Vorwort des Herausgebers

Die Komplexität des verbrennungsmotorischen Antriebes ist seit über 100 Jahren Antrieb für kontinuierliche Aktivitäten im Bereich der Grundlagenforschung sowie der anwendungsorientierten Entwicklung. Die Kombination eines instationären, thermodynamischen Prozesses mit einem chemisch reaktiven und hochturbulenten Gemisch, welches in intensiver Wechselwirkung mit einer Mehrphasenströmung steht, stellt den technologisch anspruchsvollsten Anwendungsfall dar. Gleichzeitig ist das Produkt des Verbrennungsmotors aufgrund seiner vielseitigen Einsetzbarkeit und zahlreicher Produktvorteile für sehr viele Anwendungen annähernd konkurrenzlos. Nun steht der Verbrennungsmotor insbesondere aufgrund der Abgasemissionen im Blickpunkt des öffentlichen Interesses. Vor diesem Hintergrund ist eine weitere und kontinuierliche Verbesserung der Produkteigenschaften des Verbrennungsmotors unabdingbar.

Am Institut für Kolbenmaschinen am Karlsruher Institut für Technologie wird deshalb intensiv an der Weiterentwicklung des Verbrennungsmotors geforscht. Übergeordnetes Ziel dieser Forschungsaktivitäten ist die Konzentration auf drei Entwicklungsschwerpunkte. Zum einen ist die weitere Reduzierung der Emissionen des Verbrennungsmotors, die bereits im Verlauf der letzten beiden Dekaden um circa zwei Größenordnungen reduziert werden konnten aufzuführen. Zum zweiten ist die langfristige Umstellung der Kraftstoffe auf eine nachhaltige Basis Ziel der verbrennungsmotorischen Forschungsaktivitäten. Diese Aktivitäten fokussieren gleichzeitig auf eine weitere Wirkungsgradsteigerung des Verbrennungsmotors. Der dritte Entwicklungsschwerpunkt zielt auf eine Systemverbesserung. Motivation ist beispielsweise eine Kostenreduzierung, Systemvereinfachung oder Robustheitssteigerung von technischen Lösungen. Bei den meisten Fragestellungen wird aus dem Dreiklang aus Grundlagenexperiment, Prüfstandversuch und Simulation eine technische Lösung erarbeitet.

Die Arbeit an diesen Entwicklungsschwerpunkten bestimmt die Forschungs- und Entwicklungsaktivitäten des Instituts. Hierbei ist eine gesunde Mischung aus grundlagenorientierter Forschung und anwendungsorientierter Entwicklungsarbeit der Schlüssel für ein erfolgreiches Wirken. In nationalen als auch internationalen Vorhaben sind wir bestrebt, einen wissenschaftlich wertvollen Beitrag zur erfolgreichen Weiterentwicklung des Verbrennungsmotors beizusteuern. Sowohl Industriekooperationen als auch öffentlich geförderte Forschungsaktivitäten sind hierbei die Grundlage guter universitärer Forschung.

Zur Diskussion der erarbeiteten Ergebnisse und Erkenntnisse dient diese Schriftenreihe, in der die Dissertationen des Instituts für Kolbenmaschinen verfasst sind. In dieser Sammlung sind somit die wesentlichen Ausarbeitungen des Instituts niedergeschrieben. Natürlich werden darüber hinaus auch Publikationen auf Konferenzen und in Fachzeitschriften veröffentlicht. Präsenz in der Fachwelt erarbeiten wir uns zudem durch die Einreichung von Erfindungsmeldungen und dem damit verknüpften Streben nach Patenten. Diese Aktivitäten sind jedoch erst das Resultat von vorgelagerter und erfolgreicher Grundlagenforschung.

Jeder Doktorand am Institut beschäftigt sich mit Fragestellungen von ausgeprägter gesellschaftlicher Relevanz. Insbesondere Nachhaltigkeit und Umweltschutz als Triebfedern des ingenieurwissenschaftlichen Handelns sind die Motivation unserer Aktivität. Gleichzeitig kann er nach Beendigung seiner Promotion mit einer sehr guten Ausbildung in der Industrie oder Forschungslandschaft wichtige Beiträge leisten.

Dieses Exemplar der Schriftreihe umfasst experimentelle Untersuchungen zu den ursächlichen Mechanismen und Prozesse von Vorentflammungen bei niedrigen Drehzahlen (LSPI) an einem aufgeladenen Ottomotor mit Direkteinspritzung. Durch die Synthese eines multizyklischen LSPI-Ursachenmechanismus auf Basis von in ihrer Oxidationsreaktivität gesteigerten (Ablagerungs-) Partikeln wird ein wichtiger Beitrag zur zukünftigen Entwicklung und Optimierung von Brennverfahren und Motorsystemen mit hoher Leistungsdichte erbracht.

Karlsruhe, im April 2024 Prof. Dr. sc. techn. Thomas Koch

Abstract

The concept of increasing power density is a successful approach to improving the conflict between efficiency and emission behavior of spark-ignition engine drive units for light-duty vehicles (LDV), which is dominated by the degree of efficiency (CO_2 emissions). Consequently, this leads to highly charged gasoline engines with direct injection and high specific torque and power densities, promoting a combustion anomaly known as low-speed pre-ignition (LSPI). This unpredictable, multicyclic phenomenon is not yet fully understood and therefore limits the depictable in-cylinder pressures, further efficiency gains and general engine reliability. Only with a holistic understanding of the LSPI root cause mechanisms and processes can targeted countermeasures be taken and further efficiency gains achieved. In order to meet this objective, a novel methodology pathway for LSPI root cause analysis was set up to accompany the entire LSPI event emergence process path by means of a multi-experimental approach on a modern high efficiency engine. For this purpose, a 3-cylinder turbocharged downsized spark-ignition engine with direct injection was iteratively characterized with respect to its LSPI activity under various engine parameter specifications (EPS) to identify key LSPI activity – EPS relations. In particular, an increased fuel impingement with subsequent deposit formation with oxygen availability during power and exhaust stroke was found to promote LSPI activity. On this basis, the engine operating states with pronounced LSPI activity were characterized by means of minimally invasive high-speed endoscopic imaging. Here, glowing particles originating from dislodged deposits as well as glowing deposit hotspots on the piston top land could be observed as LSPI event initiators. These particles often possessed a combustion participation history before becoming an ignition source. Additional LSPI key experiments were performed to investigate the individual participation of engine operating media in the overall LSPI process via light-induced fluorescence detection of fuel and lubricating oil, lubricating oil dosing and deposit particle injection. The chemical nature of LSPI-inducing (deposit) particles was revealed with advanced ex situ analysis of the combustion chamber deposits. Only the accumulation of inorganic substances originating from lubricating oil additive packages, caused by a specific fuel-liner/piston interaction with subsequent deposit formation through sub-stochiometric combustion, enables specific deposits/particles to ignite the surrounding mixture over a multicyclic process due to the resulting increased oxidation reactivity, insofar as the necessary in-cylinder temperature/pressure levels and oxygen availability (air-fuel equivalence ratio level) are given during power and exhaust cycles. Through a final synthesis step of all results, a multi-cycle oxidation-reactivity-enhanced deposit/particle-driven LSPI root cause mechanism is established.

1 Introduction

Against the background of global warming and the associated climate change [1, 2], with all its drastic negative effects (extreme weather events, long-term decline in global security and prosperity, etc.) [3], the reduction of anthropogenic greenhouse gas emissions is an indispensable global task for humankind. With the Paris Agreement, all parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit human-induced mean global warming to well below 2 °C (target: 1.5 °C) by reducing global greenhouse gas emissions as quickly as possible and achieving emission neutrality in the second half of this century [4]. In response, the European Union designed the European Green Deal, which includes a series of measures to achieve the goal of net-zero greenhouse gas emissions by 2050. One partial step in this process is a reduction in greenhouse gas emissions of at least 55 % by 2030 compared to 1990 levels [5]. Assuming a remaining CO_2 budget of 420 gigatons with a 66 % probability of limiting warming to 1.5 °C [2], the specific targets for Germany are implemented in the Federal Climate Protection Act for individual sectors. For the transport sector, this results in a necessary CO_2 equivalent emission reduction of approximately 37 % in 2030 compared to 2020 [6]. Comparable strategies and measures must/will exist globally. Japan, South Korea, and the United States of America have also announced carbon-neutral economies by 2050. China has similar goals by 2060 [7]. Only with a joint global effort will we succeed in limiting climate change and its consequences that threaten our very existence.

1.1 Motivation

In 2016, global road transport accounted for around 12 % of all CO_2 equivalent emissions [8]. The International Council on Clean Transportation (ICCT) estimates the current global road transport contribution to be about 9.2 gigatons CO_2 [9]. Considering the different modes of transportation, light-duty vehicles (LDV) account for the largest share of traffic at around 43 %. At the same time, the current share of worldwide automotive drive solutions with spark-ignited gasoline engines can be estimated at over 75 % [10, 11], which illustrates the current and thus also (near) future CO_2 relevance of this engine technology. As a regulatory response to climate relevance, CO_2 targets are being further tightened in all major markets (see Figure 1.1), making further efficiency improvements in propulsion technologies imperative.

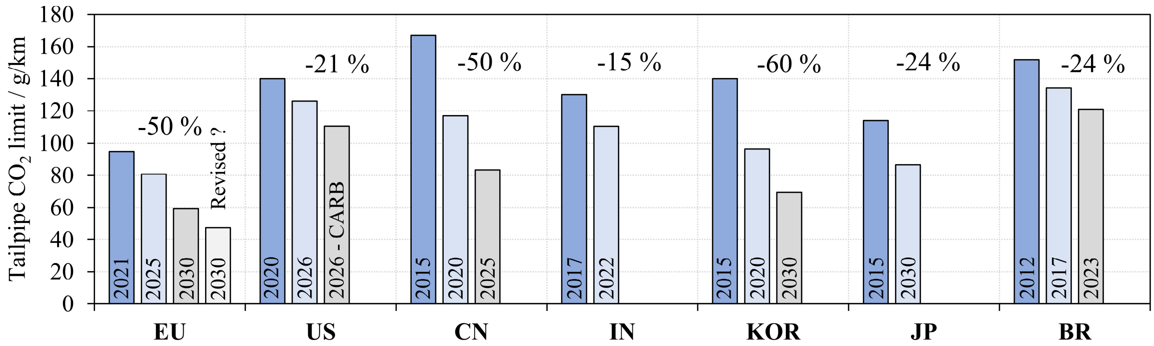

Figure 1.1: Light-duty vehicle CO_2 targets in major markets; modified from [12]

Current global LDV developments and future scenarios, especially against the background of necessary global multivalent upheavals and transformations in the energy sector [13, 14] and holistic CO_2 emission and life cycle assessments (LCA) of powertrain solutions [15, 16] indicate the necessity coexistence of different powertrain solutions [17, 18, 19] to achieve global, efficient and marketable CO_2 reduction far from dogmatic approaches [17]. The best synergy between the powertrain and the primary energy supply is elementary for this purpose [17]. Specific powertrain solutions based on electric (battery, fuel cell) [20], gaseous (hydrogen, methane, etc.) [21], and liquid energy sources [22] as well as their combination [23], can each represent advantageous solutions. In particular, liquid CO_2-neutral fuel strategies show a promising approach to solving the conflicting goals of energy density and storage capacity as well as the CO_2 reduction potential of existing powertrain technology (“Drop-in” solution) [24, 25].

Multidimensional powertrain solutions are also reflected in global sales forecasts for LDV [26, 27]. At present and also in 2040, the global share of new vehicles with an internal combustion engine will still be well over 50 %, making it the most important source of global propulsion, especially when considering the emerging socio-economic aspects of mobility. The spark-ignited gasoline engine remains the most widespread drive technology, both now and in the future. Against this background, further measures to increase efficiency are indispensable to further reduce CO_2 emissions from vehicles with gasoline engine powertrain solutions.

A successful concept for increasing efficiency in the conflicting goals of gasoline engine development between emission specifications, efficiency and performance characteristics is the targeted shifting of dominant engine load points resulting from specific performance requirements (load collectives in customer use) to areas of high efficiency optimized for the specific application “Rightsizing” through displacement reduction “Downsizing” and speed reduction “Downspeeding” while maintaining the same performance potential through forced induction [28, 29]. The implementation of this approach requires high power densities and is usually realized by means of turbocharging and gasoline direct injection [30]. The increasing market penetration of “high power density” technology [31] shows its positive trend when looking at the development of CO_2 emissions of European passenger cars [32]: Despite increasing overall vehicle weight and performance, there is a downward trend in CO_2 emissions and engine displacement.

In addition, an increasing level of engine power density can enable further efficiency gains [30], which is, however, counteracted by the increased occurrence of irregular combustion anomalies such as knocking and pre-ignition [33, 34]. The so-called low-speed pre-ignitions (LSPI) occur mainly at high engine loads and low speeds [35], can have an enormous damage potential even if they occur only once [36], cannot be specifically suppressed by control technology [37], and thus especially limit depictable in-cylinder pressures, further efficiency improvements and general engine reliability. They are characterized by an unpredictable ignition initiation of the air/fuel mixture before ignition by the spark plug, which can lead to extremely high in-cylinder pressure peaks caused by knocking combustion. The root cause of this complex phenomenon is not yet fully understood. Only a comprehensive understanding of the underlying mechanisms of efficiency-inhibiting LSPI events will allow the derivation of targeted countermeasures and thus increase the potential of spark-ignited gasoline engines.

This thesis presents a holistic experimental analysis of the LSPI phenomenon with the synthesis of the underlying LSPI root cause mechanisms on a modern high-power density 3-cylinder turbocharged downsized spark-ignition engine with direct injection.

1.2 Objective and research approach

The phenomenon of LSPI currently represents a limiting factor for increasing the efficiency and the associated direct greenhouse gas reduction potential of spark-ignited gasoline engines. Numerous studies, some with different focuses, show a complex multifactorial process that is not yet fully understood. While the focus of many studies has been on the description and investigation of LSPI influencing factors, there is still no clear understanding of the underlying LSPI root cause mechanisms.

Many LSPI root cause hypotheses are based on macroscopic phenomenon descriptions (engine parameter specifications and their statistically LSPI occurrence relation) on real engine systems or on microscopic phenomenon observations (e.g., high-speed diagnostics of the in-cylinder processes on optical single-cylinder engines or lubricating oil droplet ignition studies in rapid compression machines) on strongly reduced engine systems. The latter observations often lack transferability to real engine systems. However, only a combination of microscopic and macroscopic phenomenon analysis on the real engine system will enable a holistic LSPI mechanism picture and unlock a further engine improvement potential.

Therefore, the aim of this thesis is to improve the holistic understanding of the LSPI root cause mechanisms and processes based on a highly charged spark-ignited gasoline engine with direct injection for passenger cars. To this end, the current state of knowledge on LSPI mechanisms will be elaborated, specifically identifying gaps in understanding. Based on this, experimental methodologies for holistic (microscopic and macroscopic) analysis of LSPI processes are developed and implemented.

These include a characterization of the experimental engine under different engine parameter specifications and operating media with regard to the macroscopic LSPI tendency in order to uncover LSPI-critical engine operating conditions as a basis for further detailed "microscopic" analysis. Microscopic analysis consists of comprehensive optical in-cylinder LSPI characterization and subsequent LSPI key experiments to generate in-depth knowledge about relevant (sub-) processes. This includes the development, ex situ validation and experimental engine adaptation of novel investigation tools. From this, an LSPI mechanism will be derived by means of continuous synthesis of all macroscopic and microscopic examination results.

The methods, results and interpretations of this thesis have also been published or presented in excerpts in the publications and symposia listed in the Publication summary section.

1.3 Outline of thesis

Figure 1.2 shows the logic path of the presented thesis to synthesize LSPI root cause mechanisms. In doing so, the following Chapter 2 presents the current state of knowledge on LSPI mechanisms in discussed form and contextualizes the derived thesis objectives. In addition, all the necessary fundamentals for understanding the topic and the results discussed are described. The detailed research methodologies, as well as the approach to mechanism synthesis, are presented in Chapter 3. Chapter 4 describes the engines used, the test environment and the novel developed optical examination tools. Results from the thermodynamic, optical and key experiment studies are presented and discussed in Chapter 5 in LSPI mechanism comprehensible and interpretive order. Additionally, interpretation-supporting simulation results are shown. Chapter 6 presents the LSPI mechanism synthesized from all the research results as well as emerging further research recommendations and approaches. Finally, Chapter 7 concisely summarizes the findings and provides an outlook on the implications of future research findings.

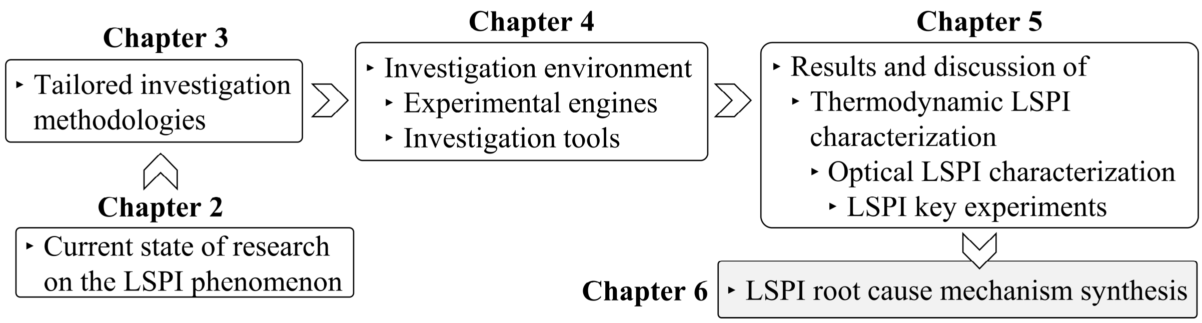

Figure 1.2: Outline of thesis