seen little research is the question how oil transport and oil flow characteristics impact LSPI. The impact of fuel properties and how fuel properties affect fuel impingement splash on oily surfaces, fuel dilution, and fuel/oil transport to the piston surface are also not well understood. This topic interacts with liner, piston, and piston ring design.
- The industry wide definition of a characteristic fuel number (akin to RON or MON) that characterizes the tendency for pre-ignition of a fuel is still missing. One reason is that the critical fuel characteristics that impact LSPI initiation are still not entirely clear. Laminar flame speed and ignitability, distillation, and deposit formation tendencies have been named as impact factors. The published results vary though. Therefore, the interaction of fuel properties and hardware characteristics needs to be clarified in this context. Do the leading LSPI characteristics of a fuel change depending on wall wetting, mixture formation, mixture location etc.? Interesting would be also the comparison of the impact of gaseous fuels, such as CNG, on LSPI.
- Fuel ageing can be expected to increase LSPI due to the change in distillation curve over time. This has not been investigated so far. It would be interesting to understand how much of a problem this really is in the field. The impact of the worldwide range of fuel components as well as fuel additives on LSPI is also not well understood.
- The impact of calibration (e.g. injection strategy, LP-EGR etc.) and boundary conditions (e.g. coolant temperature etc.) has been investigated in the past and seems well understood in the industry. The performed research, however, focuses mainly on fresh engines utilizing steady state engine tests. Transient operation, vehicle results and hardware ageing impacts are not published at this point. Additionally, studies of the interactions between calibration and hardware on one side and oil and fuels on the other side are rare. This reduces the possibility of finding synergies.

- Ring land, piston, piston ring design, and designs which impact mixture formation (e.g. charge motion, injectors, etc.) have been mentioned as impact factors regarding LSPI. The interactions and the underlying LSPI mechanism (oil transport, deposit formation or impingement) needs to be clarified.
- Transient effects are not well understood at this point. The published experimental test procedures are mainly steady state test procedures. The definition of a statistically sound transient procedure which has the potential to represent real world operating conditions much better is an open topic. How do field results correlate with lab results especially when component ageing, drift and local customer usage patterns are considered? The impact of intake valve or injector deposits and PCV system performance over time may be of interest.
- The impact of water injection on spark knock has been analyzed in several publications. The potential of water injection to suppress LSPI bursts can be theorized, but actual test data has not been published. Can water injection help to define a pre-LSPI event controls mechanism?

Keywords:	Abnormal Combustion Stochastic Pre-Ignition Low Speed Pre-Ignition Mega Knock Super Knock	***Project Supervising:*** Dr. Christoph Bollig Managing Director
Contents:	86 Pages	

Table of Contents

Page

1 Introduction & Scope of Work

Modern combustion engines must meet increasingly higher requirements regarding emission standards, fuel economy, and performance characteristics. Most recently, fuel economy and carbon dioxide (CO_2) emissions moved into public focus, not the least due to rising fuel prices and discussions about global warming. Furthermore, over a dozen countries of the European Union (EU) have already inserted CO_2 emissions into their vehicle tax formulas, including France, Italy, Spain and Germany. Therefore, downsizing measures which meet or exceed the standards concerning emissions and performance characteristics set by the customer or legislation while significantly increasing fuel efficiency are needed.

Direct-injected boosted gasoline engines with high specific power and torque output are leading the way to reduce fuel consumption in passenger car vehicles while maintaining the same performance when compared to applications with larger naturally aspirated engines. These downsized engines, however, need to reach brake mean effective pressure levels which are well in excess of 20 bar. When targeting high output levels at low engine speeds, undesired combustion events called Low Speed Pre-Ignition (LSPI) can occur. Note that publications are ambiguous in their naming convention for this undesired combustion event and have referred to it as either LSPI, Stochastic Pre-Ignition (SPI), Mega Knock (MK) or Super Knock (SK). In this literature review, pre-ignition is defined as a combustion that is initiated unintendedly and randomly before the intended start of combustion (which is normally initiated by the spark event produced from the spark plug), LSPI is used to describe pre-ignition events which may or may not include knock and (subsequent) Mega Knock is utilized for severe knock which may follow a pre-ignition event depending on the boundary conditions.

Figure 1.1 shows an example of two characteristic LSPI pressure traces with and without subsequent engine knock. It is visible that these events are typically accompanied by very high cylinder peak pressures which can lead to severe damage if the engine is not designed to withstand these high cylinder pressures.

Although these events have been reported by numerous authors, no definite root cause has been found yet. Furthermore, their occurrence is rather erratic which makes it difficult to investigate or control them.

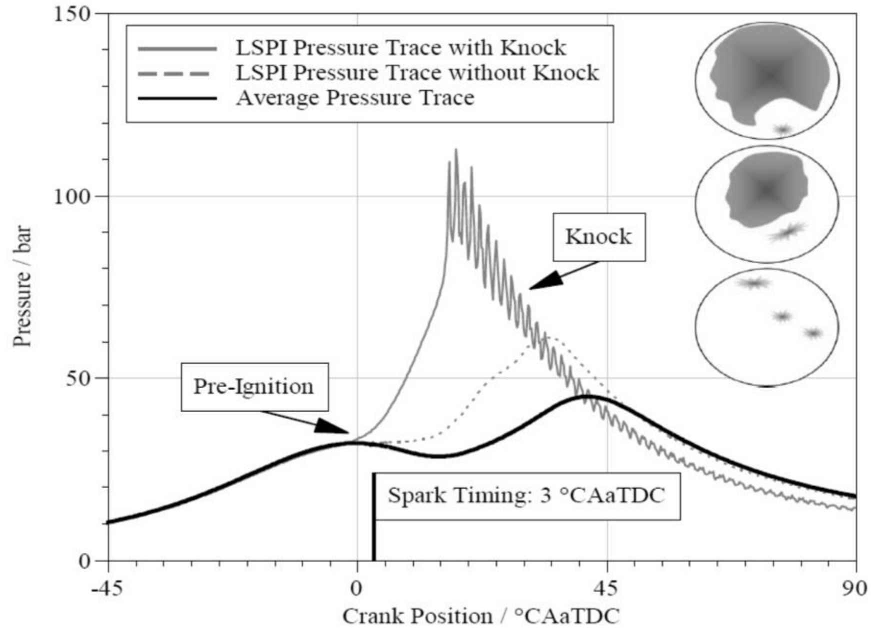

Figure 1.1 LSPI cycles with and without knock [CON20]

Scope of the project is to investigate the abnormal combustion phenomenon Low-Speed Pre-Ignition by conducting a literature review of the existing body of literature. The chosen approach is a systematic review of the available body of literature on LSPI. The literature review includes information published by interested parties such as OEMs, Tier 1 and Tier 2 suppliers, government labs, independent contractors, consortia, academia on the topic of LSPI from 1990 onwards, and materials from symposia which do not publish openly.

2 Methodology

The literature review for this study has been conducted using a three-step approach:

1. A conventional, manual search of relevant literature databases
2. A systematic literature review of said literature databases using defined search criteria
3. A manual search of conference publications, which are not listed in said databases

The results from all three steps of the search strategy has then been compiled to form the body of relevant literature for this study. The following chapter discusses the search methodology, validation, inclusion and exclusion criteria and methodology limitations of the chosen approach.

2.1 Search Criteria

Before starting the systematic literature review process, an informal search of the existing body of literature was performed. Sources included the Society of Automotive Engineers (SAE), journal publications from Sage, Elsevier, and Springer, and non-listed conference publications. This informal search was mainly based on personal knowledge of the literature as well as cross checking citation indices of publications. This conventional, manual approach identified roughly 100 relevant publications. In the following and based on this initial screening process, relevant databases, search and selection criteria as well as a validation approach have been identified for the systematic literature review.

The scope of a systematic literature review is to provide a complete and reproducible overview of the current body of literature on a defined topic. The benefit of a systematic literature review is that the conducted search can later be updated using the same methodology. To do a systematic literature review, the searched databases, the search terms and the inclusion and exclusion criteria need to be clearly defined. Finally, the results of the systematic review are recommended to be validated against knowledge based searches or reference lists to ensure that said criteria have been selected properly.

For this study, the databases outlined in table 2.1.1 have been searched. The table also outlines a non-exhaustive list of relevant conferences and journal publications found in the respective database. Please note that numerous other journals and conference anthologies form the underlying databases which have been omitted in this list due to relevance and space reasons.

Database	Publications
SAE MOBILUS	Conference Anthologies SAE Technical Papers and Conference Publications SAE Journal Publications (non-exhaustive) Intl. Journal of Fuels & Lubricants Intl. Journal of Engines etc.
Springer	Conference Anthologies E.g. Knocking in Gasoline Engines, FISITA etc. Springer Journal Publications (non-exhaustive) MTZ, MTZ extra, MTZ industrial ATZ Chemistry & Technology of Fuels & Oils Science China Flow, Turbulence & Combustion Journal of Particle Research etc.
ScienceDirect	Elsevier Journal Publications (non-exhaustive) Advanced Energy Conversion Applied Energy Combustion and Flame Energy Energy Conversion Fuel Fuel and Energy Abstracts Journal of Fuel Chemistry and Technology JSAE Review Proceedings of the Combustion Institute Proceedings of the Symposium on Combustion Progress in Energy and Combustion Science Propulsion and Power Research Transportation Research etc.
SAGE	SAGE Journal Publications (non-exhaustive) International Journal of Engine Research Intl. Journal of Spray and Combustion Dynamics Advances in Mechanical Engineering Measurement and Control Proceedings of the Institution of Automobile Engineers Proceedings of the Inst. of Mechanical Engineers Transportation Research Record Journal of Mechanical Engineering Science The Journal of Computational Multiphase Flows etc.

Table 2.1.1 Databases searched during systematic review

The actual search criteria for this study has been identified based on the manual search performed in the initial step. Recurring nomenclature for relevant publications includes:

- *“LSPI”*
- *“Pre Ignition”*
- *“Mega Knock”*
- *“Super Knock”*

Additionally, a few search criteria were added to remove a high number of false positive results. The final search criteria for this study, including logical connectors, was as follows:

("LSPI" OR "Pre Ignition" OR "Mega Knock" OR "Super Knock") AND "Engine" NOT "Hydrogen" NOT "Diesel"

The searchable timeframe for all databases was set to January 1st 1990 to May31st, 2018. Therefore, results up to May 31, 2018 have been included in this review.

2.2 Search Results

The search strategy outlined in Chapter 2.1 resulted in the review of in total 459 publication abstracts. Figure 2.2.1 outlines the publication split between SAE, Springer, Science Direct and SAGE. Additionally, Figure 2.2.1 and Figure 2.2.2 showcases the total number of accepted and rejected publications as well as the rejected publications per data source.

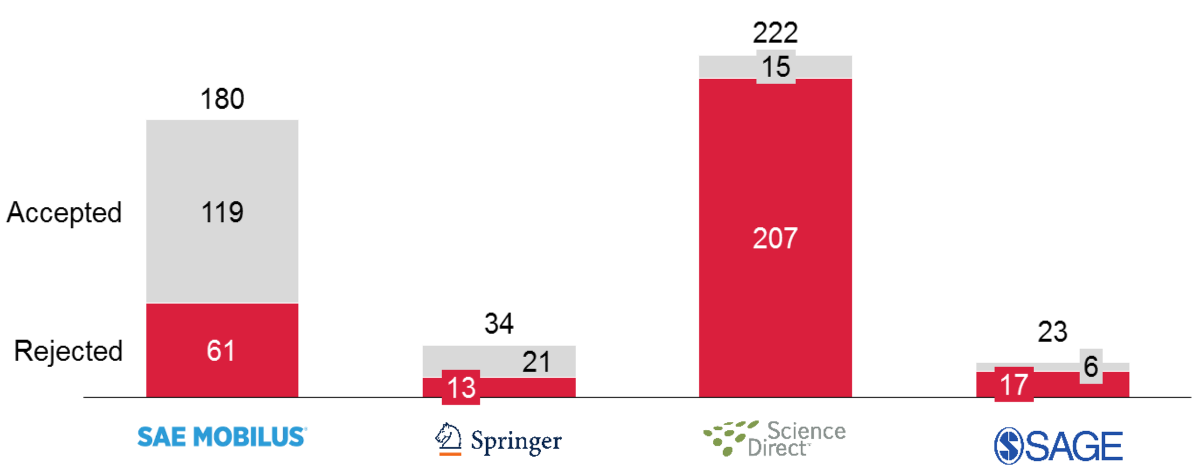

Figure 2.2.1 Database split of search results in systematic review

In total 161 (35%) of the publications from the systematic search have been accepted as relevant for this study. The remaining 298 publications from the systematic search have been rejected. Reasons for rejecting a publication have been as follows:

- The topic of the study is not related to spark ignited, internal combustion engines operated with a hydrocarbon fuel (e.g. pre-ignition in CNG engines is included where applicable, hydrogen fuel or Diesel engines are not included)
- The topic of the study is not related to unintended, abnormal combustion events occurring before the intended combustion initiation of the engine (e.g. studies of HCCI, RCCI etc. have been neglected)
- The topic of the study is not directly related and does not directly translate into the field (e.g. publications on general reaction mechanism development have been neglected unless directly transferable to LSPI)

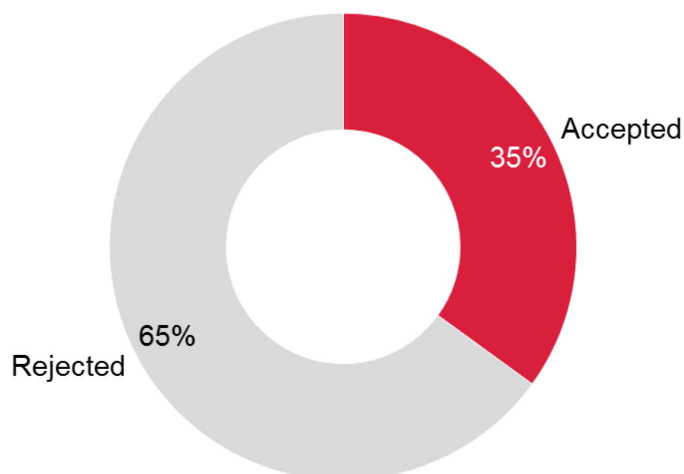

Figure 2.2.2 Percentage of rejected publications in systematic review

The majority of rejected papers in this systematic review have been rejected because of reason three: due to them not being related and closer to basic combustion research rather than engine research. This relates especially to Science Direct and SAGE publications, which include numerous publications relating to base combustion research but fewer publications that analyze applied combustion problems in internal combustion engines (e.g. Combustion and Flame, Proceedings of the Combustion Institute etc.). The inclusion of these publications in this report is in this context of limited value. Please refer to the literature list spreadsheet for a detailed overview of accepted and rejected papers.

Figure 2.2.3 shows the publication trend over time for publications that have been accepted as relevant in this study. It is visible that early publications have started to occur between 2005 and 2010 on the topic of LSPI. Between 2007 and 2012 an increasing number of research articles were published each year. At around 2013, the number of LSPI publications started to strongly increase. Note that the perceived reduction of publications in 2018 is due to a shorter report period: the numbers in this graph do not represent a full year yet but the time from January to June only.

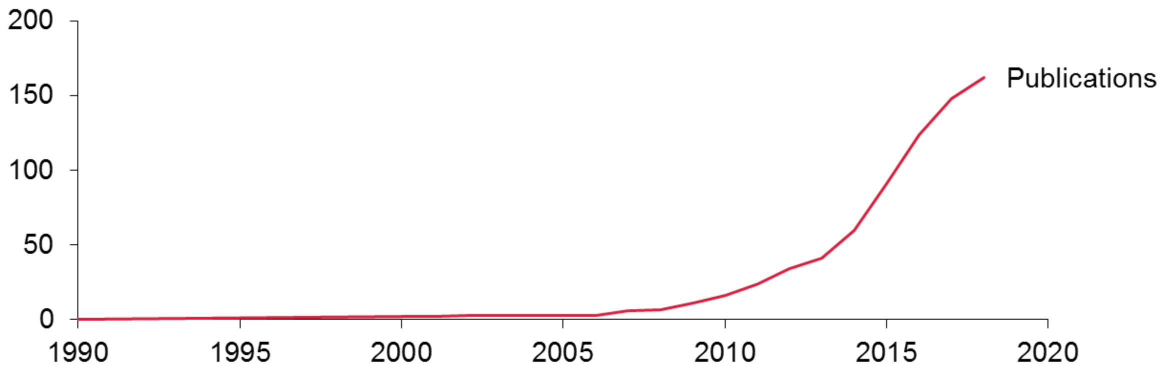

Figure 2.2.3 Cumulated publications between 1990 and 2018

2.3 Manual Search

To complement the systematic review a manual search of additional, non-databased conference publications was conducted. Table 2.3.1 summarizes the main sources that have been screened in addition to the systematic review. Similar to the systematic review, a timeframe of 1990 to 2018 was analyzed.

Figure 2.3.1 summarizes the most relevant conferences regarding LSPI. Note that some conferences have been published professionally (e.g. Springer, Elsevier) in selected years (e.g. Berlin). The publication is then listed under the systematic review for those years. Please note also that conference publications that have been published in a similar form in a reviewed Journal are only listed as the latter and have been neglected for the manual search.

Aachen	Aachen Kolloquium
Vienna	Vienna Symposium
Stuttgart	Stuttgart Symposium
Graz	The Working Process of the ICE
Baden-Baden	Int. Symposium on Internal Combustion Diagnostics
Berlin	IAV Tagung Ottomotorisches Klopfen
Detroit	SAE High Efficiency Engine Symposium
Detroit	International Multidimensional Engine Modeling
Various	CIMAC Congress
Various	FISITA Congress
Detroit	DEER Conference - DOE
Various	The Spark Ignition Engine of the Future - SIA
Publication	Oil & Gas Science and Technology - IFP
Publication	FVV Vorhaben

Table 2.3.1 Reviewed conference publications

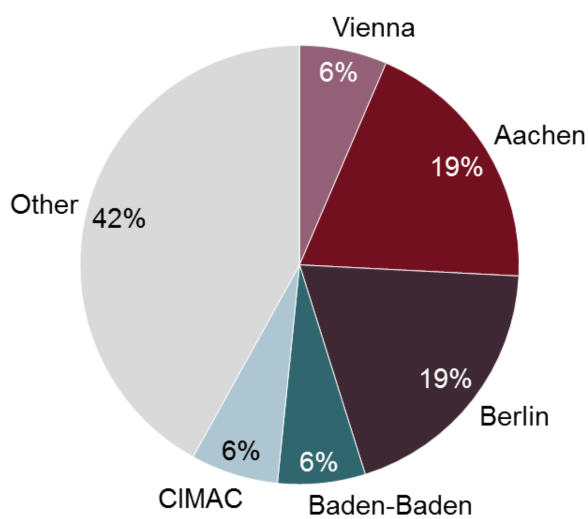

Figure 2.3.1 Origin distribution of manually searched conference publications

3 Literature Review

The literature review section is divided into six sub-chapters. The first sub-chapter is intended to give an overview of possible sources of the abnormal combustion phenomenon LSPI. The subsequent sub-chapters focus more closely on lubricant, deposit, fuel and hardware, and calibration impacts on LSPI. The final chapter gives a short outlook on the occurrence of Mega Knock that can follow pre-ignition events in some cases.

3.1 Possible Sources for LSPI

Various aspects have been linked to be the source of LSPI over time and numerous sources can indeed potentially lead to pre-ignition in boosted combustion engines. Figure 3.1.1 shows an early outline of potential sources. More recent research has broken these sources down to two major pathways: (Fuel or oil) droplet induced LSPI and deposit induced LSPI (e.g. [SPR12], [CON20], [SPR7]).

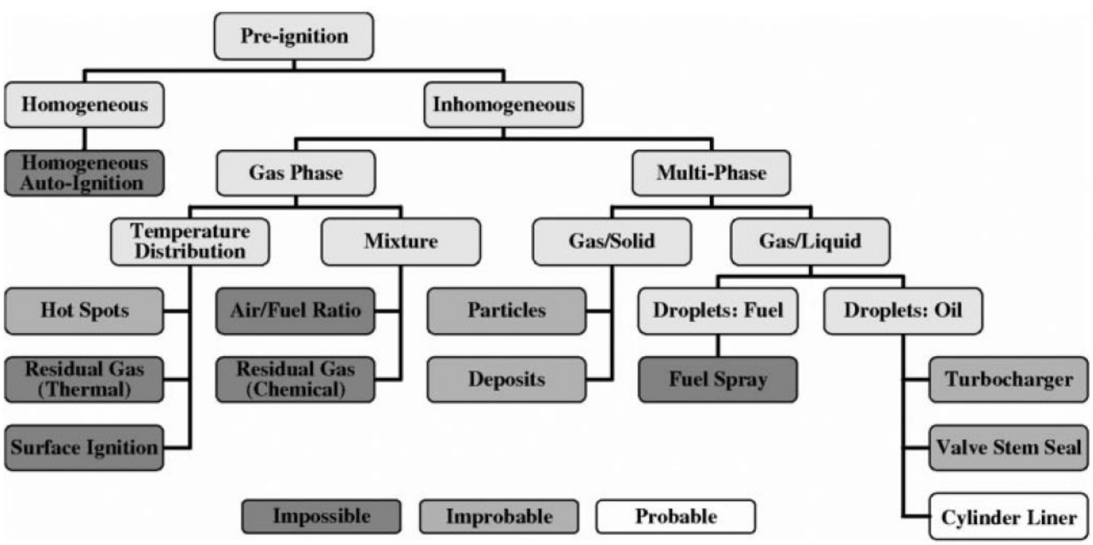

Figure 3.1.1 Potential root-causes of pre-ignition [SAG3] Reprinted by Permission of SAGE Publications, Ltd.

The theory behind droplet induced LSPI is that oil or oil-fuel mixture accumulates on the top ring land or on the cylinder wall and then gets thrown, blown, splashed, or vaporized into the combustion chamber during the gas exchange or compression stroke of the engine. These droplets can then further mix with oxygen and auto-ignite thus leading to a flame initiation and deflagration. Due to the often-early flame initiation and start of deflagration

LSPI events can subsequently lead to engine knock. Further sources for oil intrusion can be the PCV system or faulty turbo charger or valve stem seals (e.g. [SAE12]). The deposit theory adds the intermittent steps of deposit formation in the ring land, piston or head surface to the equation. Deposits can also originate from the intake manifold or can be re-breathed through the exhaust. The impact factors on both theories are largely similar as outlined in figure 3.1.2. Figure 3.1.3 presents a combined mechanism which allows different pathways particularly for first and following pre-ignition events. These approaches combine several proposed mechanisms.

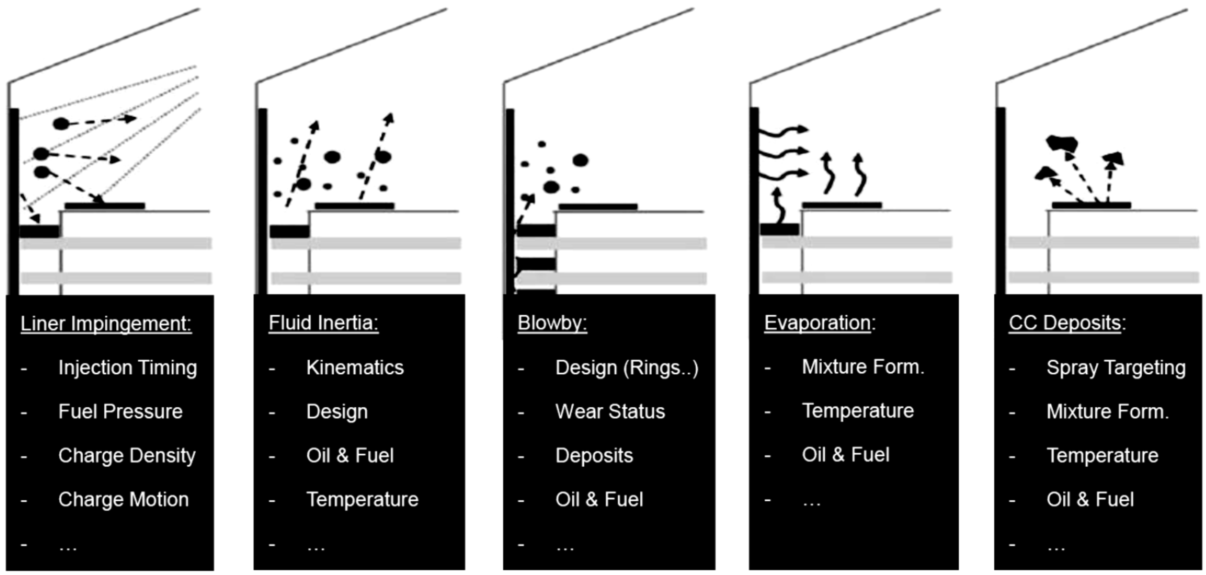

Figure 3.1.2 Possible sources for LSPI according to [SPR12] and [CON20]

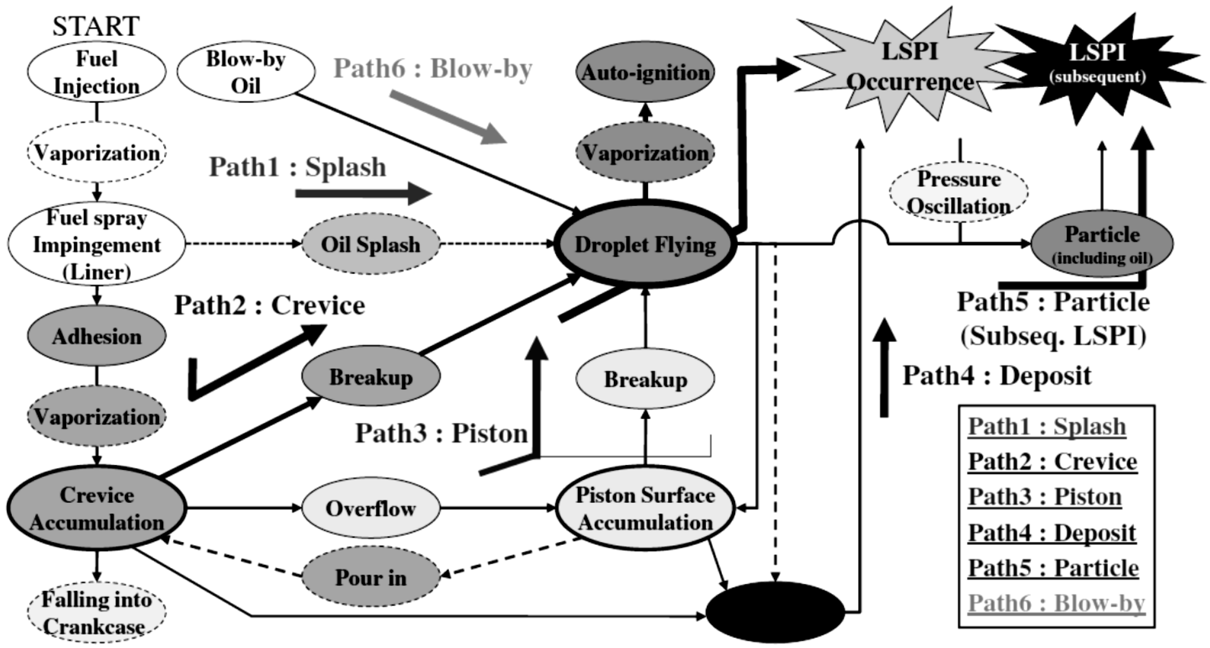

Figure 3.1.3 Combined mechanism pathway for first and following events [SPR7]

The mechanism suggested by Kassai et al. [SPR7] proposes six pathways for pre-ignition combining the above mentioned mechanisms:

1. Fuel-oil splash caused after injecting fuel into an oil film
2. Droplet transport from fuel-oil mixture from the piston crevice and ring land
3. Droplet break-up from fuel-oil mixture from piston surface accumulation
4. Deposit break-up
5. Particles from path 1-3 from the previous cycle (potentially main reason for following/intermittent LSPI)
6. Blow by / PCV etc.

All of the above mentioned mechanisms have been linked to LSPI previously in some form. Kubach et al [SAE173] developed a dimensionless parameter to rate splash caused by fuel impingement. Other recent studies have started to investigate the fuel/oil mixture and transport on the liner and ring land/crevice [SAE169, CON33, SPR5]. Zhang et al. performed simulations to study the evolution of the fuel-lubricant diffusion in the liquid film and vaporization at the liquid-gas interface at the liner-ring contact and concluded that fuel spray does not completely vaporize before the piston retracts and therefore leads to a substantial local fuel dilution. This local fuel dilution includes a significant amount of oil components that can be scraped by the top ring and potentially enter the combustion chamber.

Numerous optical studies have linked deposit flaking and flying oil droplets to LSPI occurrence. Alger et al. [SPR5] and Splitter et al [SAE181] measured the composition of the top ring fluid as the potential lead-source for LSPI. Additionally, several studies have been conducted which show that oil or oil/fuel injection [e.g. SAE128, SAE 83, SAE84, SAE85] and deposit injection [e.g. SAE82, SAE101] into a combustion chamber can artificially induce LSPI-like pre-ignition events in a research setting.

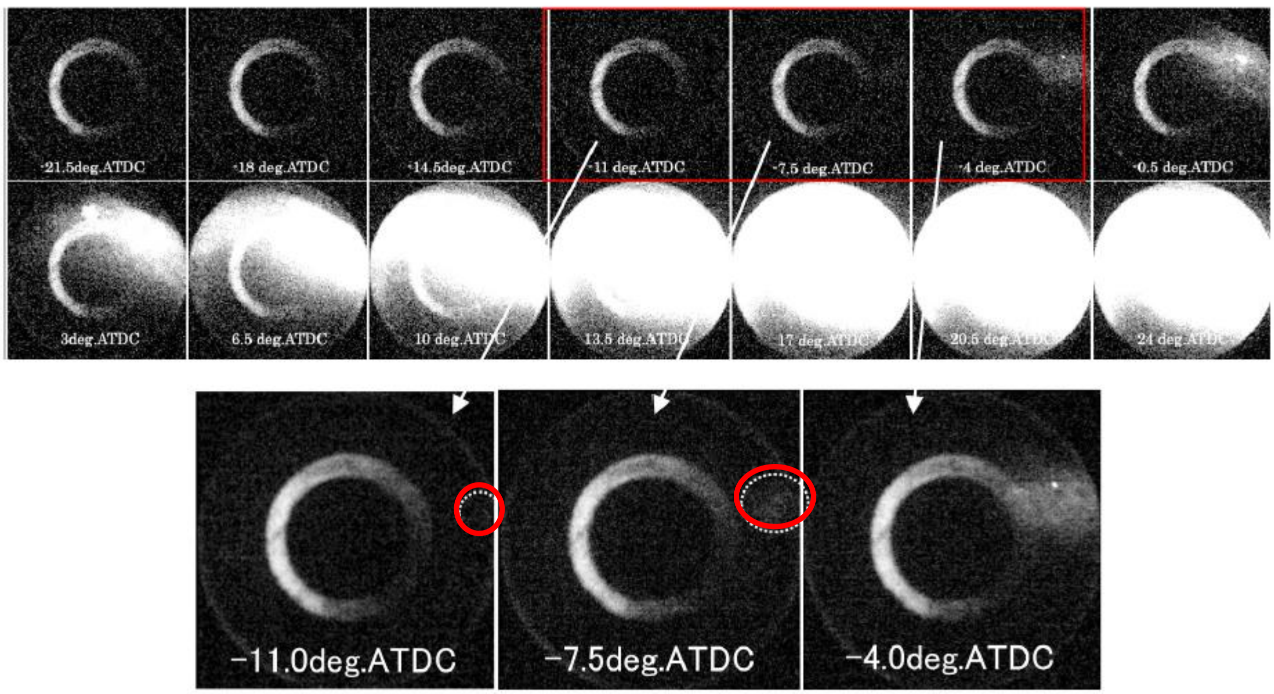

Figure 3.1.4 Optical investigation of first and following LSPI events [SAE106]

Figure 3.1.4 shows pictures presented by Kuboyama et al. [SAE106]. The pictures show how oil or mixture of oil and liquid fuel is accumulated in the piston crevice area and burns under low oxygen condition during the expansion stroke.

A few studies have analyzed the impact of initiation sources and concluded that more than one combustion cycle is necessary to initiate LSPI. Results from Ohtomo et al. [SAG2] indicate that an oil droplet does not cause low-speed pre-ignition if said droplet flies into the combustion chamber unless it remains in the chamber over the exhaust stroke. Similarly, Gupta et al. [SAE164] found that only particles which either survive the gas exchange process or are rebreathed into the combustion chamber can be sufficiently hot enough to induce pre-ignition. This is an interesting finding and potentially explains the intermittent burst effect other authors also reported [e.g. SAE153]. This finding, however, could be

controversial to some of the optical investigations: As shown in figure 3.1.5, some optical investigations link first LSPI events with droplets while linking following burst events with deposits [SAE81]. More research is needed to clarify this potential discrepancy.
Figure 3.1.6 [SAG1] and Figure 3.1.7 [SAE111] summarize a combined explanation approach: Macroscopic effects defined by the designer and physiochemical mechanisms affecting local properties can lead to the violation of fundamental threshold parameters for auto-ignition.

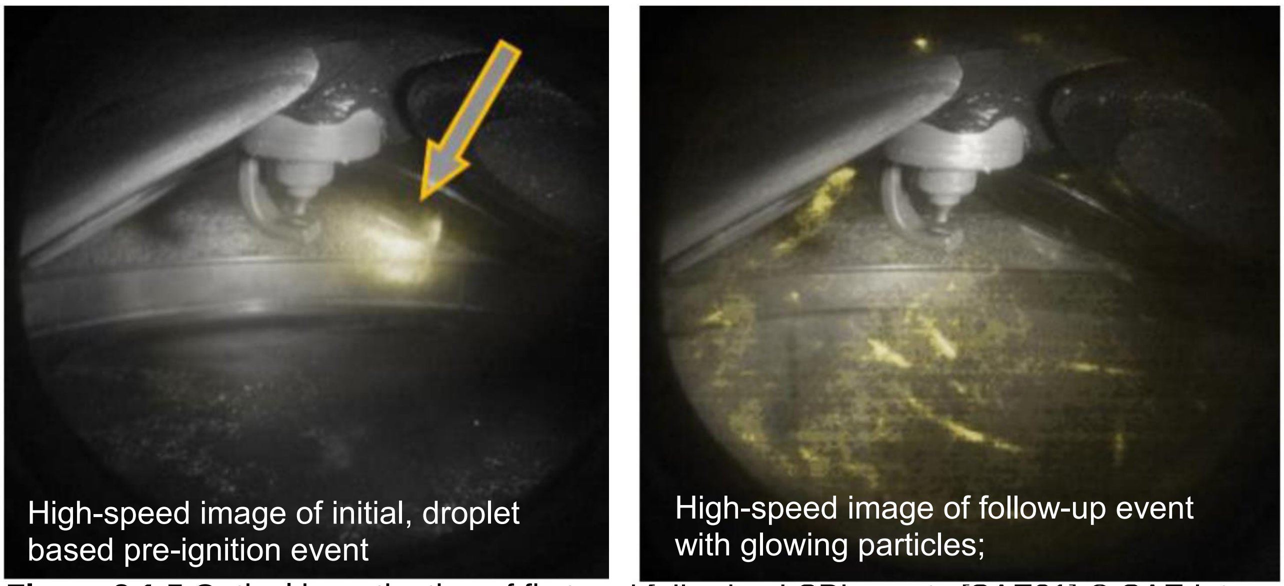

Figure 3.1.5 Optical investigation of first and following LSPI events [SAE81]

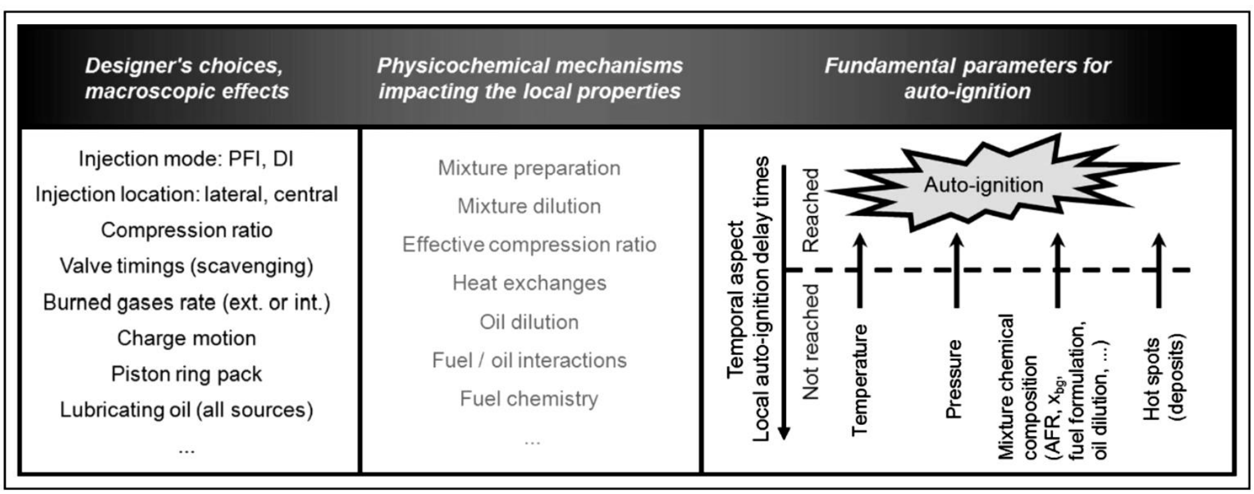

Figure 3.1.6 Combination of analyzed aspects impacting LSPI [SAG1] Reprinted by Permission of SAGE Publications, Ltd.

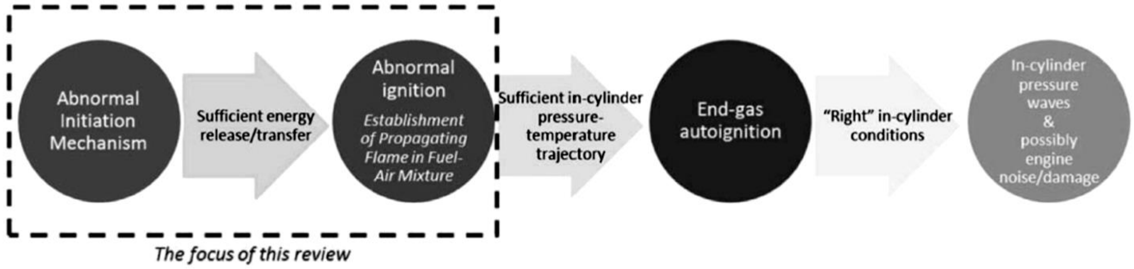

Figure 3.1.7 LSPI development steps [SAE111]

This leads to stochastic cases where the combination of an initiation event (e.g. an oil droplet or deposit breaking off) meets said unfavorable boundary conditions (pressure, mixture, temperature etc.) and results in a pre-ignition event. This early pre-ignition and developing deflagration can then develop into knock and detonation when the conditions are right.

3.2 Lubricant Impact on LSPI

One of the main LSPI research focuses between 2008 and 2018 has been the analysis of the impact of lubricant properties and lubricant composition on pre-ignition. As already discussed in the previous sub-chapter, lubricants have been suggested to impact LSPI in two main ways:

1. Firstly, lubricants can impact deposit formation. Flaking deposits have been linked to LSPI occurrence in several studies [e.g. SAE53, SAE82, SAE92, SAE101, SAE145, SAE164]. In this context, lubricants can potentially influence deposit-born pre-ignition events both by the number and size of the resulting deposits as well as by their composition.

2. Secondly, lubricant composition and properties can impact the behavior and physical and chemical properties as well as the ignitability of potential liquid fuel/lubricant droplets or vapor that are either flung, blown, splashed or evaporate into the combustion chamber.

Both mechanisms have been suggested to cause LSPI. The main underlying mechanisms are outlined schematically below in Figures 3.2.1 and 3.2.2. Figure 3.2.1 shows the suggested mechanism for liquid oil/fuel droplet ignition following the theory outlined in Teng et al. [SAE161], while Figure 3.2.2 shows the suggested mechanism for solid particle ignition according to Gupta et al. [SAE164]. Note, for both cases, the auto ignition happens in the gas phase around the deposit or droplet. The droplet mechanism suggests, however, that the ignition occurs in a fuel/oil vapor while, the ignition in the deposit mechanism occurs in the fuel-air charge. Nonetheless, lubricant composition has the potential to influence both of the outlined mechanisms.

Since most LSPI studies focusing on the impact of lubricants on LSPI cannot identify the exact source of the pre-ignition events and cannot determine if droplets, flaking deposits or both are the ultimate source, it must be noted that many of the findings outlined in the following can also apply to sub-chapter 3.3 analyzing the impact of deposits on LSPI. Please also note that the interaction between fuel and oil is crucial not only for deposit formation but also for the fuel-oil droplet formation process and for the vapor cloud ignitability. Please refer to sub-section 3.4 for a more detailed look on the impact of fuel properties on LSPI.

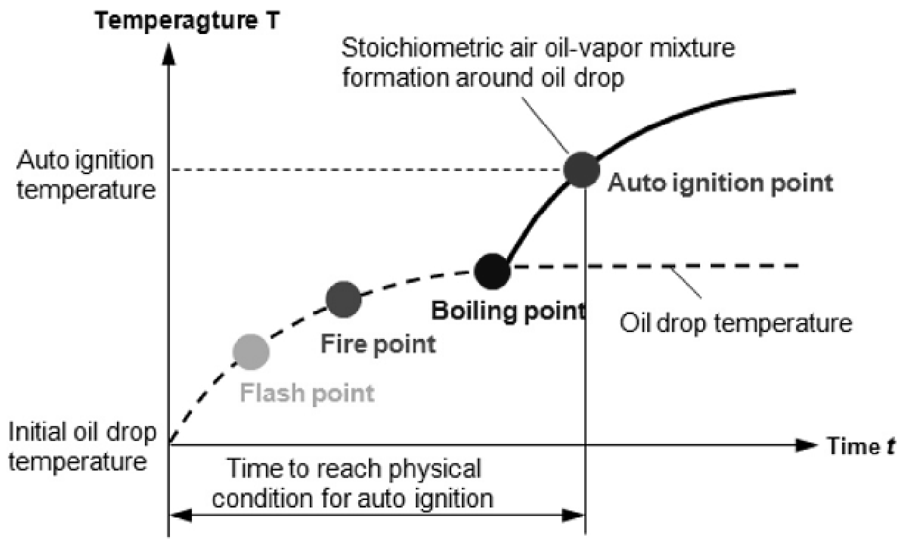

Figure 3.2.1 Suggested schematic for liquid oil/fuel droplet ignition [SAE161]

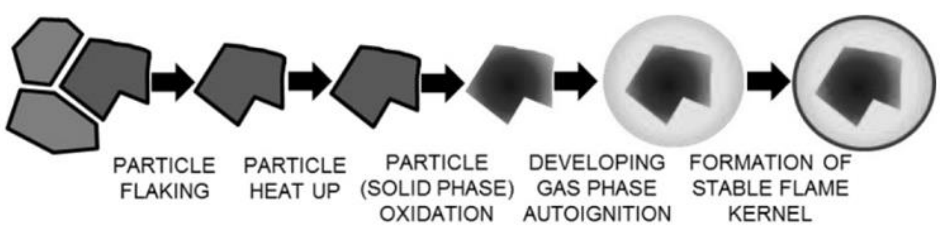

Figure 3.2.2 Suggested schematic for solid particle ignition [SAE164]

Early investigations into the phenomenon of Low Speed Pre-Ignition quickly led to the assumption that oil droplets, and therefore oil formulation, could be of importance [SAE46]. In the following years, numerous researches focused on this topic. The early investigation of Zahdeh et al. [SAE51] concluded that optimized oil formulation with low sulfate ash, low calcium, and a low Noack volatility, that defines the evaporative loss of lubricants in high-temperature service, should be preferable for low numbers of LSPI events. In addition, a formulation that has the potential to reduce oil intrusion into the combustion chamber should be of importance. The investigation of Takeuchi et al. [SAE62], however, did not confirm the importance of the Noack volatility. The negative impact of calcium detergent additives could, however, be confirmed. In addition, Takeuchi et al. found that both MoDTC and ZnDTP have the potential to prevent LSPI. The authors of the study also suggested to evaluate oxidative reactivity of engine oils using High-Pressure Differential Scanning

Calorimetry (HP-DSC), which correlated well with their LSPI results. Follow-up studies from numerous authors have since confirmed the general impact of calcium additives as well as MoDTC and ZnDTP [e.g. SAE112, SAE115, SAE125, SAE128, SAE 130, SAE132, SAE136, SAE138, SAE140, SAE141, SPR19]. Shock tube [SAE132], CATA burner [SAE130] and optical engine tests, where the additives have been mixed into the test fuel [ASE93, SAE95, SAE118], have partially confirmed the initial multi-cylinder engine test results, too. However, significantly more fundamental work is needed to understand the underlying reaction mechanism and to develop predictive simulations.

More recent investigations on the impact of oil additives on LSPI from Kocsis et al. [SAE151], Ritchie et al. [SAE125], or Fletcher et al. [SAE138] have analyzed a wider variety of additives. Kocsis et al. [SAE151] conducted testing on a multi-cylinder engine using test oils formulated according to a systematic additive metals matrix including zinc, calcium sulfonate, and a molybdenum based additive. Increasing the concentration of calcium again lead to the expected increase in LSPI occurrence. However, the impact of the zinc and molybdenum additives was only seen at higher calcium concentrations. Fletcher et al. [SAE138] included in their study various additional detergent and dispersant additives, concluding that both ashless and ash-containing additives can impact LSPI and that the additive formulation needs to be optimized. Ritchie et al. [SAE125] performed tests that confirmed the impact of calcium detergents independent of the type of calcium additive used in the detergent but did not find an effect of Magnesium detergents on LSPI. Additionally, sodium detergents seemed to interact with calcium and can act as LSPI promoters in the presence of calcium. ZnDTP was confirmed as an LSPI quencher. Additionally, viscosity grade showed a non-statistically significant, directional effect towards more LSPI at lower grades. Interactions between chemical and physical oil transport characteristics may become of importance depending on the application. Figures 3.2.3 to 3.2.5 show some of the oil additive effects described above.

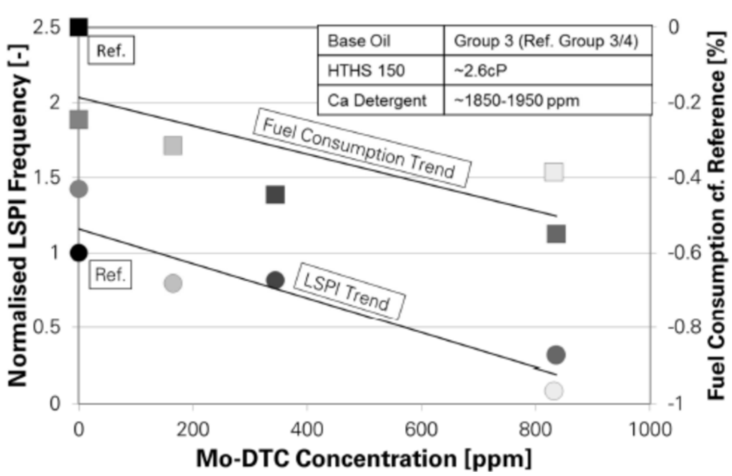

Figure 3.2.3 The impact of molybdenum-based additives on LSPI [CON22]

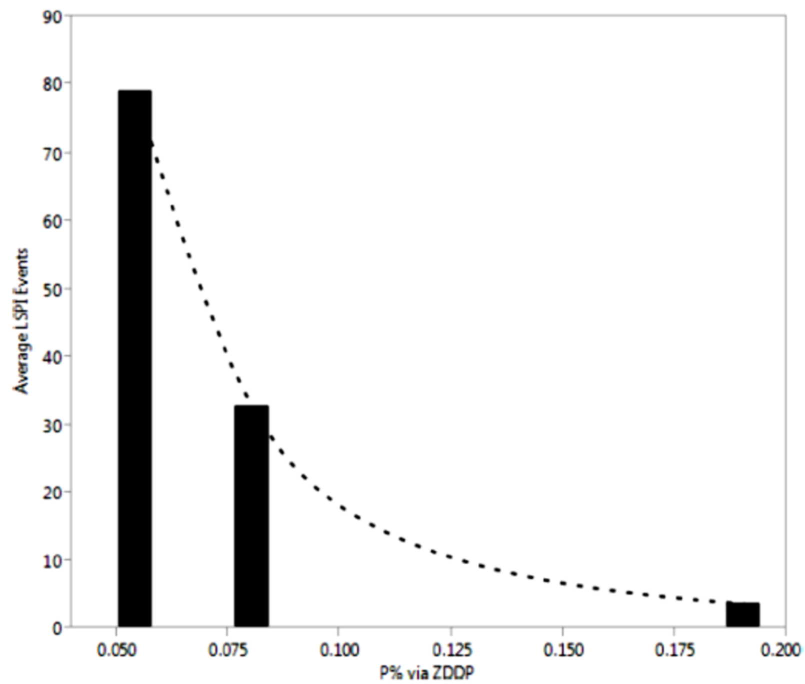

Figure 3.2.4 The impact of ZDDP additives on LSPI [SAE125]

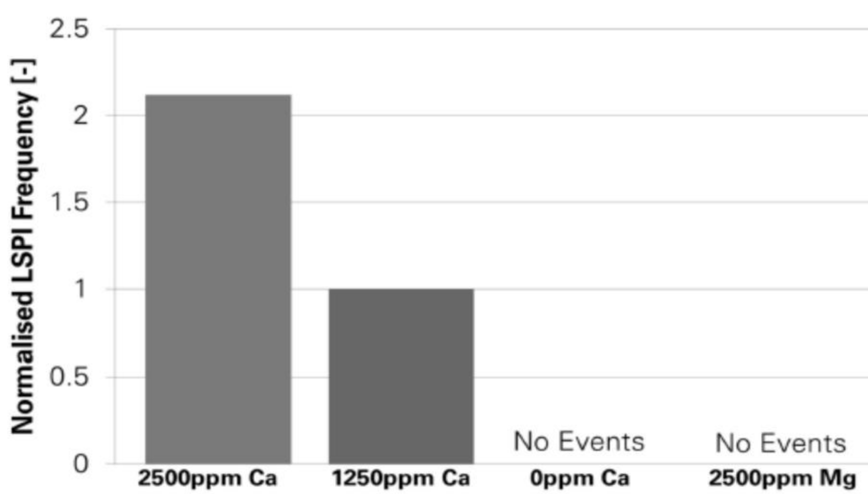

Figure 3.2.5 The impact of calcium additives on LSPI [CON22]

In comparison to the performed research on the impact of additives on LSPI, the impact of base stocks has been analyzed by few researchers. Base stock effects have been analyzed by Welling et al. [SAE80], Takeuchi et al. [SAE62], Kuti et al [SCD12] and Andrew et al. [SAE143]. Welling et al. [SAE80] concluded that low base stock reactivity and fuel absorption tendencies are recommended properties in base stocks due to the high reactivity increase when (local) fuel dilution occurs. Andrew et al. analyzed 11 engine oils with various base stocks from Group I, II, III, and IV and a common additive system for their pre-ignition tendency in a test engine and came to similar conclusions [SAE143]. Takeuchi et al. [SAE62] have presented a different trend regarding LSPI occurrence in base stock qualities of Group I-III oils: Their investigation revealed a decreasing LSPI activity with increasing base stock number while Welling et al. show an increased activity in said base stock groups I-III. A differentiation of physical and chemical effects of the oils in a specific test setting may explain these differences but more work may be needed to fully understand the driving effects. Figure 3.2.6 and 3.2.7 show the different trends discussed above.

A method to potentially explain this behavior has been presented by Takeuchi et al. [SAE62]. Takeuchi et al. found a strong correlation between auto ignition temperature and LSPI frequency at 10atm (not at 1atm though). The correlation is shown in Figure 3.2.8.

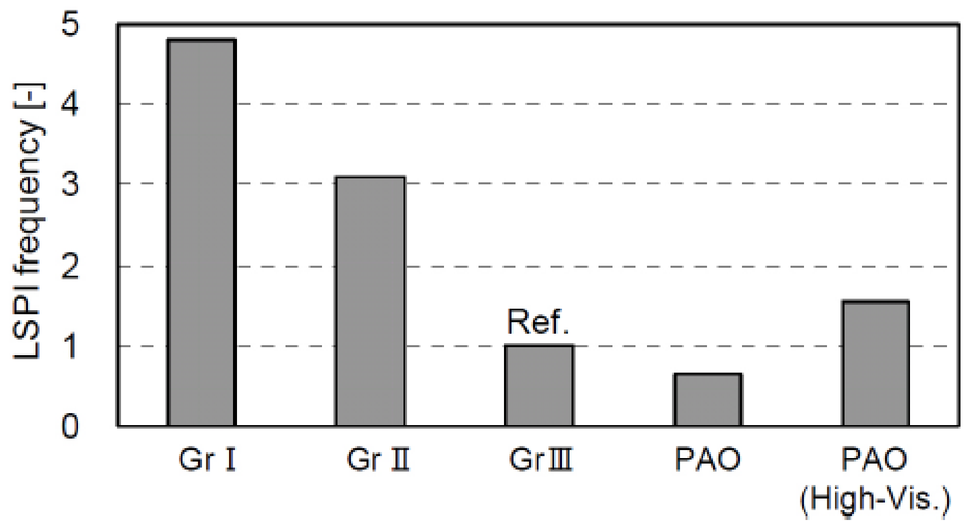

Figure 3.2.6 The impact of base stock on LSPI [SAE62] © SAE International. All rights reserved.

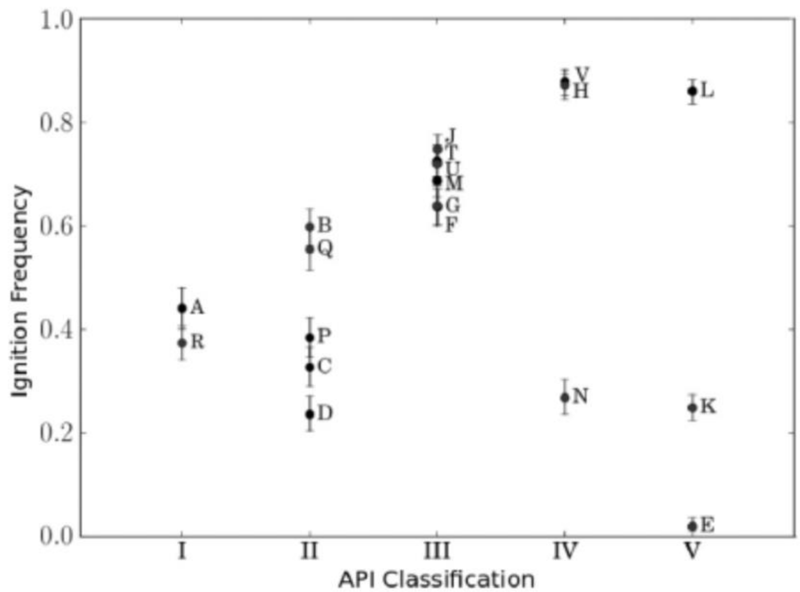

Figure 3.2.7 The impact of base stock on LSPI [SAE143] © SAE International. All rights reserved.

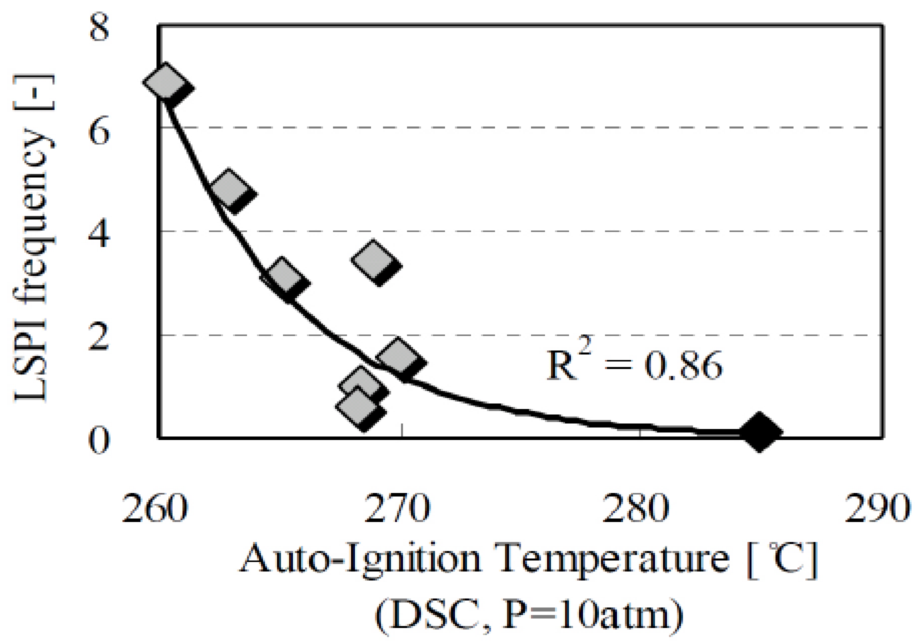

Figure 3.2.8 The impact of base stock on LSPI [SAE62] © SAE International. All rights reserved.

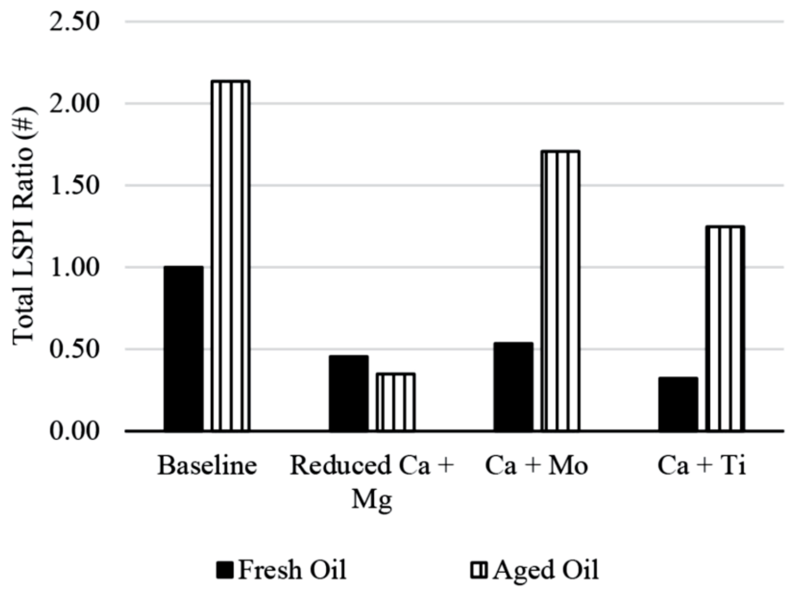

Figure 3.2.9 LSPI ratio from fresh and 100h aged oil [SAE170] © SAE International. All rights reserved.

The impact of oil ageing has not been extensively analyzed to this point. An early study by Hirano et al. [SAE74] concluded that LSPI occurrence was in general affected by oil degradation when comparing fresh and aged oil from vehicle tests. However, the trend was not defined and factors to explain the variation of the performed test results remained unclear. Since then, little work has been published, which analyzes real world oil ageing. Recently, Michlberger et al. have published a more detailed study that analyzed fresh and aged oil for LSPI propensity [SAE170]. They found that even though the tested formulations behaved comparably at a fresh stage, the LSPI occurrence was different after ageing. After aging, both calcium and molybdenum and calcium aund titanium formulations were observed to have high LSPI densities while a reduced calcium and magnesium formulation maintained strong LSPI mitigating performance. Figure 3.2.9 outlines these results. The authors concluded that current industry specifications, which only analyze fresh oil performance are not adequate to effectively protect engines from LSPI in the field. Leach et al. [CON22] found similar results in their study, showing LSPI propensity nearly doubled with used oils compared to fresh oil samples. Understanding oil ageing behavior and its impact on LSPI occurrence better is an area where more research is needed in the future.

3.3 Deposit Impact on LSPI

As outlined in the previous sub-chapters, deposits have been shown to impact LSPI occurrence in numerous studies [e.g. SAE53, SAE82, SAE92, SAE101, SAE145, SAE164]. Three potential pathways can be identified in this context.

1. Deposit layers can lead to a slight increase in compression ratio and thermal insulation of the combustion chamber, thus leading to higher compression temperature and pressure
2. Flaking deposits can go through heat cycles and function as a thermal initiation source for LSPI events (see also Figure 3.2.2)
3. Deposit formation in the ringland area can increase oil intrusion into the combustion chamber by affecting ring sealing

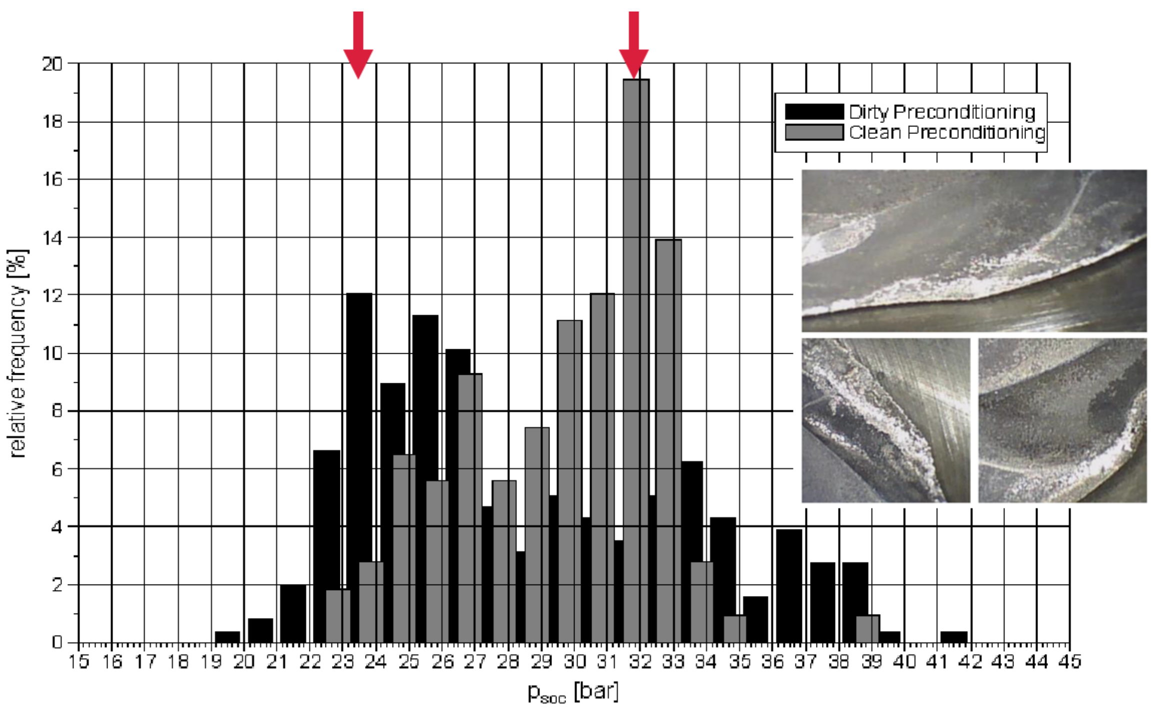

Figure 3.3.1 Effect of combustion chamber deposits on LSPI [SAE53]

Deposits have been linked to LSPI occurrence early after the first reports of the phenomenon have been published. Haenel et al. [SAE53] performed a Taguchi DoE parameter study of design, of calibration parameters and their impact on LSPI with combustion chamber pre-conditioning as noise factor. They concluded that deposits reduced the LSPI threshold for all tested configurations and attributed this to flaking combustion chamber deposits. Figure 3.3.1 shows this behavior: The pressure at which LSPI occurs (pressure of start of combustion: PSOC) is strongly reduced when operating with combustion chamber deposits. An optical follow-up study by the same researchers and the same test setup found traces of glowing deposits flying through the combustion chamber, which caused pre-ignition events [CON31]. Okada et al. [SAE82] performed similar optical tests and confirmed this observation. The images identified solid particulate substances that bounced from the surface of the piston as the likely pre-ignition source.

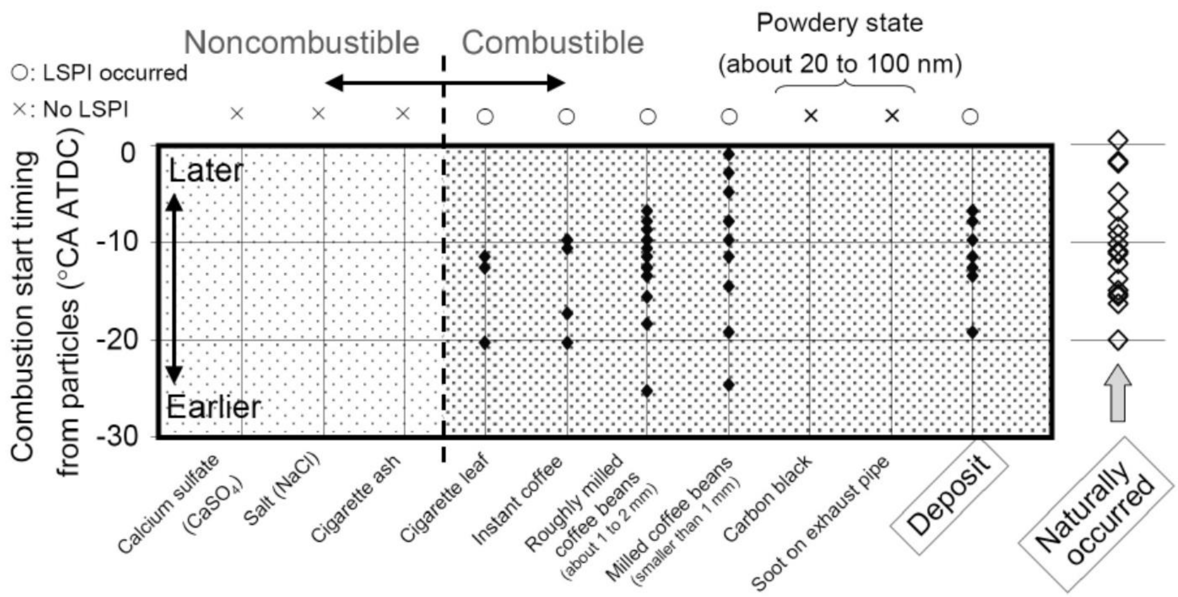

Figure 3.3.2 Effect of different particles on LSPI [SAE82]

Tests injecting different deposits into the combustion chamber generated pre-ignition with similar characteristics to naturally occurring events. Figure 3.3.2 shows the investigations of Okada et al. that lead to the conclusion that deposits need to be combustible, need to have a minimum size, and need to undergo a heat cycle to be able to result in pre-ignition [SAE82].

Other researchers found similar optical evidence for glowing deposits initiating LSPI [e.g. SAE102, SAE106]. Tamura et al. [SAE92] and Shimizu et al [SAE145] investigated the impact of oil based deposits, from oil doped with calcium, zinc and molybdenum additives in an optical research engine. The researchers concluded that calcium derived and ZnDTP-derived deposits facilitated auto-ignition and increased knock intensity, whereas MoDTC-derived deposits did neither. Wang et al. [SAE101] investigated the impact of deposits and particulates on LSPI in both a single cylinder engine (with deposit dosage) and a conventional 4-cylinder engine. They concluded that pool fires can lead to high concentration soot particles under unfavorable injection conditions that cause wall wetting, which subsequently increase the LSPI occurrence. Additionally, carbon particles induced into the single cylinder engine also triggered LSPI. They also found that knock intensity increased with increasing particle diameter and temperature. Most recently, Gupta et al. [SAE164] performed simulations of deposit induced pre-ignition to analyze the mechanism and the elementary steps involved in more depth. The authors concluded that only particles surviving the gas exchange process or rebreathed into the combustion chamber can be hot enough to induce pre-ignition. This is an interesting finding, and can potentially explain the intermittent burst effect other authors also reported [e.g. SAE153, SAE106]. Figures 3.4.4 and 3.4.5 outline the theory and optical results from explaining burst events: Following pre-ignitions in burst events are triggered by residual particles that are heated during the subsequent combustion cycle and rebreathed or re-circulated. The simulation further predicted that small particle size, a decrease in engine speed, engine load, and lambda, and an increase in EGR has the potential to suppress LSPI. Figure 3.3.3 summarizes some of their findings.

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

Figure 3.3.3 Effect of deposit properties on LSPI [SAE164] © SAE International. All rights reserved.

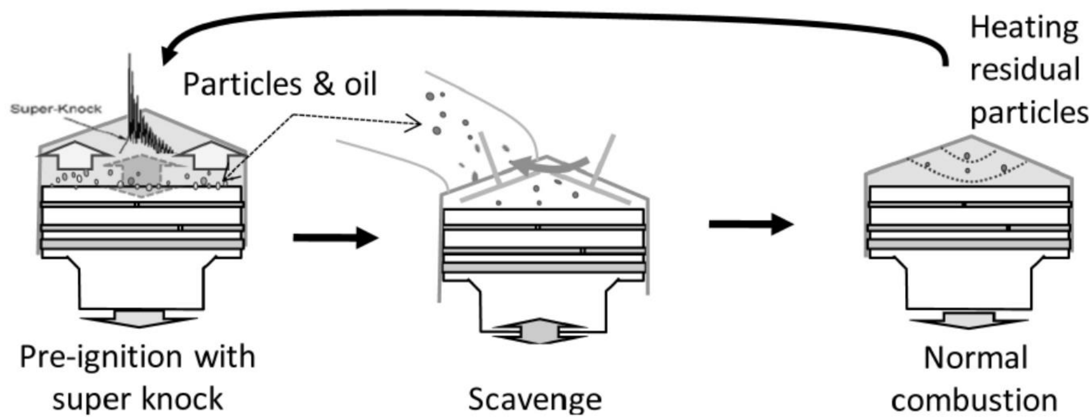

Figure 3.3.4 Theory to explain LSPI burst events [SAE106]

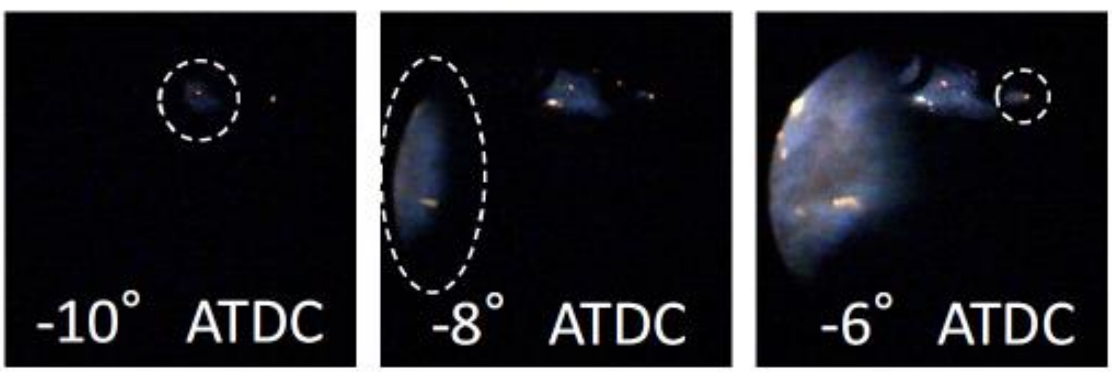

Figure 3.3.5 Optical investigation of LSPI burst events [SAE106]

No investigations of the impact of deposits on oil transport and how this may affect LSPI have been performed up to this point.

It must be noted that fuels and lubricants can potentially influence deposit-born pre-ignition events both by the number and size of the resulting deposits as well as by their composition. The findings of sub-chapter 3.2 and 3.4 can therefore be considered in this section.

3.4 Fuel Impact on LSPI

Following the proposed LSPI mechanisms, fuel properties have the potential to impact LSPI propensity in numerous ways: Fuel evaporative behavior impacts both mixture formation, homogeneity, liner/crevice accumulation, and deposit formation. Additionally, laminar flame speed impacts the initial flame initiation while ignitability can impact knock occurrence. Fuel composition is, therefore, an obvious contributor to most mentioned LSPI pathways.

The impact of gasoline fuels on LSPI has been analyzed in numerous studies. Early studies quickly realized that LSPI cannot be avoided with high octane fuels [e.g. SAE46, SAE52, SAE53]. Chapman et al. [SAE86] confirmed this with a more detailed study and expanded the discussion to volatility effects of gasoline. The authors concluded in this context that fuels with lower evaporation rates in the 120°C to 130°C range (based on the ASTM D86 evaporation curve analysis) show higher LSPI rates due to this temperature range being representative of the piston top-land crevice temperatures at the LSPI test condition, thus leading to increased fuel accumulation in the crevice regions. Other authors have since then found additional links between fuel volatility and LSPI occurrence. The results of Xu et al. [SAE123] indicate a correlation between the high end of the boiling curve and LSPI. Similarly, Kassai et al. [SAE141], Leach et al. [CON22] and Mayer et al. [SAE127] also found a correlation between fuel distillation and LSPI (described by a correlation of T90 and LSPI). All groups concluded that heavier fuel can lead to higher LSPI frequency. Figures 3.4.1 and 3.4.2 outline this trend. Mayer et al. [SAE 127] have correlated in this context the integrated fuel percentage above an assumed liner temperature of 150°C with LSPI occurrence and found a notably high correlation (Figure 3.4.2).

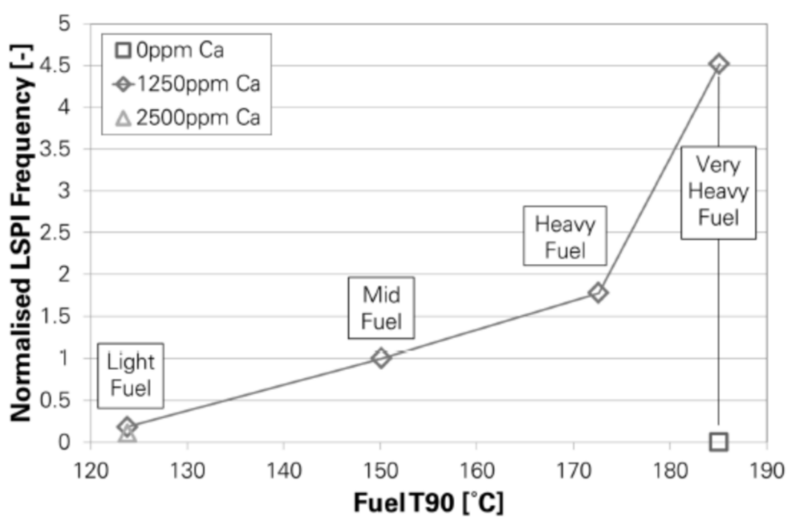

Figure 3.4.1 Effect of fuel T90 on LSPI [CON22]

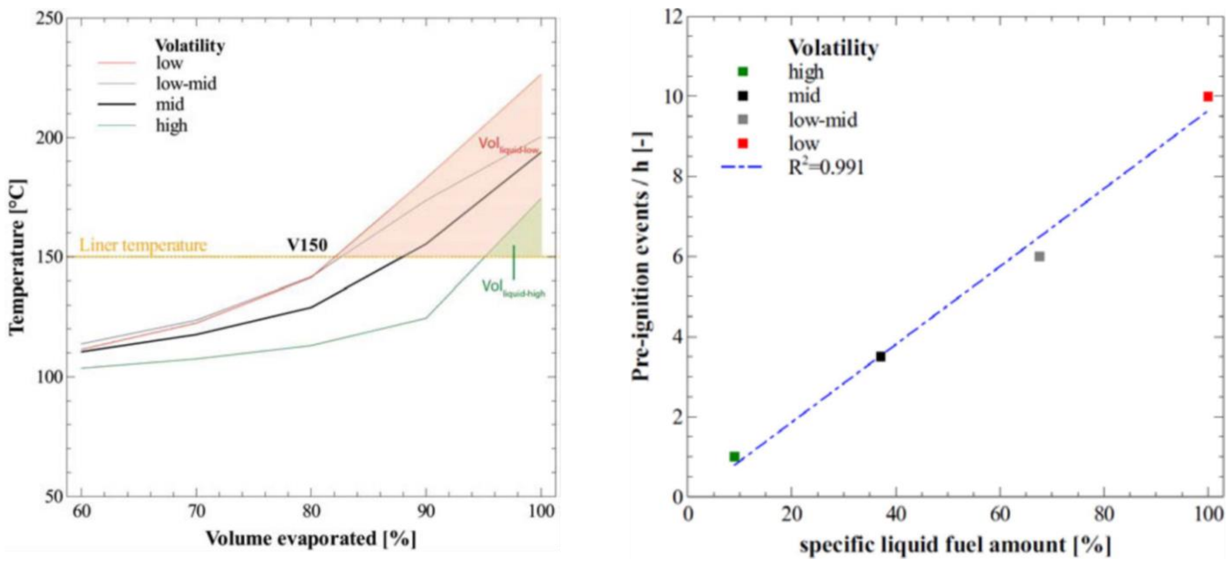

Figure 3.4.2 Effect of the integrated fuel percentage above 150°C on LSPI [SAE127]

Since distillation curves and fuel composition cannot easily be separated, results from composition effect tests need to be compared with the volatility investigations. Early composition effect tests performed by Amann et al [SAE52] showed that fuel chemical composition has a strong impact on the likelihood of occurrence and intensity of LSPI: Fuel blends with high levels of aromatics increased the occurrence of LSPI while oxygenated fuels, and especially low aromatic blends reduced the frequency at which LSPI occurred. The effect of aromatics on LSPI has also been investigated by Mansfield et al. [SAE129, SCD7], confirming the strong impact of heavy aromatics on LSPI occurrence. Figure 3.4.3 shows this correlation.

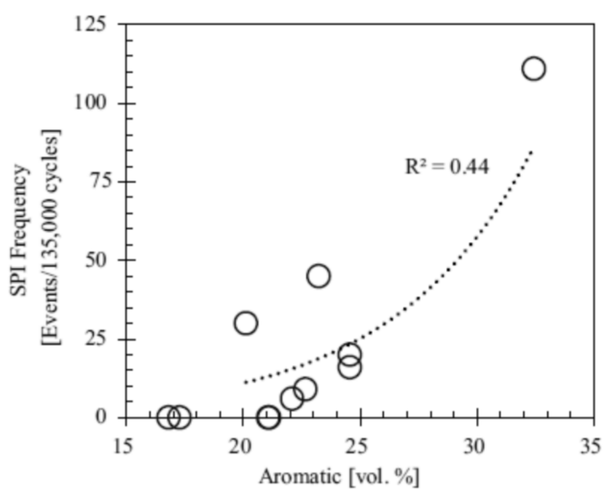

Figure 3.4.3 Effect of Aromatics on LSPI [SCD7]

The effect of oxygenates, on the other hand, has been controversial. While investigations by Mayer et al. [SAE127] and Haenel et al. [SAE153] showed increased LSPI rates with higher ethanol content in multi-cylinder engines (E10 up to E50; see Figure 3.4.4), other investigations have shown the opposite trend [CON11, CON12, SPR14]. The main reason for this behavior can be differences in the leading mechanism. Mayer et al. [SAE127], for example, reported a high correlation between pre-ignition tendency and the calculated liquid fuel amount in the piston crevice volume. Similarly, Haenel et al. [SAE153] linked the increase in LSPI activity and the measurable hydrocarbon spike during the gas exchange before cycles with LSPI occurrence to increased wall wetting with splash blended ethanol blends in a side DI engine. However, surface ignition and gas-phase auto-ignition can be assumed to be the leading mechanisms [SPR14]. The separation of the physical effect of fuel wetting cylinder walls and chemical auto-ignition characteristics needs to be analyzed further. The interaction of said impacts on LSPI with engine hardware and calibration is also not analyzed yet. Kocsis et al. [SAE174] performed a matrix study of different fuel compositions in a multi cylinder engine and confirmed the conclusion that aromatic content correlates with higher LSPI rates while olefin content was not linked to be affecting LSPI. Kocsis et al. also found that ethanol content increases LSPI (ethanol was varied between 0-15% in the study) leading to the conclusion that fuel volatility is a significant factor for LSPI, and, furthermore, reducing the distillation temperature in the T50-T90% range can substantially reduce LSPI.

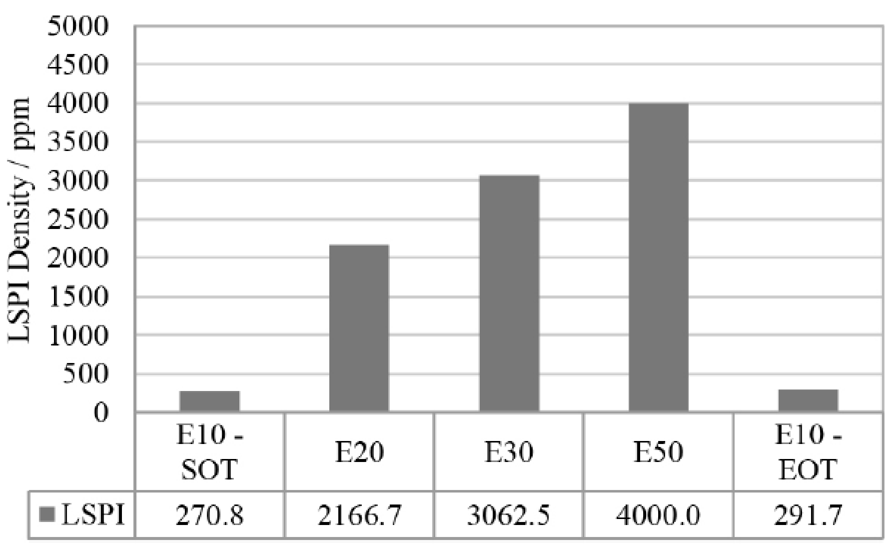

Figure 3.4.4 Effect of splash blended ethanol fuels on LSPI [SAE153] © SAE International. All rights reserved.

Few publications analyzing fuel additives have been published up to this point. Nomura et al. [SAE171] have conducted a study of gasoline fuel additives common in many parts of the world. They found that higher manganese concentrations led to a greater frequency of LSPI occurrences as well as that the frequency of LSPI occurrences increased when both volatility is lowered and manganese concentrations were increased. Optical investigations revealed deposits floating in the combustion chamber, starting to glow under compression and subsequently leading to pre-ignition. Figure 3.4.5 shows this impact quantitatively. It is observed that both fuel volatility (Fuel 1: Low volatility → Fuel 4: High volatility) as well as manganese addition lead to higher LSPI frequencies. The theory behind this behavior is that low volatility leads to increased numbers of fuel/oil droplets or flaking deposit that can act as potential ignition sources. Using volatility indices such as the simplified particulate mass index (PMI) or L150 to organize the data demonstrates that the frequency of LSPI occurrences increases as the volatility of the base gasoline becomes lower. This effect is visible independent of the manganese concentration. Furthermore, manganese increases the likelihood of LSPI occurrence via the exothermic reaction pathways of MnO and Mn_3O_4 according to Nomura et al. [SAE171].

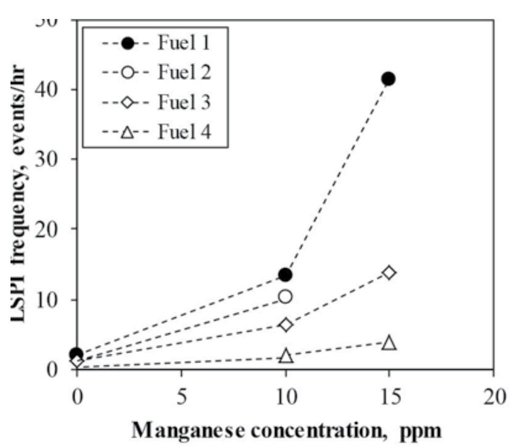

Figure 3.4.5 Impact of manganese and simplified PM Index on LSPI [SAE171]

3.5 Calibration & Hardware Impact on LSPI

Not surprisingly, unfavorable calibration and hardware configurations can have the potential to lead to pre-ignition events. Surface ignition and thermal (high-speed) pre-ignition events have been reported from early engine development projects for decades and have been the focus of continuous design efforts. Design and calibration solutions that optimize mixture formation, reduce wall impingement and oil intrusion (via rings or PCV), and minimize hot spots in the engine are favorable.

With the advent of boosted GTDI engines and the first occurrence of LSPI in the field early investigations have focused on calibration topics. Dahnz et al. [SAE46] investigated the positive impact of enrichment and the negative impact of colder (liner) coolant temperature on LSPI, while Zahdeh et al. [SAE51] looked into engine temperature, fueling, multi-injection strategies, and increased ring tension as parameters to reduce LSPI. Haenel et al. [SAE53] investigated the impact of injector targeting, residual gas, and spark plug design. Inoue et al. investigated the impact of blow-by and spark plug design. Similar to the findings in [SAE53] Inoue et al. concluded that properly designed spark plugs that are optimized for thermal behavior and use in GTDI engines do not contribute to LSPI. Amann et al. [SAE59] studied the impact of piston design and injection strategy on LSPI most notably finding that a strong correlation exists between the increase in frequency at which LSPI occurs and increased top land height and, to a lesser degree, the chamfer angle of a piston. Both measures increase the crevice volume of the piston which can be seen as support for the theory that the accumulation and release of oil /fuel mixtures from the top land crevice is one of the sources for LSPI. However, Zahdeh et al. [SAE51] found that an increased crevice volume showed repeatedly lower numbers of LSPI events in their engine tests. More work, especially analyzing the interaction of injection timing, injector design (e.g. central vs. side injection) spray targeting, charge motion and piston crevice design is recommended to understand this phenomenon better.

Some of the key calibration contributions on mitigating LSPI are outlined in Figures 3.5.1 (colder charge air temperature reduces LSPI propensity), 3.5.2 (hotter engine block temperature reduces LSPI propensity), 3.5.3 (mid stroke injection timing with minimal wall wetting reduces LSPI propensity), and 3.5.4 (multi injection strategy and charge motion increase improves mixture formation and reduces LSPI propensity).

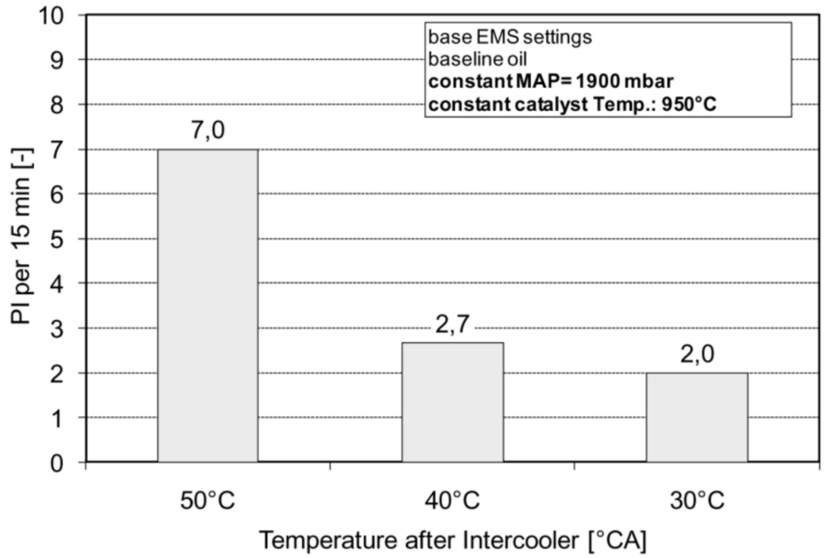

Figure 3.5.1 Impact of charge air temperature on LSPI [SAE51]

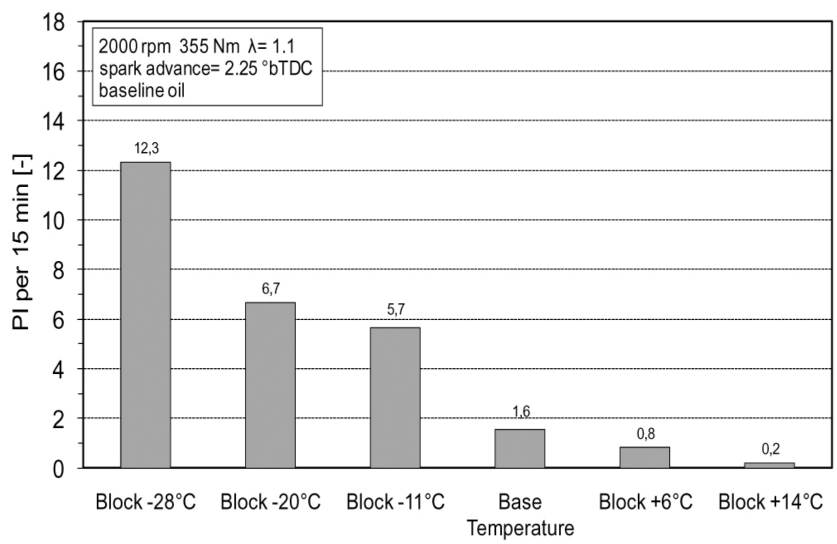

Figure 3.5.2 Impact of engine block temperature on LSPI [SAE51]

Multiple subsequent publications have been released confirming the positive impact of optimized injection targeting, multi injection strategies, enrichment and warmer liner temperatures on LSPI tendencies [e.g. SAE71, SAE79, SAE97, SAE100, SAE104, SAE180 etc.]. It can therefore be said that hardware and calibration solutions that minimize the fuel collection on the top ring have been identified to reduce LSPI.

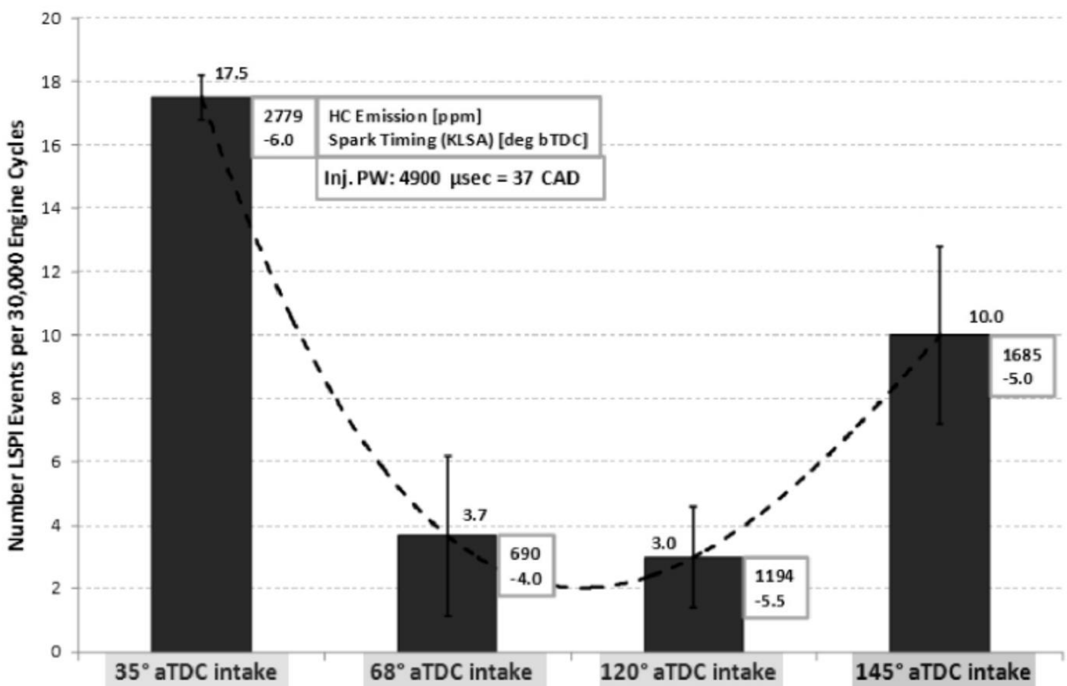

Figure 3.5.3 Impact of early and late injection timing on LSPI [SAE59] © SAE International. All rights reserved.

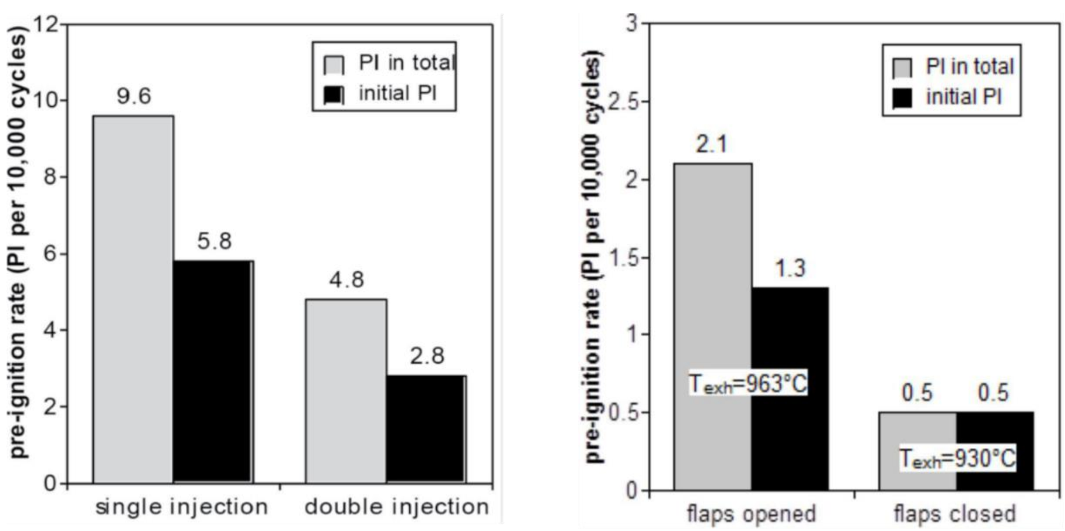

Figure 3.5.4 Impact of multi injection strategies and increased tumble motion on LSPI [SAE173] © SAE International. All rights reserved.

Additionally, Magar et al. [SAE102] also confirmed the positive impact of increased ring tension, thus the reduction of oil consumption. A more recent study of Mayer et al. [SAE126] investigated the impact of oil cooling jets and found that active piston cooling jets can increase LSPI occurrence. The summary of all these publications leads to the recommendation that minimized oil consumption is of importance to reduce LSPI. Mixture homogeneity and charge cooling [e.g. SPR25] have also been linked to reducing LSPI.

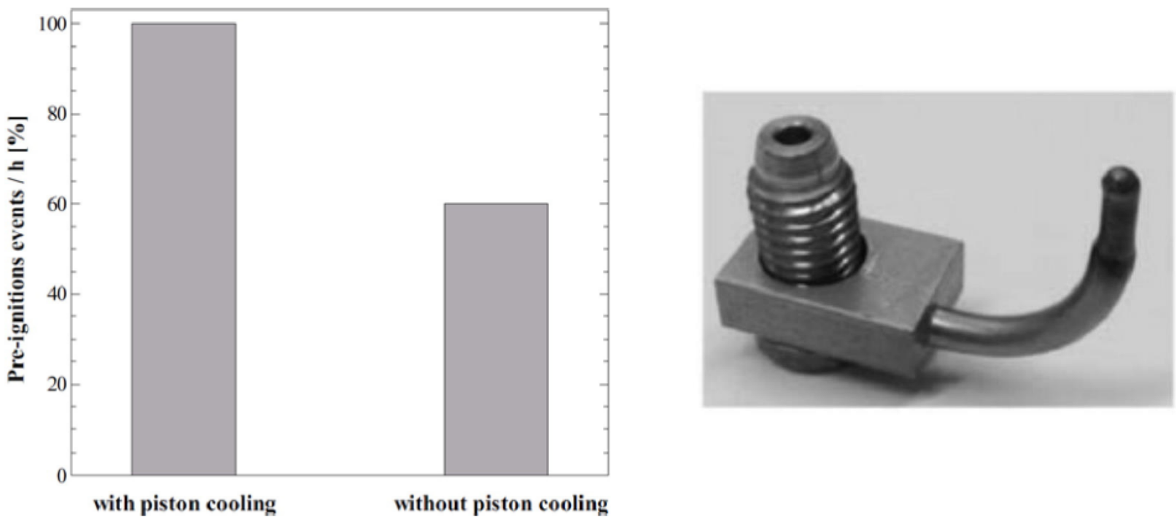

Figure 3.5.5 Impact of piston cooling jets on LSPI activity [SAE126]

Only limited studies are available to analyze newer technologies like water injection or cooled low pressure EGR. The latter has been analyzed by Amann et al. [SAE50] who concluded that cooled low pressure EGR has the potential to reduce LSPI. Few publications are available that analyze LSPI-caused engine failures. Passow et al. [SAE160] have recently published a review of engine failures. The typical damage seen on the piston due to LSPI events is second land breakage on the thrust side of the piston. Figure 3.5.6 shows an example for such a failure. Passow et al. suggest a fatigue caused by repeated overload of the piston leading to initiating cracks, usually in the lower root radius of the top ring groove, which then propagate through additional LSPI events, and then eventually lead to catastrophic failure of the piston, as a reason for this type of failure. Solutions can, for example, include asymmetric top ring groove root fillets or the incorporation of a high strength ring carrier. Other typical LSPI failure modes are shown in Figure 3.5.7 and Figure 3.5.8 and can include piston ring coating chippings or cracks on the anti-thrust side of the piston. Solutions for these failure modes can be stronger skirts or thinner ring coating materials according to Passow et al. [SAE160].

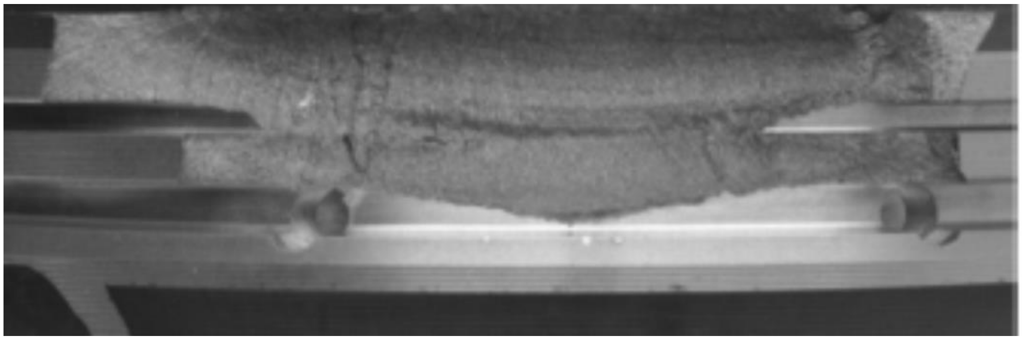

Figure 3.5.6 Second land breakage piston damage after LSPI events [SAE160] © SAE International. All rights reserved.

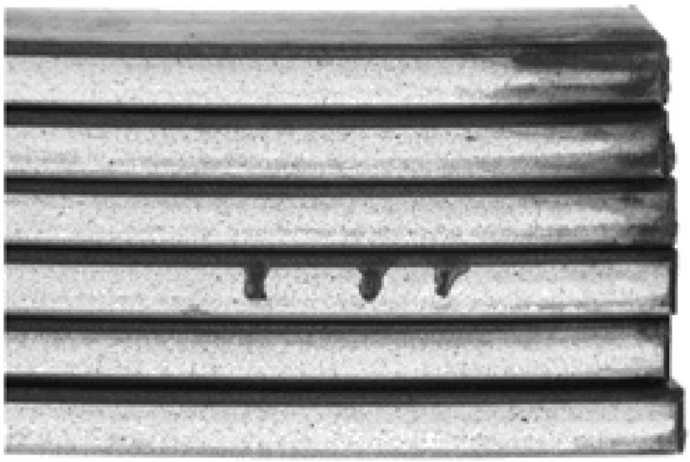

Figure 3.5.7 Piston ring coating chippings after LSPI events [SAE160] © SAE International. All rights reserved.

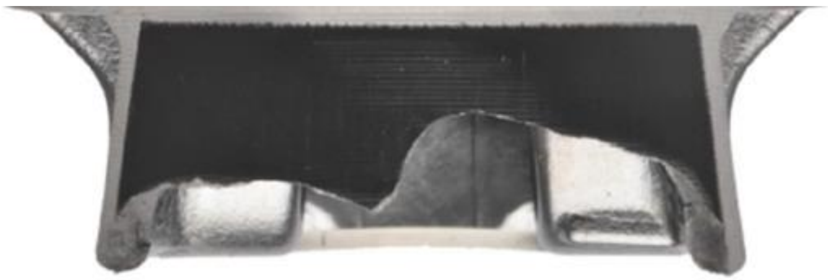

Figure 3.5.8 Cracks on the anti-thrust side after LSPI events [SAE160] © SAE International. All rights reserved.

3.6 Subsequent Mega Knock

In many cases, strong knock events follow the initial pre-ignition event. Similar to the high peak pressure when pre-ignition occurs very early in the pressure cycle, this so called Mega or Super Knock is an important factor potentially leading to catastrophic engine damage. Please note that early publications on the topic call the unintended start of combustion pre-ignition event itself “Mega-Knock” or “Super-Knock”. Figure 3.6.1 shows an example for pre-ignition events with and without knock. The depiction in the right corner shows a schematic of the difference between spark knock (top), Mega-Knock (middle) and pre-ignition (bottom). While pre-ignition describes a flame initiation in the combustion chamber ahead of the intended combustion initiation by the spark plug, spark knock and Mega-Knock both describe auto-ignitions ahead of an established flame front at later or earlier times in the combustion process. When analyzing the occurrence of pre-ignition induced engine knock, strong commonalities can be found to common spark knock in both frequency and intensity. Liu et al [SAE122] have identified the energy density of the unburned end-gas mixture at the onset of knock as the criterion for Super-Knock. When the energy density of the unburned end-gas mixture exceeded 30 MJ/m3, Super-Knock was always observed. For lower energy densities, knock or non-knock was observed. Several studies have also identified the occurrence of deflagration-to-detonation transition during severe and damaging knock events comparable to Mega Knock after LSPI events [e.g. SCD1, SCD6, SCD8, SCD14, SAE166].

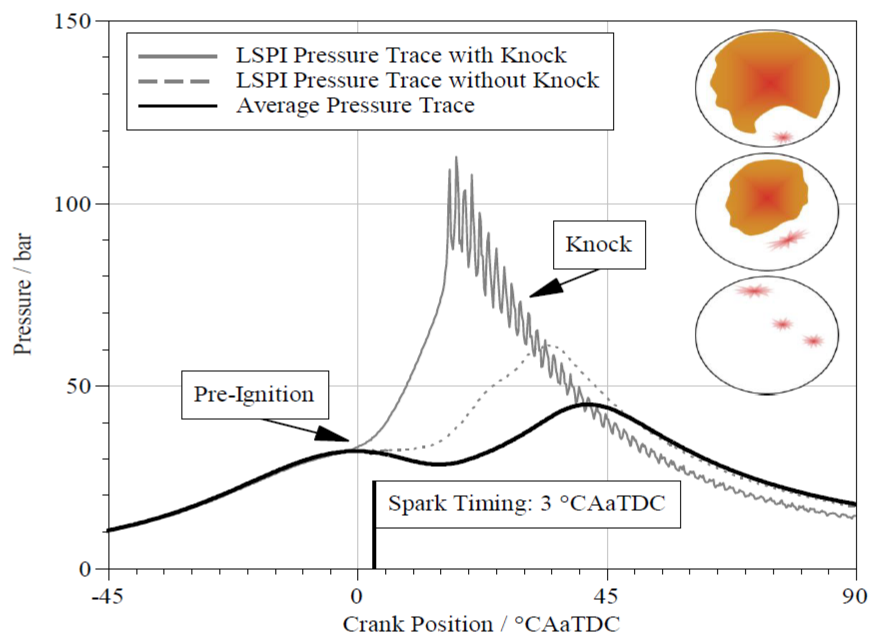

Figure 3.6.1 LSPI cycles with and without knock [CON20]

Figure 3.6.2 and Figure 3.6.3 show the results of investigations by Leach et al. [CON22] and Haenel et al. [SAE153] that indicate the suppressing impact of a fuels octane rating increase on Mega-Knock: In this Mega-Knock behaves similar to conventional spark knock.

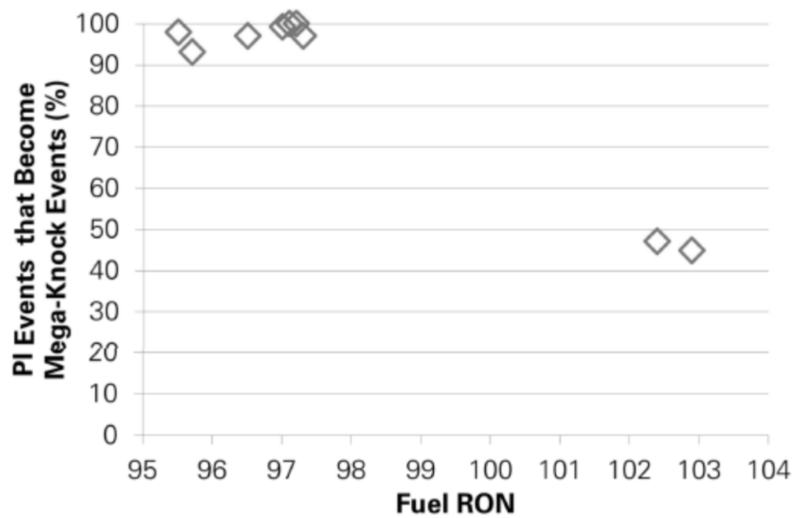

Figure 3.6.2 Effect of RON on Mega-Knock [CON22]

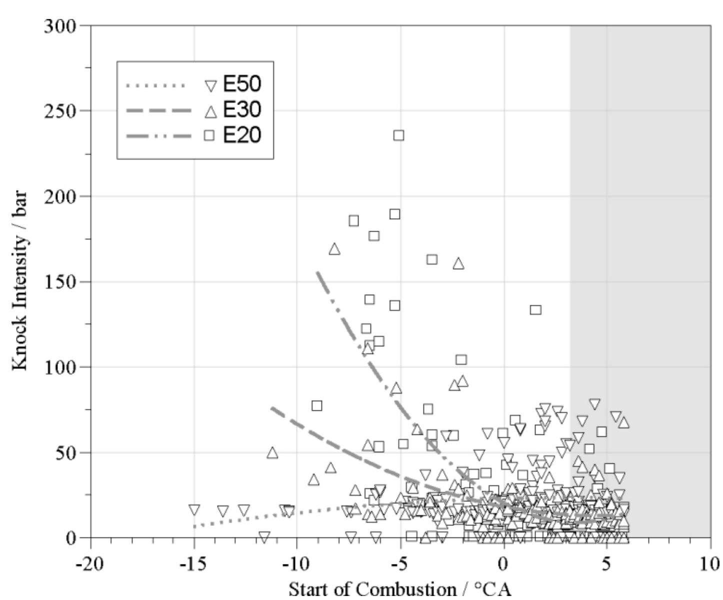

Figure 3.6.3 Effect of ethanol increase on Mega-Knock [SAE153]

Literature Review

The scope of this report is to understand the phenomenon Low Speed Pre-Ignition. The analysis of resulting knock is outside of the scope and to fundamentally investigate the phenomenon, a detailed analysis of spark knock would be also necessary. Therefore, only a few review publications shall be mentioned in this context and for further reading. Most notably, Wang et al. have published a comprehensive review paper of the status of knocking combustion in spark-ignition engines which includes conventional spark knock as well as research regarding Super - or Mega Knock [SCD18]. An additional valuable source for further insights on spark knock is the publication from Mr. Kalghatgi [CON15].

4 Summary & Research Gaps

Low Speed Pre-Ignition is a complex problem that combines interacting factors from fuel, oil formulations and characteristics, engine hardware and calibration, engine boundary conditions and engine operating history (e.g. deposits). One single LSPI initiation mechanism can, therefore, not be derived from the published literature. While more research to identify the detailed mechanism behind LSPI is encouraged, the reason for this ambiguity may be that modern highly boosted GTDI engines operate close enough to auto-ignition limits that various LSPI initiation mechanisms may come into play depending on the exact design and boundary conditions in a specific engine. Therefore deposit, oil/fuel droplet and surface initiated pre-ignition events have been reported. Across platforms, however, this literature search did identify some aspects which have repeatedly shown to improve LSPI behavior of engines, even though the utilized measurement equipment, research methodologies, hardware and even definitions of what constitutes pre-ignition varied significantly between studies. Some general outcomes and main research gaps are outlined below.

It can be generally stated that an improved oil formulation and oil ignitability as well as a design that leads to reduced oil intrusion from, for example, the crankcase ventilation system or past the piston rings is of benefit. Oil properties that have been consistently linked to low LSPI counts in the past are low calcium and high ZnDTP or MoDTC formulations. Individual studies have shown other additives and base stocks to have an impact also. This can therefore lead to the conclusion that individual formulation details can still have significant impact on LSPI occurrence beyond these three additives, thus a more holistic look is needed to develop a final guideline for better LSPI mitigation. On the fuel side, high fuel volatility and proper mixture formation by either fuel formulation, high charge motion, optimized injection hardware or calibration (e.g. targeting or split injection) avoids increased wall wetting, local fuel dilution and deposits, thus affecting both the deposit and the droplet initiation path. Higher engine block operating temperatures can additionally reduce some of the negative impact of fuel impingement onto cylinder walls or the piston surface. Fuel properties that reduce the amount of accumulated fuel in the top ring land and fuels with low aromatics content are also linked to better LSPI performance. While high octane fuels do not necessarily suppress LSPI occurrence, an increase in knock resistance can help to mitigate the effect of subsequent mega knock that can damage the engine. Additionally, calibration measures that reduce the reactivity and temperature of the mixture towards the end of compression can also suppress LSPI. These measures can include cooled LP-EGR, fuel enrichment, and improved scavenging of the residual gas. Finally, an overall engine design that reduces the formation of deposits (injector, combustion chamber and intake valve) is recommended.

Even though the existing body of research is already quite extensive, numerous open questions and research gaps can be identified based on the performed literature search. It would be generally helpful to establish a consensus on how to define Pre-Ignition, Mega

Knock and LSPI events and how to count and detect these events. Currently, no common methodology is used or established which reduces the comparability of the existing literature. Elliott et al. [SAE116] and Boese et al. [SAE124] outlined the need for a coordinated analysis. Additionally, a few topics stand out as the most pressing research gaps:

- Numerous articles have been published on how (fresh) oil formulation impacts LSPI. However, an LSPI oil benchmarking performed by FEV in 2017 revealed that oils in the market still show a massive variation in LSPI occurrence. Even though the body of literature on this topic is substantial, this topic can still be further investigated, specifically, the question of how additives interact in different formulations.
- Reaction mechanisms which include lubricants and additives are not available. This limits opportunities to simulate effect interactions.
- The leading LSPI mechanism in lubricants is currently not well understood. Understanding the impact of lubricant formulation on local deposit formation and deposit ignition likelihood, as well as the ignition of liquid or gaseous oil/fuel mixtures could help. How does this effect differ for first and following LSPI events, single, burst, or intermittent LSPI burst events?
- The impact of oil ageing on LSPI behavior is not well understood at this point. This has the potential to lead to significant field issues. This includes e.g. the impact of additive consumption, base oil degradation, engine wear or fuel dilution on LSPI over one oil change interval.
- Another topic of interest that has seen little research is the question of how oil transport and oil flow characteristics impact LSPI. The impact of fuel properties and how fuel properties affect fuel impingement splash on oily surfaces, fuel dilution, and fuel/oil transport to the piston surface are also not well understood. This topic interacts with liner, piston, and piston ring design.
- The industry wide definition of a characteristic fuel number (akin to RON or MON) that characterizes the tendency for pre-ignition of a fuel is still missing. One reason is that the critical fuel characteristics that impact LSPI initiation are still not entirely clear. Laminar flame speed and ignitability, distillation, and deposit formation tendencies have been named as impact factors. The published results vary though. Therefore, the interaction of fuel properties and hardware characteristics needs to be clarified in this context. Do the leading LSPI characteristics of a fuel change depending on wall wetting, mixture formation, mixture location etc.? Interesting would be also the comparison of the impact of gaseous fuels, such as CNG, on LSPI.
- Fuel ageing can be expected to increase LSPI due to the change in distillation curve over time. This has not been investigated so far. It would be interesting to understand how much of a problem this really is in the field. The impact of the worldwide range of fuel components as well as fuel additives on LSPI is also not well understood.

- The impact of calibration (e.g. injection strategy, LP-EGR etc.) and boundary conditions (e.g. coolant temperature etc.) has been investigated in the past and seems well understood in the industry. The performed research, however, focuses mainly on fresh engines utilizing steady state engine tests. Transient operation, vehicle results and hardware ageing impacts are not published at this point. Additionally, studies of the interactions between calibration and hardware on one side and oil and fuels on the other side are rare. This reduces the possibility of finding synergies.
- Ring land, piston, piston ring design, and designs which impact mixture formation (e.g. charge motion, injectors, etc.) have been mentioned as impact factors regarding LSPI. The interactions and the underlying LSPI mechanism (oil transport, deposit formation or impingement) needs to be clarified.
- Transient effects are not well understood at this point. The published experimental test procedures are mainly steady state test procedures. The definition of a statistically sound transient procedure which has the potential to represent real world operating conditions much better is an open topic. How do field results correlate with lab results especially when component ageing, drift and local customer usage patterns are considered? The impact of intake valve or injector deposits and PCV system performance over time may be of interest.
- The impact of water injection on spark knock has been analyzed in several publications. The potential of water injection to suppress LSPI bursts can be theorized, but actual test data has not been published. Can water injection help to define a pre-LSPI event controls mechanism?

5 Acronyms

ATZ	Automobiltechnische Zeitung
CIMAC	Conseil International des Machines à Combustion
CNG	Compressed Natural Gas
CRC	Coordinating Research Council
DEER	Directions in Engine Efficiency and Emissions Research
DOE	Department of Energy
EU	European Union
FISITA	Fédération Internationale des Sociétés d'Ingénieurs des Techniques de l'Automobile
FVV	Forschungsvereinigung Verbrennungsmotoren
GTDI	Gasoline Turbo Direct Injection
HCCI	Homogeneous Charge Compression Ignition
HP-DSC	High Pressure Differential Scanning Calorimetry
ICE	Internal Combustion Engine
IFP	Institut Francais de Petrol
JSAE	Society of Automotive Engineers of Japan
LP-EGR	Low Pressure Exhaust Gas Recirculation
LSPI	Low Speed Pre-Ignition
MK	Mega-Knock
MoDTC	Molybdenum Dithiocarbamate
MON	Motor Octane Number
MTZ	Motorentechnische Zeitung
OEM	Original Equipment Manufacturer
PCV	Positive Crankcase Ventilation
PM	Particulate Matter
PMI	Particulate Matter Index
RCCI	Reactivity Controlled Compression Ignition
RON	Research Octane Number
SAE	Society of Automotive Engineers
SIA	Société des Ingénieurs de l'Automobile
SK	Super-Knock
SPI	Stochastic Pre-Ignition
ZnDTP	Zinc Dialkyldithiophosphates

6 References

The references listed below represent the accepted publications from the systematic literature review. Details regarding the systematic literature review are outlined in Chapter 2. The naming convention and order of the publications in the listing below is as follows:

- SAE Mobilius database: *SAExxx*
- Springer online database: *SPRxxx*
- SAGE online database: *SAGxxx*
- Science Direct database: *SCDxxx*

Publications that have been added based on a manual literature screening of Conference proceedings are listed as follows:

- Conference proceedings *CONxxx*

Please refer to the document *LSPI-Literature-Review_Literature-List.xls* for a more detailed overview of the reviewed publications. Te document also includes additional metadata and abstracts.

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[CON25] H.-B. Snuis, "Method to quantify and visualize abnormal combustion of a SI engine", CIMAC Congress, Shanghai, 2013

[CON26] P. Adomeit, J. Dohmen, M. Thewes, J. Ewald, M. Günther, B. Morcinkowski, S. Pischinger, "Effect of fuel and combustion system on the pre-ignition of boosted SI engines", 34. Internationales Wiener Motorensymposium, 2013

[CON27] C. Dahnz, K.-M. Han, M. Magar, "Vorentflammung bei Ottomotoren", FVV - Vorhaben Nr. 931, Final Report, 2010

[CON28] G. Prochazka, P. Hofmann, B. Geringer, J. Willand, C. Jelitto, "Comparison of the phenomena of autoignition in highly charged SI Engines with external and internal mixture formation", FISITA Congress, Shanghai, 2006

[CON29] S. Pischinger, H. Olivier, M. Jakob, M. Günther, Y. Uygun, "Kraftstoffkennzahlen für alternative Ottokraftstoffe – Beschreibung der Glühzündungs-, Vorentflammungs-, und Klopfempfindlichkeit insbesondere hochklopffester Alkoholkraftstoffe", FVV Heft R560, 2012

[CON30] S. Yasueda, K. Takasaki, H. Tajima, "The Abnormal Combustion caused by Lubricating oil on High BMEP Gas Engines.", 13. Tagung "Der Arbeitsprozess des Verbrennungsmotors", 2011

References

[CON31] P. Haenel, H. Kleeberg, D. Tomazic, “Optical Investigation of Pre-ignition in a Direct-Injected Turbocharged Gasoline Engine”, Directions in Engine-Efficiency and Emissions Research, Detroit, 2011

7 Appendix

An industry survey was conducted to investigate the status and the internal perception of internal industry LSPI research and development efforts. The acces controlled and blind surey was conducted online and included 20 questions addressing different aspects of LSPI testing methodologies.

The invite for the survey was sent to a CRC generated list of industry experts. Additionally, the survey was shared within organizations to cover the personnel working on the LSPI challenge. In total, 175 people accessed the survey, 106 of which (60.57%) started the survey and answered all or a subset of questions. Since it was allowed to skip questions, not all questions of the survey were answered by all participants.

Some general tendencies of the industry survey can be summarized as follows:

- LSPI is mainly tested in multi cylinder engines under steady-state, engine dynamometer conditions.Transient and vehicle operation are less use for LSPI tests, likely due to resulting statistical difficulties when analyzing the test data
- There is quite some ambiguity regarding how to define, detect, and analyze LSPI in the industry. Part of this ambiguity can be explained by the different goals of the analysis (e.g. in mechanical durability tests versus fundamental combustion research)
- The confidence within the industry that the currently used LSPI test procedures are able to assess the issue how it occurs in the field is overall low
- The industry assumes the main reason behind LSPI occurrence to be oil, fuel and deposit related (in that order). Specifically oil composition is seen critically in regards to LSPI occurrence
- The industry seems to have a more defined opinion on impact factors causing LSPI occurrence than on factors affecting LSPI severity

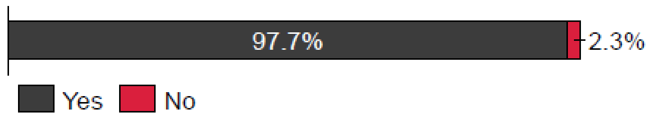
The questions and answers of the survey are outlined in the following pages.

\# NUMBER OF ANSWERS: 87

Question 1

Have you heard of the phenomenon commonly known as Low Speed Pre-Ignition (LSPI), Stochastic Pre-Ignition (SPI), Mega-Knock or Super-Knock, which is characterized by a seemingly random, stochastic behavior as opposed to classic hot-spot, runaway pre-ignition?

Results Q.1



Note

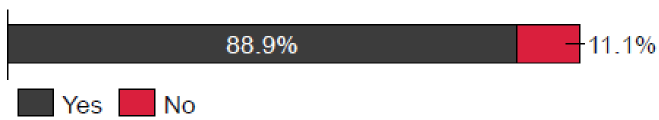
The survey is aborted if question 1 is not answered with “Yes”

\# NUMBER OF ANSWERS: 81

Question 2

Are you working or have you actively worked on this phenomenon?

Results Q.2



Note

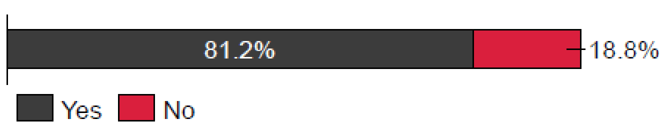
The survey is aborted if question 2 is not answered with “Yes”

\# NUMBER OF ANSWERS: 69

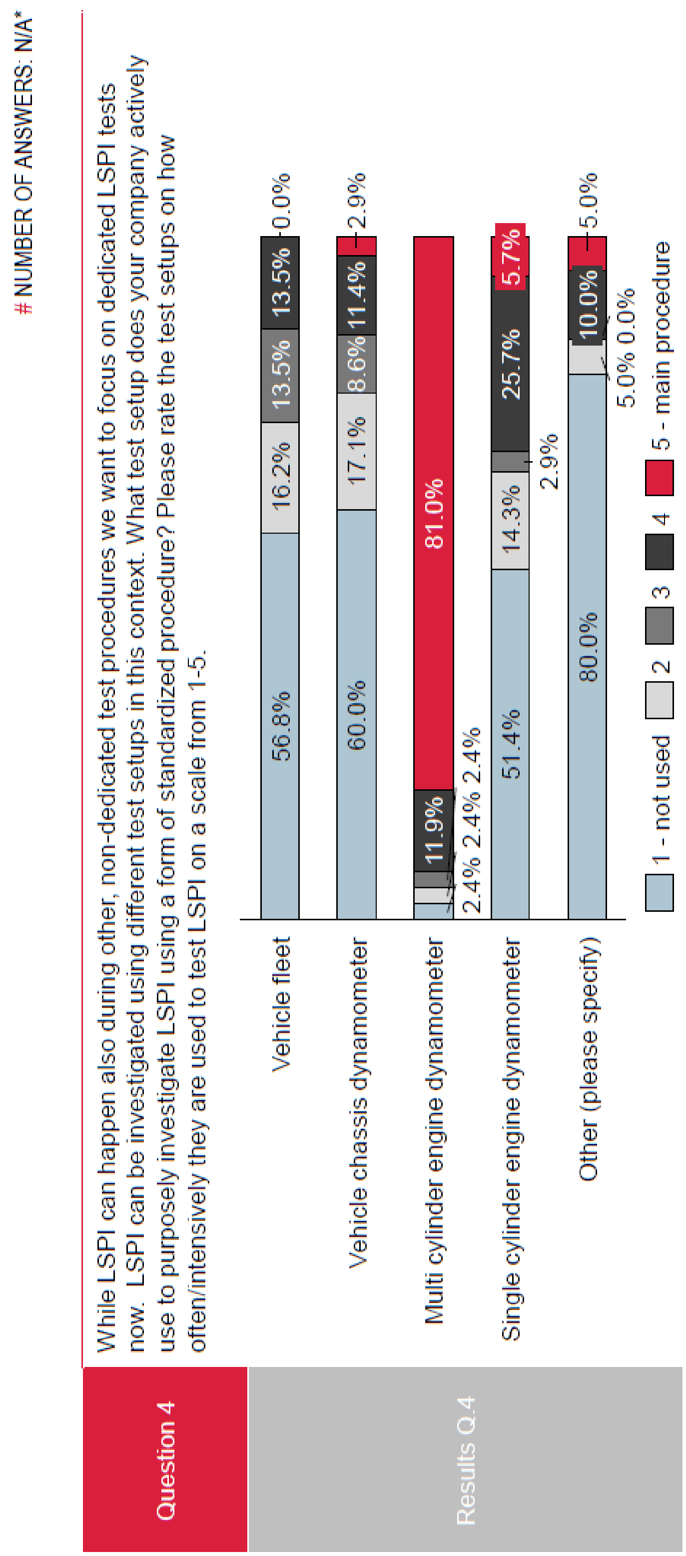
Question 3

LSPI in combustion engines can be tested in many different ways. Does your company have a standardized LSPI test procedure to analyze the presence, frequency or severity of this phenomenon?

Results Q.3



Appendix



NUMBER OF ANSWERS: N/A*
Question 4
While LSPI can happen also during other, non-dedicated test procedures we want to focus on dedicated LSPI tests now. LSPI can be investigated using different test setups in this context. What test setup does your company actively use to purposely investigate LSPI using a form of standardized procedure? Please rate the test setups on how often/intensively they are used to test LSPI on a scale from 1-5.
Results Q.4
Vehicle fleet
56.8%
16.2%
13.5%
13.5%
0.0%
Vehicle chassis dynamometer
60.0%
17.1%
8.6%
11.4%
2.9%
Multi cylinder engine dynamometer
2.4%
2.4%
2.4%
11.9%
81.0%
Single cylinder engine dynamometer
51.4%
14.3%
2.9%
25.7%
5.7%
Other (please specify)
80.0%
5.0%
0.0%
10.0%
5.0%
1 - not used
2
3
4
5 - main procedure

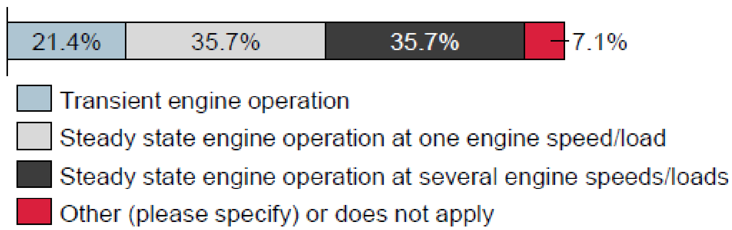
Appendix

NUMBER OF ANSWERS: 42

Question 5

How would you describe the main engine operating mode of your most important, dedicated LSPI test procedure? Please check the characteristics that describes this procedure most.(Steady state operation describes e.g. prolonged engine operation at constant engine speed and load while transient operation describes e.g. speed and load ramps etc.)

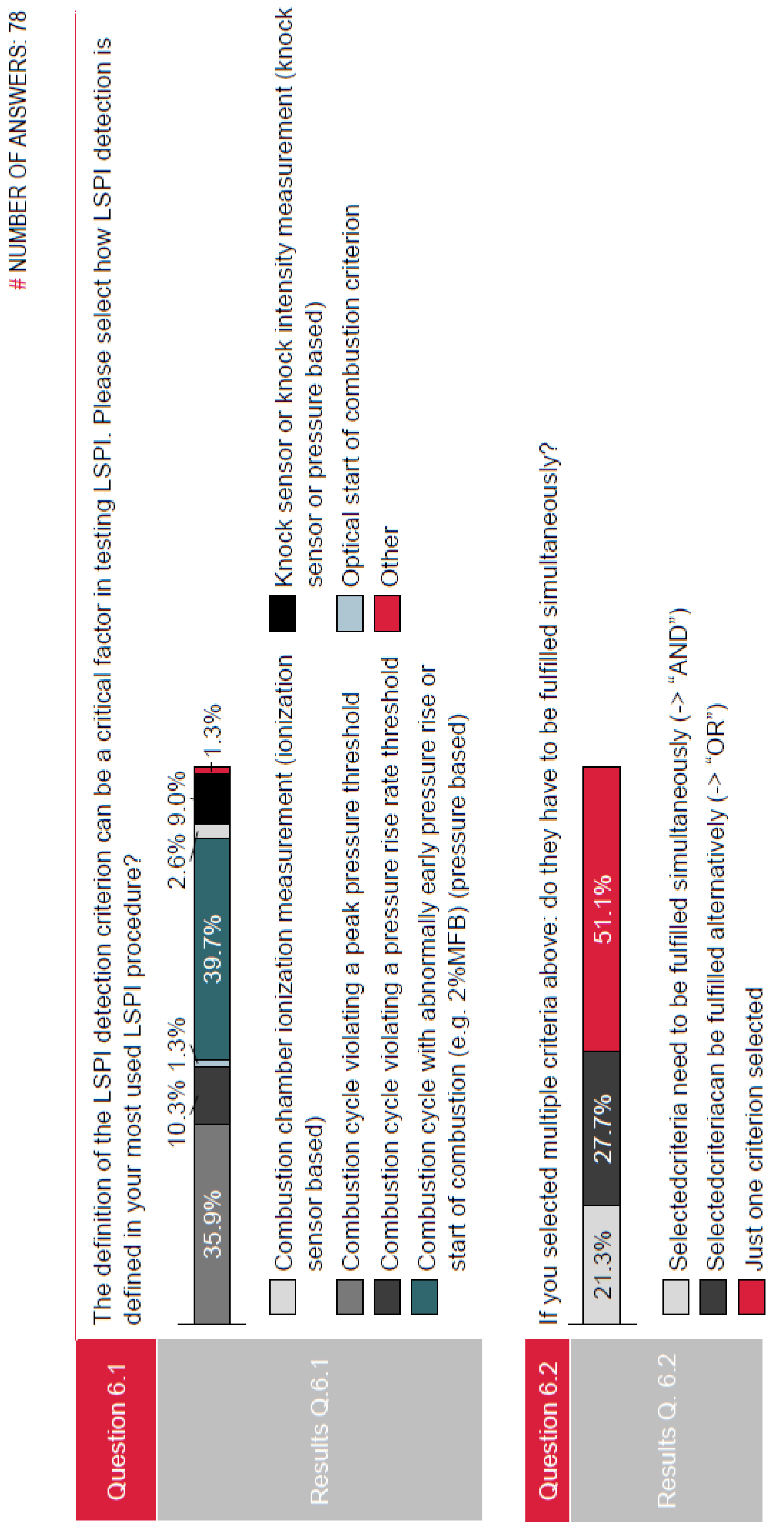
Results Q.5



Specifications "other"

- Combination of above options
- Steady status and transient status
- Both

Appendix



NUMBER OF ANSWERS: 78
Question 6.1
The definition of the LSPI detection criterion can be a critical factor in testing LSPI. Please select how LSPI detection is defined in your most used LSPI procedure?
Results Q.6.1
35.9%
10.3% 1.3%
39.7%
2.6% 9.0%
1.3%
Combustion chamber ionization measurement (ionization sensor based)
Combustion cycle violating a peak pressure threshold
Combustion cycle violating a pressure rise rate threshold
Combustion cycle with abnormally early pressure rise or start of combustion (e.g. 2%MFB) (pressure based)
Knock sensor or knock intensity measurement (knock sensor or pressure based)
Optical start of combustion criterion
Other
Question 6.2
If you selected multiple criteria above: do they have to be fulfilled simultaneously?
Results Q. 6.2
21.3%
27.7%
51.1%
Selectedcriteria need to be fulfilled simultaneously (-> “AND”)
Selectedcriteriacan be fulfilled alternatively (-> “OR”)
Just one criterion selected

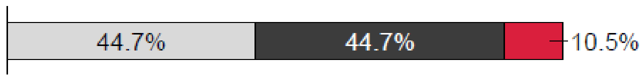
Appendix

NUMBER OF ANSWERS: 38

Question 7

LSPI events in one cylinder can occur in specific patterns. Often, LSPI events in one cylinder occur in bursts (LSPI – LSPI – LSPI…) or intermittent burst events (LSPI – no LSPI – LSPI – no LSPI…). How do you count these burst events?

Results Q.7

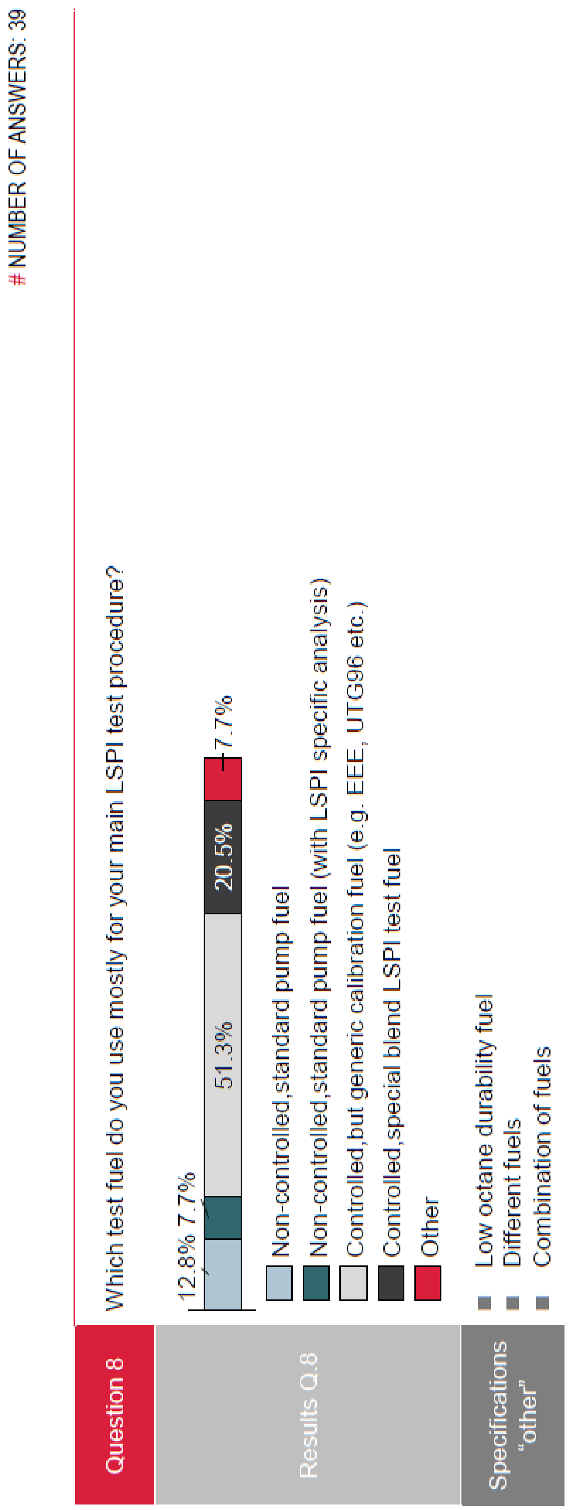


- Burst or intermittent burst events are counted as one LSPI event, independent of the actual burst length (burst length may be reported as an additional characteristics)
- AllLSPI events arecounted as individual, independent events
- Other (please specify) or does not apply

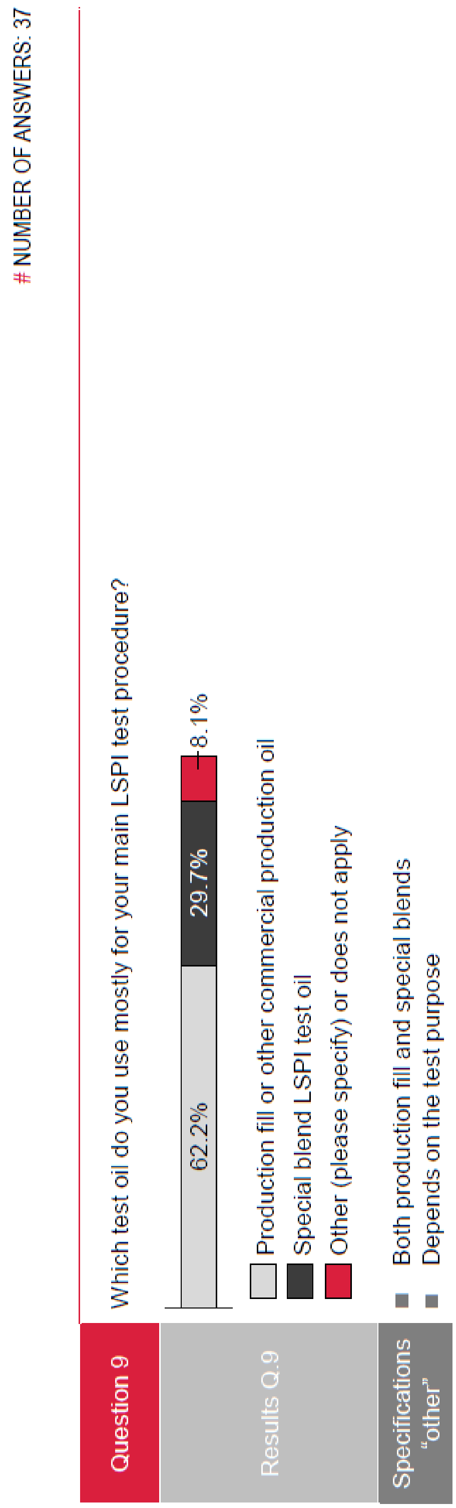
Specifications "other"

- Both methods are used
- Bursts are classified as such, but total number of events are also counted separately

Appendix



NUMBER OF ANSWERS: 39
Question 8
Which test fuel do you use mostly for your main LSPI test procedure?
Results Q.8
12.8%
7.7%
51.3%
20.5%
7.7%
Non-controlled,standard pump fuel
Non-controlled,standard pump fuel (with LSPI specific analysis)
Controlled,but generic calibration fuel (e.g. EEE, UTG96 etc.)
Controlled,special blend LSPI test fuel
Other
Specifications "other"
Low octane durability fuel
Different fuels
Combination of fuels



NUMBER OF ANSWERS: 37
Question 9
Which test oil do you use mostly for your main LSPI test procedure?
Results Q.9
62.2%
29.7%
8.1%
Production fill or other commercial production oil
Special blend LSPI test oil
Other (please specify) or does not apply
Specifications "other"
Both production fill and special blends
Depends on the test purpose

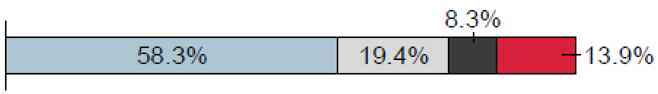
Appendix

NUMBER OF ANSWERS: 36

Question 10

Which oil temperature do you operate your engine at during your main LSPI test?

Results Q.10



- As calibrated
- Colder than calibrated
- Hotter than calibrated
- Other (please specify) or does not apply

Specifications "other"

- Control to 100°C
- Both calibrated and cooler temperatures
- Depends on the test purpose

Comments

"Easy way to influence LSPI propensity, but unnecessary."

"Full range even for hot climate countries is considered."

"Tests have been performed in the past with various temperatures."

"Not directly controlled - linked to coolant temp (which is controlled) via standard vehicle oil/coolant heat exchanger."

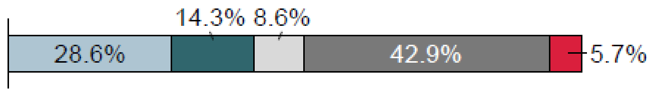
Appendix

NUMBER OF ANSWERS: 35

Question 11

Which spark timing do you operate your engine at during your main LSPI test?

Results Q.11



- As calibrated, spark knock detection active
- As calibrated, spark knock detection not active
- Pre-defined, fixed spark settings, spark knock detection active
- Pre-defined, fixed spark settings, spark knock detection not active
- Other (please specify) or does not apply

Specifications "other"

- Spark timing differs from fuel to fuel, knock detection during procedure not active

Comments

"Active knock control is likely to be an important factor in LSPI propensity."

"Pre-defined as well as running 'As Calibrated'. We use both means."

"In General as calibrated but variation with turbo boost and max spark retard in various tables under different criteria."

"Knock sensor(s): Installed and functioning so that a knock ratio can be calculated, but with range of authority set to 0 so ignition timing is not automatically adjusted during testing."

"Retarded 1.5 degrees from standard calibration to ensure no intervention of knock control system on => 95 RON fuel during test conditions. Knock control active for emergency engine protection."

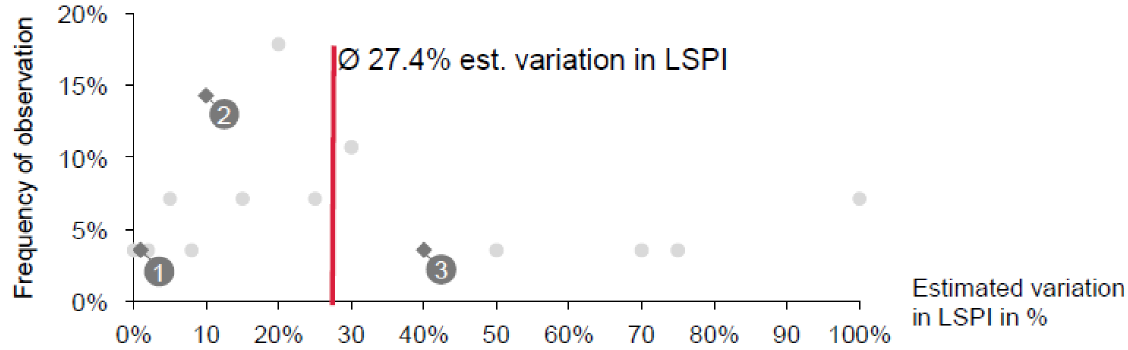
Appendix

NUMBER OF ANSWERS: 25

Question 12

Please write down an estimate how much % variation in LSPI events you typically expect to see when repeating tests using your main LSPI test procedure?

Results Q.12



Comments

1. "Small variation with one main procedure. 20% variation when focusing on purely natural events."

   "LSPI events are generated when commanded, so minimal variability."

2. "It is very difficult to answer this question since the amount of LSPI events can depend on the detection criterion."
   "up to 10% within Initial tests under same conditions, next tests w/o defined pre-conditioning will show clearly lower numbers due to e.g. removal of deposits.."

3. "The variability is extremely high. The biggest challenge we have at the moment in defining a robust test procedure."

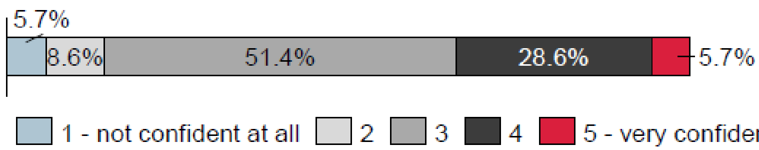
Appendix

NUMBER OF ANSWERS: 35

Question 13

How confident are you that your main LSPI test procedure captures real world conditions? Please rate your level of confidence from 1-5 (1: not confident at all → 5: very confident)

Results Q.13



Comments

"Captures one mechanism of LSPI that could happen in real world conditions. There are various LSPI initiators that are not captured that could also happen."

"Operating an engine for 20 minutes at steady state load of 100% or beyond and low speed is not at all relevant to actual real world conditions"

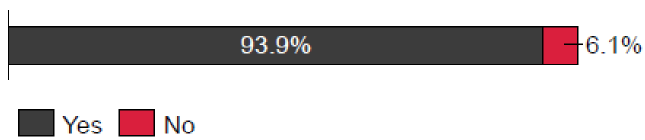
"Dyno test for reference to achieve results with reasonable money and time effort, to be confirmed by vehicle testing"

NUMBER OF ANSWERS: 33

Question 14

Are there regions in the world that are more or less prone to LSPI?

Results Q.14



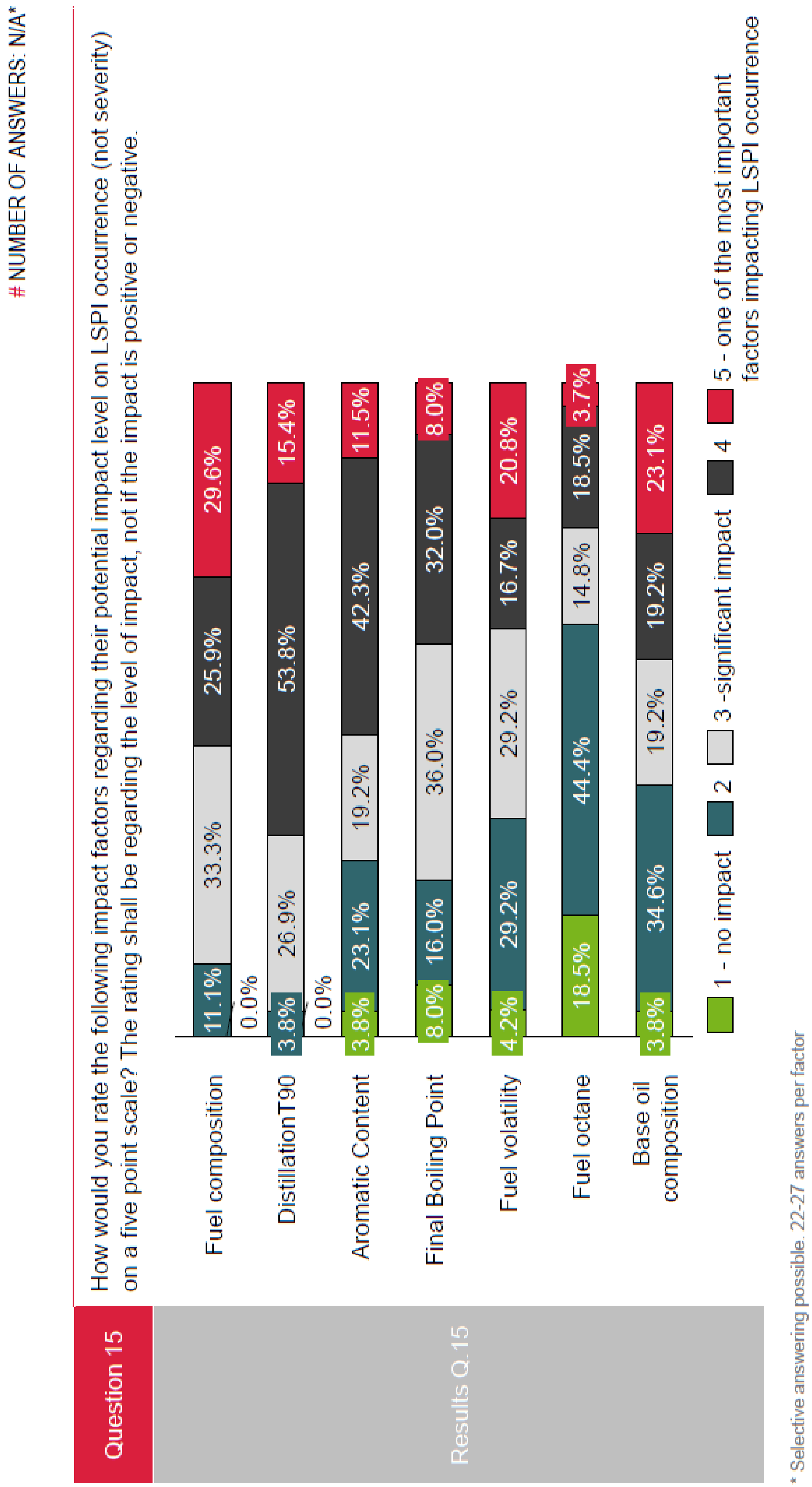
Comments

"This question is too vague and subjective"

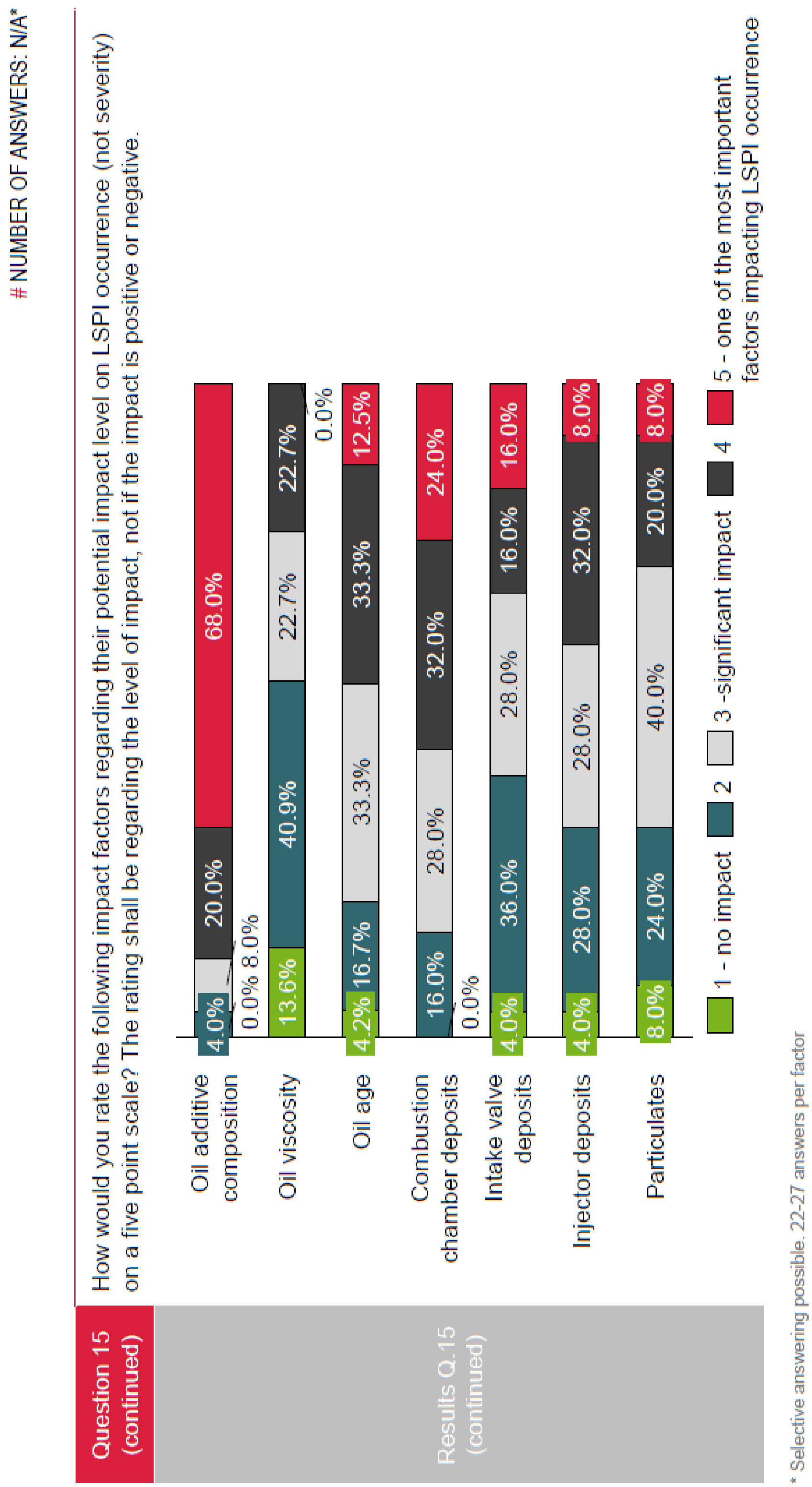
"I wouldn't comment as to what region, it is the fuel, oil, driving cycle that matters."

"Regions with small vehicles that don't need to spend much time in the 'low speed- high load ' areas of the map"

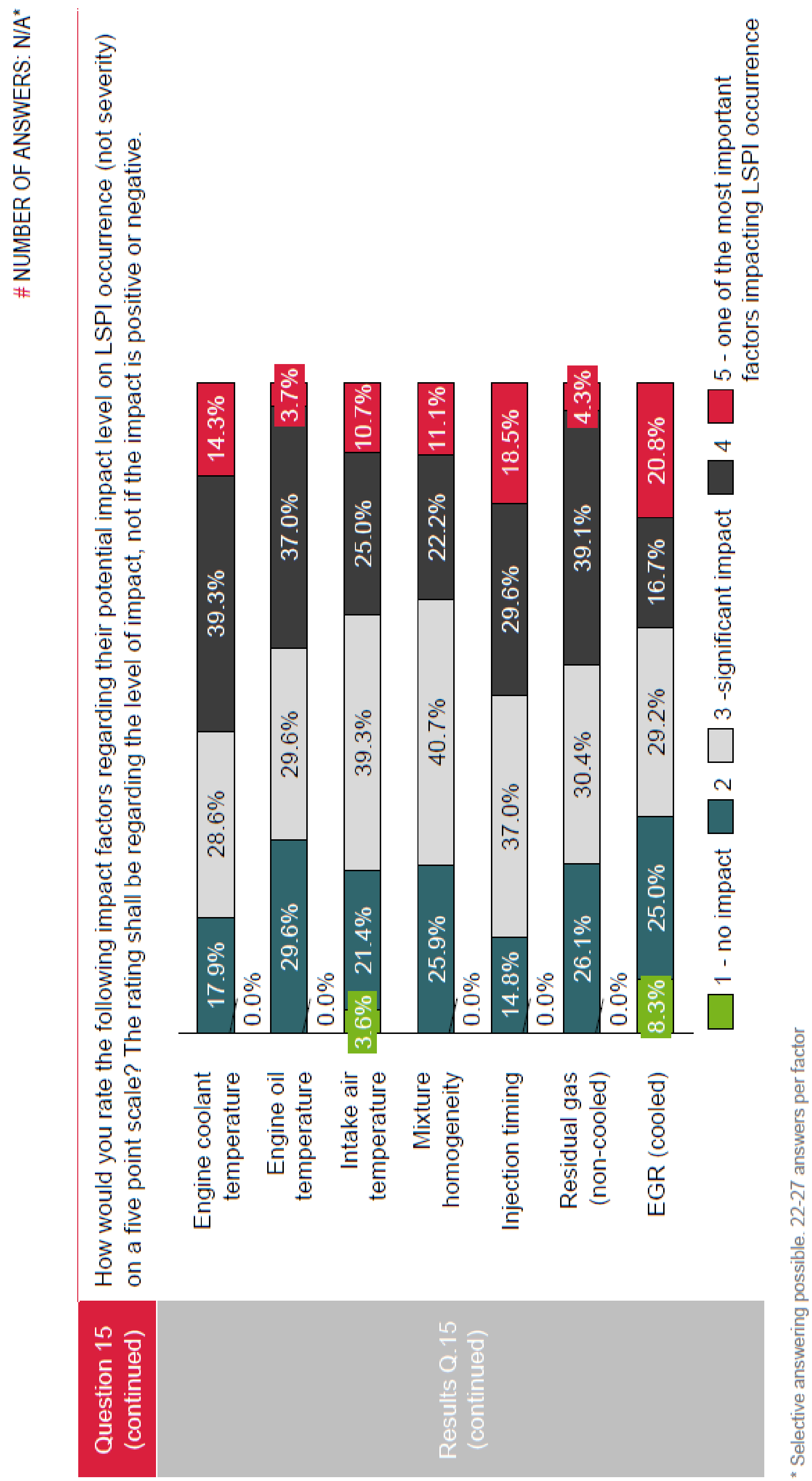
Appendix


Question 15
How would you rate the following impact factors regarding their potential impact level on LSPI occurrence (not severity) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.
NUMBER OF ANSWERS: N/A*
Results Q.15
Fuel composition: 0.0% | 11.1% | 33.3% | 25.9% | 29.6%
DistillationT90: 0.0% | 3.8% | 26.9% | 53.8% | 15.4%
Aromatic Content: 3.8% | 23.1% | 19.2% | 42.3% | 11.5%
Final Boiling Point: 8.0% | 16.0% | 36.0% | 32.0% | 8.0%
Fuel volatility: 4.2% | 29.2% | 29.2% | 16.7% | 20.8%
Fuel octane: 18.5% | 44.4% | 14.8% | 18.5% | 3.7%
Base oil composition: 3.8% | 34.6% | 19.2% | 19.2% | 23.1%
1 - no impact
2
3 -significant impact
4
5 - one of the most important factors impacting LSPI occurrence
* Selective answering possible. 22-27 answers per factor

Appendix


Question 15 (continued)
Results Q.15 (continued)
How would you rate the following impact factors regarding their potential impact level on LSPI occurrence (not severity) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.
NUMBER OF ANSWERS: N/A*
Oil additive composition
4.0%
0.0% 8.0%
20.0%
68.0%
Oil viscosity
13.6%
40.9%
22.7%
22.7%
0.0%
Oil age
4.2% 16.7%
33.3%
33.3%
12.5%
Combustion chamber deposits
16.0%
0.0%
28.0%
32.0%
24.0%
Intake valve deposits
4.0%
36.0%
28.0%
16.0%
16.0%
Injector deposits
4.0%
28.0%
28.0%
32.0%
8.0%
Particulates
8.0%
24.0%
40.0%
20.0%
8.0%
1 - no impact
2
3 -significant impact
4
5 - one of the most important factors impacting LSPI occurrence
* Selective answering possible. 22-27 answers per factor

Appendix


Question 15 (continued)
Results Q.15 (continued)
How would you rate the following impact factors regarding their potential impact level on LSPI occurrence (not severity) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.
NUMBER OF ANSWERS: N/A*
Engine coolant temperature
0.0%
17.9%
28.6%
39.3%
14.3%
Engine oil temperature
0.0%
29.6%
29.6%
37.0%
3.7%
Intake air temperature
3.6%
21.4%
39.3%
25.0%
10.7%
Mixture homogeneity
0.0%
25.9%
40.7%
22.2%
11.1%
Injection timing
0.0%
14.8%
37.0%
29.6%
18.5%
Residual gas (non-cooled)
0.0%
26.1%
30.4%
39.1%
4.3%
EGR (cooled)
8.3%
25.0%
29.2%
16.7%
20.8%
1 - no impact
2
3 -significant impact
4
5 - one of the most important factors impacting LSPI occurrence
* Selective answering possible. 22-27 answers per factor

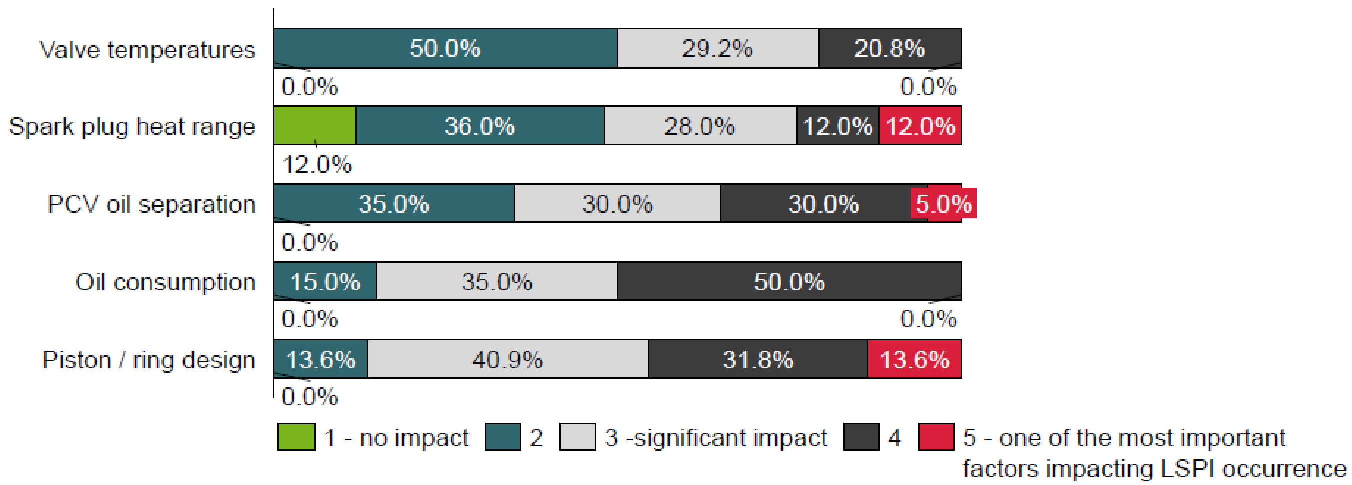
Appendix

NUMBER OF ANSWERS: N/A*

Question 15 (continued)

How would you rate the following impact factors regarding their potential impact level on LSPI occurrence (not severity) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.

Results Q.15 (continued)

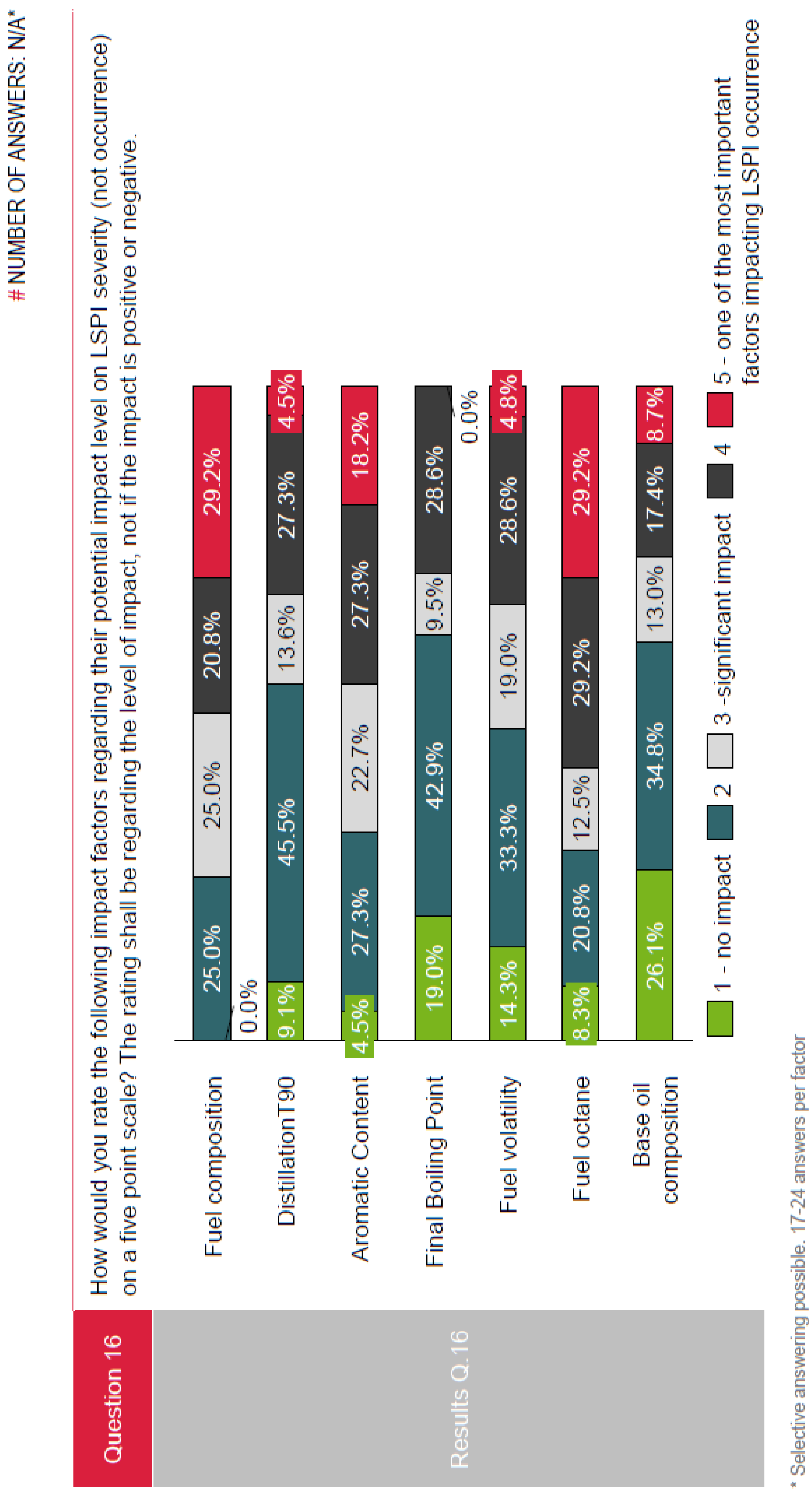


Comments

"As mentioned before: different mechanisms can lead to LSPI, and not a single one. Depending on the considered engine, all the factors listed above will have different impacts."

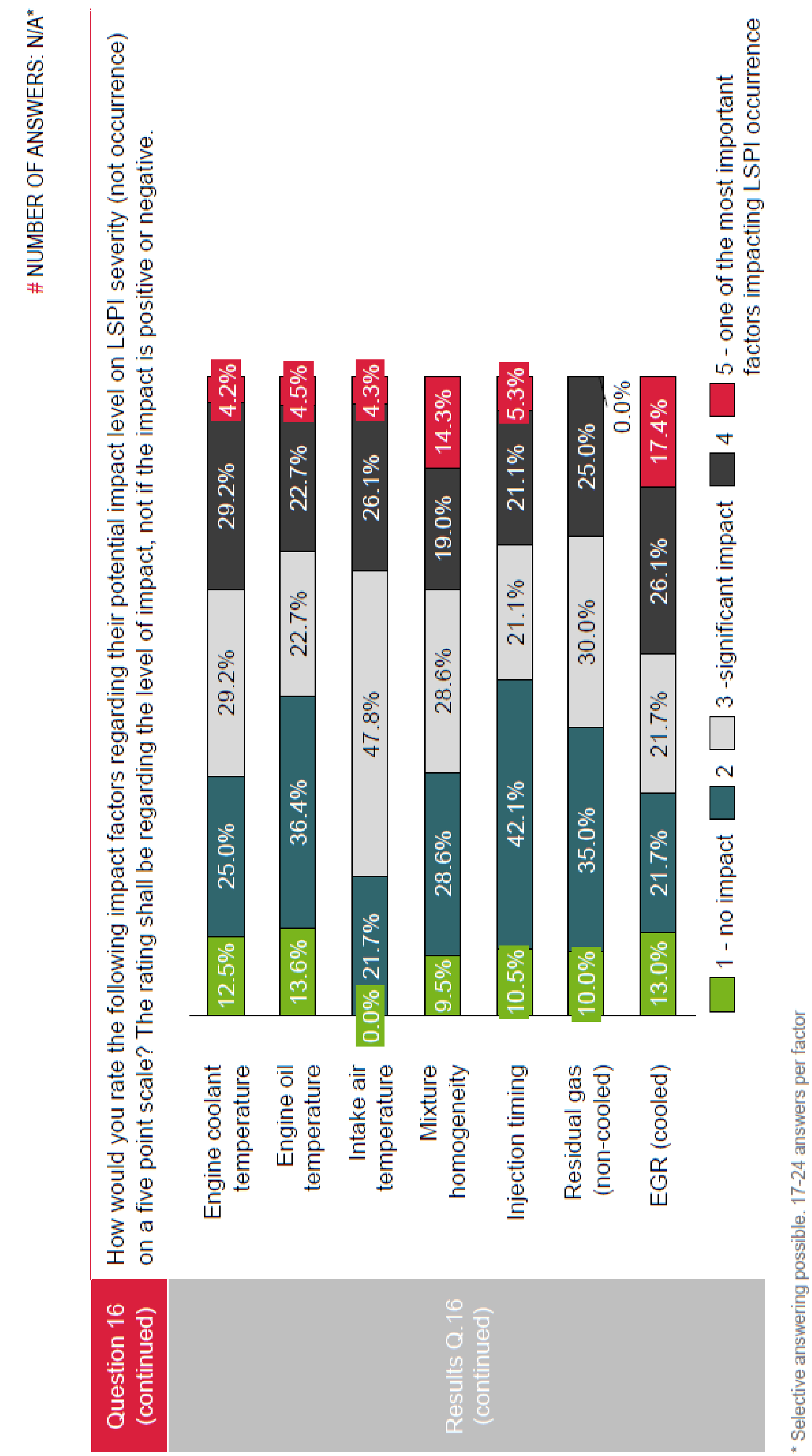
* Selective answering possible. 22-27 answers per factor

Appendix



NUMBER OF ANSWERS: N/A*
Question 16
How would you rate the following impact factors regarding their potential impact level on LSPI severity (not occurrence) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.
Results Q.16
Fuel composition
0.0%
25.0%
25.0%
20.8%
29.2%
DistillationT90
9.1%
45.5%
13.6%
27.3%
4.5%
Aromatic Content
4.5%
27.3%
22.7%
27.3%
18.2%
Final Boiling Point
19.0%
42.9%
9.5%
28.6%
0.0%
Fuel volatility
14.3%
33.3%
19.0%
28.6%
4.8%
Fuel octane
8.3%
20.8%
12.5%
29.2%
29.2%
Base oil composition
26.1%
34.8%
13.0%
17.4%
8.7%
1 - no impact
2
3 -significant impact
4
5 - one of the most important factors impacting LSPI occurrence
* Selective answering possible. 17-24 answers per factor

Appendix


Question 16 (continued)
Results Q.16 (continued)
How would you rate the following impact factors regarding their potential impact level on LSPI severity (not occurrence) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.
NUMBER OF ANSWERS: N/A*
Engine coolant temperature
12.5%
25.0%
29.2%
29.2%
4.2%
Engine oil temperature
13.6%
36.4%
22.7%
22.7%
4.5%
Intake air temperature
0.0%
21.7%
47.8%
26.1%
4.3%
Mixture homogeneity
9.5%
28.6%
28.6%
19.0%
14.3%
Injection timing
10.5%
42.1%
21.1%
21.1%
5.3%
Residual gas (non-cooled)
10.0%
35.0%
30.0%
25.0%
0.0%
EGR (cooled)
13.0%
21.7%
21.7%
26.1%
17.4%
1 - no impact
2
3 -significant impact
4
5 - one of the most important factors impacting LSPI occurrence
* Selective answering possible. 17-24 answers per factor

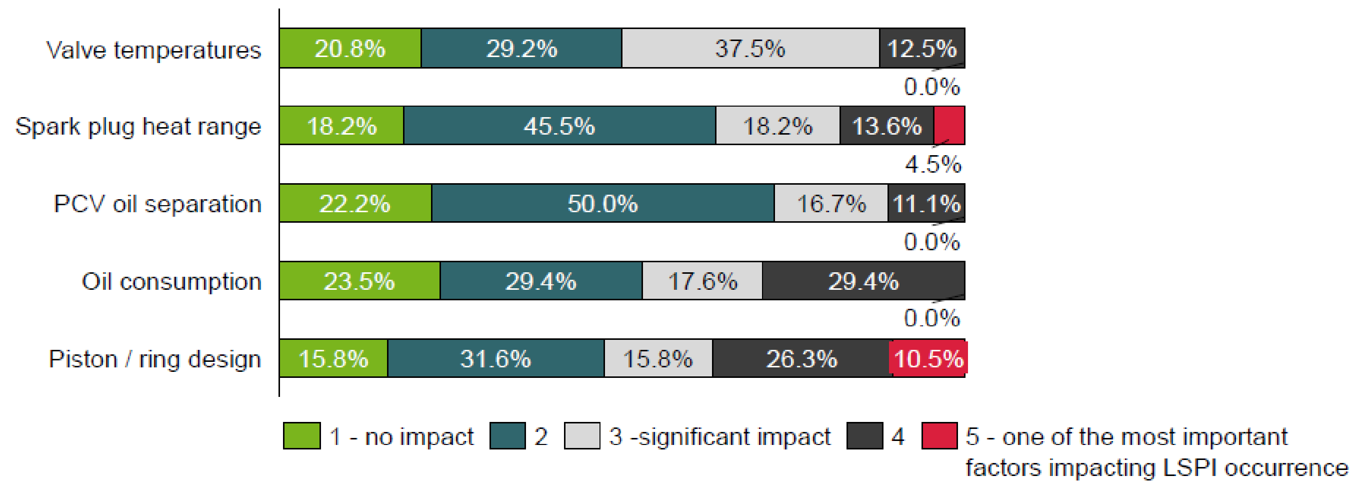
Appendix

NUMBER OF ANSWERS: N/A*

Question 16 (continued)

How would you rate the following impact factors regarding their potential impact level on LSPI severity (not occurrence) on a five point scale? The rating shall be regarding the level of impact, not if the impact is positive or negative.

Results Q.16 (continued)



Comments

“We do not have a good handle on what affects the severity of LSPI events. Seems to be totally random.”

“SIDI engines most critical due to burning process and mixture Quality challenges.”

“This is difficult to rate these on severity because most often the pressure is only measured in one static location, and this location may or may not capture the actual highest pressure in the cylinder during a pre-ignition event. The supersonic burn causes extreme localized pressure. In order to rank the above, pressure measurements all over the combustion chamber would really be needed.”

* Selective answering possible. 17-24 answers per factor

Appendix

NUMBER OF ANSWERS: 29

Question 17 Please describe your role (e.g. combustion, base engine, controls, formulation etc.).

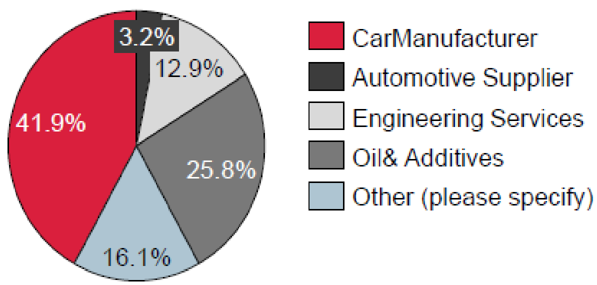
Results Q.17 The question has been omitted due to difficulties to analyze the broad spectrum of answers

Appendix

\# NUMBER OF ANSWERS: 31

Question 18 Which industry are you in?

Results Q.18



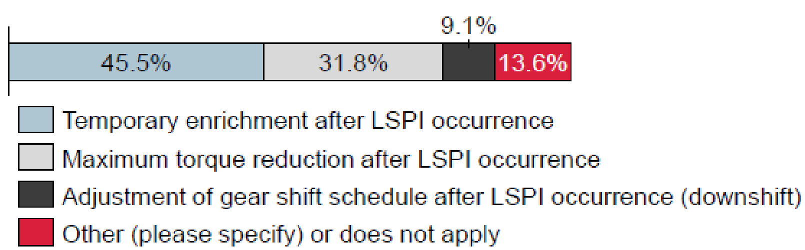
Specifications "other"

- Test lab operator
- Research and/or Development center
- Fuel and / or lubricants supplier

\# NUMBER OF ANSWERS: 22

Question 19 Do you utilize intrusive controls mechanisms to protect the engine from LSPI damage in the field? Please select or specify all applied controls mechanism if possible.

Results Q.19



Specifications "other"

- Combination of multiple mechanisms

Comments

"I don´t know all."

"Individual cylinder enrichment after LSPI occurrence to mitigate burst events."

Appendix

NUMBER OF ANSWERS: 15

Question 20

How do you account for LSPI events while designing an engine/piston? Do you design the engine/piston for a specific number of LSPI events or LSPI events with certain cylinder pressure profiles?

Results Q.20

- Design the engine/piston for a specific number of LSPI events
- Design the engine/piston for a specific number of LSPI events with certain cylinderpressure profiles
- Other (please specify) or does not apply

Specifications "other"

- Engine design for no occurrence of LSPI
- We design the components as durable as possible, without violating other properties too much
- Hope for the best

Comments

"Ring land reinforcement by steel ring insert."

"Engine must pass a minimum of 400 LSPI hits per cylinder at a minimum of 150 bar peak pressures."