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FlexHD

Pilot- and demonstration of variable valve control strategies for efficient heavy-duty engines

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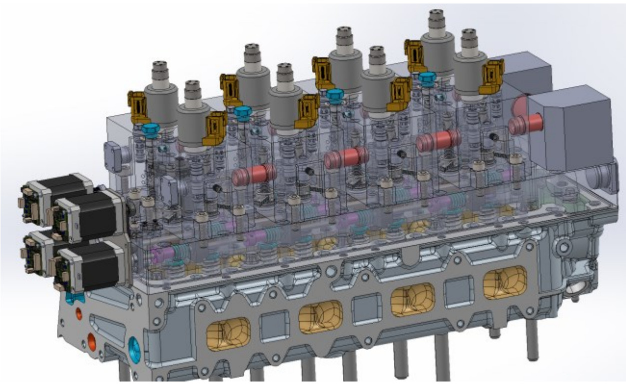
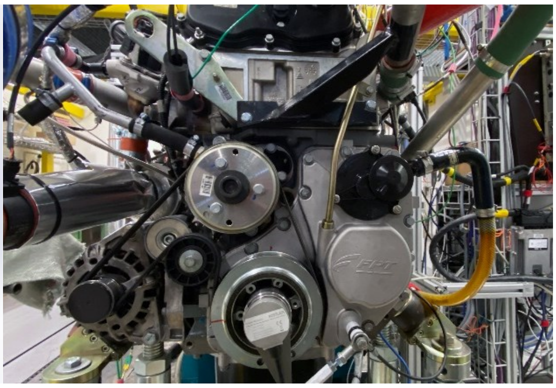

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Zusammenfassung

Verbrennungsmotoren im Nutzfahrzeugen wurden immer auf maximale Effizienz ausgelegt. Die Treibstoffkosten sind ein dominanter Kostenfaktor in diesem Segment und hohe Effizienz verspricht einen direkten Wettbewerbsvorteil. Allerdings war bis jetzt immer klar: der mit Abstand grösste Teil der Nutzfahrzeugmotoren wird mit fossilem Diesel, allenfalls mit Biodieselanteil, betrieben.

Aufgrund der Notwendigkeit, innerhalb von drei Jahrzehnten von fossilen Treibstoffen komplett wegzukommen, ist die Nutzfahrzeugindustrie im Umbruch. Diverse Anwendungen mit geringen Anforderungen an Hochlast und Autonomie werden in Zukunft elektrifiziert werden. Die anspruchsvollen Anwendungen im Bereich des Langstreckenverkehrs sowie der Arbeitsmaschinen werden aber weiterhin auf die enorme Energiedichte von chemischen Energieträgern angewiesen sein. Allerdings wird sich vermutlich nicht ein einziger erneuerbarer chemischer Energieträger etablieren, sondern verschiedene, je nach Kostenstruktur, Marktgegebenheiten, Gesetzgebung und technischen Fortschritten. Neben Biotreibstoffen (Problem: zu geringes Mengenpotential), sind sogenannter Fischer-Tropsch basierte Drop-In Treibstoffe (Problem: hohe Kosten) sowie einfacher herzustellende erneuerbare Treibstoffe wie Wasserstoff, Methan, Ammoniak, Methanol, Dimethylether vielversprechende Kandidaten.

Die Industrie steht also vor der Aufgabe, Energiewandler für diverse zukünftig bedeutsame Treibstoffe zu entwickeln. Im Bereich der Verbrennungsmotoren bedeutet dies, dass Motoren möglichst einfach an Treibstoffe adaptiert werden sollen und diese für jeden Treibstoff maximale Effizienz liefern müssen. Ein wichtiger Baustein dafür ist es, den Gaswechsel von Motoren so flexibel wir möglich zu gestalten. Ziel dieses P&D Projektes ist es darum, einen vollvariablen Ventiltrieb für einen Nutzfahrzeugmotor zu entwickeln und ihn damit auszurüsten. Mit dieser neuen Flexibilität soll, in einem ersten Schritt mit konventionellem Diffusionsbrennverfahren, die Motoreffizienz, das Volllastverhalten und das Thermomanagement verbessert werden. In einem darauf aufbauenden Forschungsprojekt sollen dann Potenziale für andere Treibstoffe und Brennverfahren betrachtet werden.

Im Rahmen dieses Projektes wurden auf der Seite der Ventiltriebsauslegung diverse Anforderungen an den Ventiltrieb systematisch erfasst und mittels Multiphysik-Simulationen bewertet. Begleitend zur Simulation wurden stets die konstruktiven Machbarkeiten geprüft. Dabei stellte sich heraus, dass die Anforderungen, speziell der sehr knappe Bauraum und allfällige Bremsfunktion in 2-Takt-Betriebsweise, herausfordernd sind und die Auslegung/Konstruktion sehr sorgfältig iteriert werden muss. Dabei entstand eine neue Möglichkeit, die ursprünglich paarweise geplante Betätigung der Ventile via Doppel-Schlepphebel durch hydraulische Einzelbetätigung zu ersetzen, wodurch Drall-Steuerung zur Verbrennungsbeeinflussung möglich wird.

Das Projektteam hat sich für diesen Weg entschieden, da so der Vielfachnutzen des elektrohydraulischen Ventilbetätigungssystems am besten demonstriert werden kann und Industrialisierungschancen steigen. Heute darf die Konfiguration als simulativ bestätigt und konstruktiv gelöst gelten. Die Fertigung von Teilen hat begonnen, Anfangs 2024 wird der Aufbau der Hardware starten.

Parallel zur Entwicklung des Ventiltriebs wurden die Vorbereitungsarbeiten auf der Motorenseite abgeschlossen. Dies umfasste einerseits die Konzeptionierung einer Rapid Prototyping Steuerungsumgebung, den Aufbau und die Basisvermessung des Serienmotors mit der Serienmotorsteuerung, die Programmierung der Rapid Prototyping Steuerungsumgebung sowie den befeuerten Betrieb des Grundmotors damit. Dabei wurde die Ansteuerung / Regelung des Grundmotors für stationären Betrieb vergleichbar mit der Serienmotorsteuerung umgesetzt. Damit steht dem Projekt nun eine voll flexible Steuer- und Regelungsplattform zur Verfügung, mit welcher im

weiteren Projektverlauf die neu dazukommenden Komponenten des vollvariablen Ventiltriebs angesteuert werden können.

Résumé

Les moteurs à combustion des véhicules utilitaires ont toujours été conçus pour une efficacité maximale. Le coût du carburant est un facteur de coût dominant dans ce segment et une efficacité élevée promet un avantage concurrentiel direct. Cependant, il a toujours été clair jusqu'à présent que la majorité des moteurs de véhicules utilitaires fonctionnent au diesel fossile, éventuellement avec une part de biodiesel.

En raison de la nécessité de se passer complètement des carburants fossiles dans les trois décennies à venir, l'industrie des véhicules utilitaires est en pleine mutation. Diverses applications peu exigeantes en termes de charge élevée et d'autonomie seront électrifiées à l'avenir. Les applications exigeantes dans le domaine du transport longue distance ainsi que les machines de travail continueront toutefois à dépendre de l'énorme densité énergétique des sources d'énergie chimiques. Toutefois, il est probable qu'il n'y aura pas un seul vecteur d'énergie chimique renouvelable, mais plusieurs, en fonction de la structure des coûts, des conditions du marché, de la législation et des progrès techniques. Outre les biocarburants (problème : potentiel quantitatif trop faible), les carburants "drop-in" à base de Fischer-Tropsch (problème : coûts élevés) ainsi que les carburants renouvelables plus faciles à produire comme l'hydrogène, le méthane, l'ammoniac, le méthanol, l'éther diméthylique sont des candidats prometteurs.

L'industrie est donc confrontée à la tâche de développer des convertisseurs d'énergie pour divers carburants importants à l'avenir. Dans le domaine des moteurs à combustion, cela signifie que les moteurs doivent être adaptés le plus facilement possible aux carburants et qu'ils doivent fournir une efficacité maximale pour chaque carburant. Pour cela, il est important de rendre le changement de gaz des moteurs aussi flexible que possible. L'objectif de ce projet P&D est donc de développer une commande de soupape entièrement variable pour un moteur de véhicule utilitaire et de l'équiper de cette commande. Cette nouvelle flexibilité doit permettre, dans un premier temps, d'améliorer le rendement du moteur, le comportement à pleine charge et la gestion thermique grâce à un procédé de combustion par diffusion conventionnel. Dans un projet de recherche ultérieur, les potentiels d'autres carburants et procédés de combustion seront examinés.

Dans le cadre de ce projet, diverses exigences concernant la conception de la commande des soupapes ont été systématiquement saisies et évaluées au moyen de simulations multiphysiques. Parallèlement à la simulation, la faisabilité de la construction a toujours été examinée. Il s'est avéré que les exigences, en particulier l'espace de montage très restreint et l'éventuelle fonction de freinage en mode de fonctionnement à deux temps, sont un défi et que la conception/construction doit être itérée très soigneusement. Une nouvelle possibilité a ainsi vu le jour : remplacer l'actionnement des soupapes par paire, initialement prévu, par un actionnement hydraulique individuel via un double levier traînant, ce qui permet de contrôler le tourbillon pour influencer la combustion.

L'équipe de projet a opté pour cette solution, car elle permet de démontrer au mieux les multiples avantages du système de commande électro-hydraulique des soupapes et augmente les chances d'industrialisation. Aujourd'hui, la configuration peut être considérée comme confirmée par la simulation et résolue par la construction. La fabrication des pièces a commencé et l'installation du matériel débutera début 2024.

Parallèlement au développement du système de commande des soupapes, les travaux préparatoires ont été achevés du côté du moteur. Cela comprenait d'une part la conception d'un environnement de commande de prototypage rapide, le montage et la mesure de base du moteur de série avec la

commande de moteur de série, la programmation de l'environnement de commande de prototypage rapide ainsi que le fonctionnement à feu du moteur de base avec celui-ci. La commande/régulation du moteur de base pour un fonctionnement stationnaire a été réalisée de manière comparable à la commande du moteur de série. Le projet dispose ainsi d'une plateforme de commande et de régulation entièrement flexible, qui permettra de piloter les nouveaux composants de la commande de soupape entièrement variable au cours de la suite du projet.

Summary

Internal combustion engines in commercial vehicles have always been designed for maximum efficiency. Fuel costs are a dominant cost factor in this segment, and high efficiency promises a direct competitive advantage. However, until now it has always been clear that by far the largest proportion of commercial vehicle engines run on fossil diesel, with a biodiesel component at best.

Due to the need to completely move away from fossil fuels within three decades, the commercial vehicle industry is in a state of upheaval. Various applications with low demands on high load and autonomy will be electrified in the future. However, the demanding long-haul and mobile machinery applications will continue to rely on the tremendous energy density of chemical fuels. It is unlikely that a single renewable chemical energy source will become established, but rather various ones, depending on the cost structure, market conditions, legislation, and technological advances. Besides biofuels (problem: too low volume potential), so-called Fischer-Tropsch based drop-in fuels (problem: high cost) as well as easier to produce renewable fuels like hydrogen, methane, ammonia, methanol, dimethyl ether are promising candidates.

As part of this project, various valve train design requirements were systematically recorded and evaluated using multiphysics simulations. Accompanying the simulation, the design feasibilities were always examined. It turned out that the requirements, especially the very tight installation space and possible braking function in 2-stroke operation, are challenging and the design/construction must be iterated very carefully. This resulted in a new possibility of replacing the originally planned paired actuation of the valves via double cam followers with individual hydraulic actuation, thus enabling swirl control to influence combustion.

The project team opted for this approach because it is the best way to demonstrate the multiple benefits of the electrohydraulic valve actuation system and increase the chances of industrialization. Today, the configuration can be considered as simulatively confirmed and constructively solved. The production of parts has begun, and the construction of the hardware will start at the beginning of 2024.

In parallel with the development of the valve train, the preparatory work on the engine side was completed. This included the conceptual design of a rapid prototyping control environment, the construction and basic measurement of the series engine with the series engine control, the programming of the rapid prototyping control environment and the firing of the basic engine with it. The control of the basic motor for stationary operation was implemented in a manner comparable to the series motor control. This means that the project now has a fully flexible open-loop and closed-loop control platform with which the newly added components of the fully variable valve train can be controlled in the further course of the project.

Contents

Abbreviations

ATS	After Treatment System
BEV	Battery Electric Vehicle
BSFC	Brake Specific Fuel Consumption
CAD	Computer Aided Design
CI	Compression Ignition
CO_2	Carbon Dioxide
DME	Dimethyl Ether
FB	Feedback
FC	Fuel Cell
FEM	Finite Element Method
FPGA	Field Programmable Gate Array
HD	Heavy Duty
HP	High Pressure
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
LCA	Life Cycle Analysis
LP	Low Pressure
MABX	Microautobox
OME	Oxymethylene Ethers
PID	Proportional Integral Derivative
PtX	Power-to-X (X stands for any chemical energy carrier)
SI	Spark Ignition
TTL	Transistor-Transistor Logic
TTW	Tank to Wheel

1 Introduction

1.1 Background information and current situation

In the European passenger car segment, tailpipe CO_2 limits exist since many years and technological development led to a CO_2 reduction (in terms of CO_2 per vehicle mass). Recently, a tailpipe CO_2 reduction scheme came also on the legislative agenda for certain on-road heavy-duty segments with high CO_2 emission premiums if the goals are not met [1]. However, low fuel consumption, and therefore low CO_2 emissions, were always a main development goal in the heavy-duty segment as fuel costs are a dominating factor for heavy-duty vehicle operators and efficient engines were always a competitive advantage. Therefore, further CO_2 reductions are particularly difficult to achieve in this segment.

The introduction of renewable chemical energy carriers in combination with efficient energy converters is the key, as it is also highlighted in the Swiss Energy Research Masterplan 2021-2024 [2]. In the heavy-duty transport and off-road sector, electrification will not be a viable option for all applications. Chemical energy sources will very likely continue to play an important role in high-continuous-power and long-range on- and non-road applications. This is mainly because of their superior volumetric and gravimetric energy densities, excellent storability and transportability as well as the potential for fast refueling.

Considerable efforts are underway to bring drop-in replacements for the classical fossil fuels to technical and economical maturity. However, alternative fuels such as hydrogen, ammonia or alternative hydrocarbons are likely to gain importance as they offer certain advantages:

1. Hydrogen as the simplest chemical energy carrier which can be sustainably produced e.g. by electrolysis [3] from surplus or stranded electricity and from reforming or pyrolysis of renewable hydrocarbons [4] [5]. The main challenge for hydrogen solutions are the complex and costly solutions for re-fueling and storage – both for gaseous H_2 approaches at 350 or 700 bar tank pressure level as well as for liquid H_2 solutions. There is recent evidence that hydrogen has an surprisingly high indirect short-term global warming potential [6]. This calls for a very careful design of production, transport, storage and conversion technologies to minimize hydrogen emissions.
2. Ammonia as a fuel which is straightforward to produce from hydrogen and N_2 abundant in the atmosphere, e.g. in offshore production units [7][8]. It has a high toxicity, poor combustion behavior and no global warming potential. Hydrogen addition, e.g. by partial ammonia reforming, may be a way to enhance the poor combustion behavior. Limiting NO_x (toxic) and especially N_2O (very potent greenhouse gas) emissions remain major challenges [9].
3. Alternative hydrocarbons such as synthetic methane (CH_4), methanol (CH_3OH) or DME (H_3C-O-CH_3) as the simplest hydrocarbons which can be synthesized from H_2 and CO_2, or via direct pathways from biomass or waste [10–13].
4. More complex fuels with drop-in potential, usually produced by Fischer-Tropsch processes driven by chemical or solar heat [14][15], with deteriorating efficiency for longer chain-length; or by hydrotreatment (catalytic cracking or catalytic hydrodeoxygenation) of bio-oils [16], as for example HVO.

On a pure energetic point of view, a direct electrification has for most ways of power production clear advantages versus hydrogen, methane, methanol, DME or Fischer-Tropsch solutions [17]. However, as mentioned, for certain classes/use cases of vehicles, a direct battery-electrification is not feasible and chemical energy carriers have distinct advantages. In addition to practical advantages of chemical energy carriers for such application, the decoupling of energy harvesting and use in terms of time or geographical region is likely to become important as well, despite lower efficiencies of electrochemical (PtX) or thermochemical (solar fuels) pathways. This is why the authors believe that internal combustion engines, especially for the heavy-duty on- and non-road segment, have to be developed further but with a special focus on renewable chemical energy carriers. This is supported by the BFE Energy Perspectives 2050+ [18] where the "ZERO Basis" scenario estimates a PtX demand of the Swiss road traffic sector of 15.6 TWh/a.

Ammonia is mainly discussed as a potential fuel for large (>10 MW propulsion power) deep-sea-going maritime applications where adequate safety measures can be put in place in commercial ports as well as on the large commercial vessels [19][20].

We will not discuss Ammonia here because the application range which is in the focus of this project is the product range of FPT, which is roughly in the 100 kW … 1 MW class of heavy-duty-powertrains. The best technical solution for each application depends mainly on the daily energy need and its autonomy. On one side, a communal light duty truck can survive with less than 50 kWh daily energy need, including multiple opportunities for recharging or refilling events- On the other side a heavy duty agricultural machines may need above 5000 kWh operating energy over a working day with minimal opportunities to refill the power storage. A long-haul heavy-duty truck is located in between these two examples with around 1000 kWh daily traction energy need.

Based on these numbers, different de-carbonization strategies can be derived. Table 1 shows as an example of a possible manufacturer’s assessment matrix for the case of a 40-ton long-haul heavy-duty truck. For the autonomy of 1’000 km, today’s Diesel solutions need a Diesel tank of around 270 liters capacity. Drop-in solutions (Fischer-Tropsch Diesel, HVO) need basically the same powertrain and energy storage configurations but they have an issue with fuel costs or their very limited potential for the large quantities needed. Direct electrification solutions have the benefit of zero Tank-to-Wheel greenhouse gas emissions, which is very important for the manufacturers to meet legislative goals. Unfortunately, practical aspects (costs of overhead wires, costs and mass of batteries, costs of MW charging infrastructure) do not make direct electrification feasible solutions for this class of vehicles from a techno-economical point of view. Ammonia (LNH_3) has, as discussed above, a safety problem when used on the road, which leaves renewable methanol, renewable DME, renewable OME, renewable ethanol, renewable hydrogen and renewable methane as potential future chemical energy carriers. Bio-ethanol has a limited potential in terms of quantities and OME has most likely a cost problem. As a result, hydrogen, methane, methanol, DME and drop-in Fischer Tropsch solutions are likely to become the most relevant future fuels for this segment of vehicles.

Table 1: Author’s assessment for different powertrain technologies for long-haul truck applications (1’000 km autonomy)

Concept	Conversion (current state-of-the-art)	Potential for fast vehicle deployment	Potential for retrofit of Diesel solutions	Estimated TTW efficiency	Energy storage volume for 1'000 km range [l]	Added mass rel. to diesel (fuel inluding tanks etc.) [kg]	Renewable production potential	Renewable fuel cost	Fueling station / infra-structure costs	Powertrain / energy storage costs	System safety / accident safety	Overall CO2 reduction potential (relevant for climate goals)	TTW CO2 reduction potential (likely relevant for EU legisation)
REFERENCE CASES													
Diesel (B7)	ICE / CI			45%	270								
LNG @ -160 °C	ICE / SI			40%	480	205							
DIRECT ELECTRIFICATION													
BEV (Lithium, current)	EM			80%	6500	8100			MW FstChg			MW FstChg	
BEV (Lithium, far future)	EM			80%	1500	3350			MW FstChg			MW FstChg	
Overhead wire	EM			90%	0	-500							
ALTERNATIVE CHEMICAL ENERGY CARRIERS													
CNG @ 300 bar	ICE / SI			40%	1100	230							
HVO	ICE / CI			45%	280	0							
FischerTropsch (drop-in) Diesel	ICE / CI			45%	270	0							
Methanol	ICE / SI			40%	670	370							
Methanol	HT PEM FC + EM			40%	670	150							
Ethanol	ICE / SI			40%	510	210							
DME @ 6 bar	ICE / CI			46%	490	380							
OME1	ICE / CI			45%	480	220							
OME3-5	ICE / CI			45%	470	330							
H2 @ 350 bar	ICE / SI			42%	3000	1100							
H2 @ 350 bar	PEM FC + EM			45%	2800	920							
H2 @ 700 bar	ICE / SI			42%	1500	1270							
H2 @ 700 bar	PEM FC + EM			45%	1400	1080							
LH2 @ -253 °C	ICE / SI			42%	1200	600							
LH2 @ -253 °C	PEM FC + EM			45%	1120	460							
LNH3 @ -33 °C	ICE / CI			38%	900	950							

Currently, FPT is providing mainly Diesel and Natural Gas / Biogas (CNG, LNG) engines to their customers. Figure 1 shows the lineup of the current available energy converters and a possible strategy for the future.

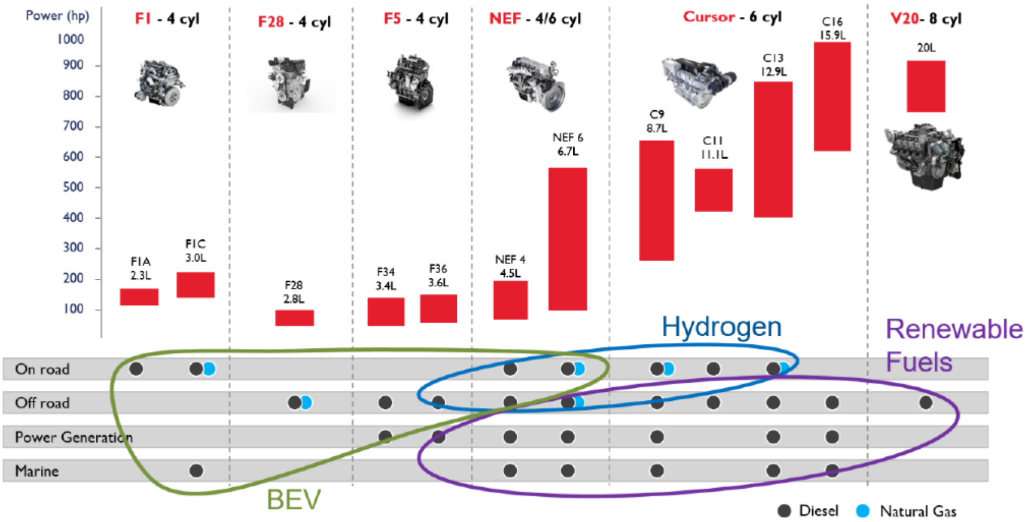

Figure 1: Current FPT powertrain lineup and a possible replacement strategy

It is very likely that typical missions in the lower power range of engines will be covered in the future mainly by battery-electric solutions; this technology is being developed at the moment. Hydrogen will likely be a primary choice for medium range/power applications – the according technologies for internal combustion engines as well as for fuel cells are being developed at the moment as well[1]. The most demanding applications with long range, high continuous power and/or fast refilling needs will most likely dominantly rely on renewable hydrocarbons. This of course includes hybrid-electric structures in use cases where this makes sense.

As introduced earlier, renewable fuels for the envisaged applications include hydrogen, methane, methanol, DME as well as drop-in Fischer-Tropsch fuels and HVO. All these fuels can be converted in internal combustion engines. Making such engines as efficient as possible is a key success factor as the sector of investment goods is highly competitive and fuel costs dominate often the total cost of ownership in the heavy vehicle segments.

This project focuses on increasing powertrain efficiency and making the system ready for the relevant alternative fuels mentioned above. Powertrain efficiency increase can be achieved by optimizing the engine as well as by optimizing the use of the engine, for example through hybridization. Engine efficiency increase is very hard to achieve without changing major design features.

One design feature which is classically very inflexible and cannot react on changing requirements regarding engine operating conditions as well as on the fuel quality is the gas exchange mechanism on an engine. The gas exchange valves are typically operated using a camshaft, which defines the valve lift curve profile versus the engine's crank angle. Making this as flexible as possible would give an engine manufacturer the possibility to optimize engine efficiency further e.g. by implementing so-called Miller operation on demand, by setting internal EGR rates, by controlling the charge motion, by adjusting the effective compression/expansion ratios, by deactivating cylinders or operate them in a skip-fire mode, by implementing more efficient thermal management measures and so on. Such a

[1] Internal combustion engines and fuel cell solutions have very similar efficiency levels for high-load applications and it is not yet clear which technology will be technically and economically more feasible in the future.

flexibility would be especially helpful if the fuel changes – so the effective compression ratio could for example be adjusted to the cetane/octane behavior for high/low reactivity fuels.

In this P&D project, a flexible electrohydraulic valve train is to be designed and implemented on a commercial vehicle engine and its energy potential demonstrated on the engine test bench for high-reactivity fuels (diesel, HVO). Based on this project, a separate R&D project is investigating the potential of such a fully variable valve system for a variety of low-reactivity fuels as well[2].

The improvement of the sustainability and reduction of the costs of sustainable fuels and platform chemicals is the main topic of the recently granted SWEET project "ReFuel.ch"[3]. Please consult the communication and the publications of this project to learn more about the potentials of such renewable chemical energy carriers for the Swiss situation.

1.2 Purpose of the project

Irrespective of the fuel used, increasing efficiency and, where applicable, hybridization[4] are the most relevant measures to lower CO_2 emissions. Apart from personnel costs, fuel costs are usually among the largest cost factors in the commercial transport and mobile machinery sector. Thus, an increase in efficiency brings not only improved environmental aspects, but also cost savings and is therefore an important competitive advantage. Therefore, maximizing powertrain efficiency has always been a key factor for heavy duty engine manufacturers. In future, where renewable fuels will likely be expensive before large-quantity production in suitable world regions will bring the costs down again, efficiency will remain a very important competitive advantage.

The manufacturers of heavy-duty powertrains face the challenge that the future is quite uncertain with respect to future solutions. Especially manufacturers which produce for a global market see increasingly different decarbonization strategies in different world regions with certain regions focusing mainly on TTW considerations and other on broader LCA-derived approaches. Besides of assessing potential large-quantity trends such as BEV, hydrogen, methane, methanol, DME and Fischer-Tropsch Diesel, local strategies have to considered as well (HVO, ethanol). This leaves the challenging task to develop a large number of powertrain technologies in parallel (BEV, ICEs for a number of fuels, fuel cells) while keeping the running business profitable.

For heavy-duty ICE development, the focus lies on making the engines compatible to as many fuels as possible while maximizing engine efficiency. Unfortunately, the different fuels established above have very different physicochemical properties. Some are of high-reactivity (Fischer-Tropsch Diesel, HVO, DME) asking for compression ignition engine concepts. Some are of low-reactivity (hydrogen, methane, methanol, ethanol) asking for external ignition concepts. In addition, different properties such as knock resistance, mixing behavior, flammability limits, adiabatic flame temperature and laminar flame speed ask for very different process parameters. Therefore, engine-relevant parameters such as injection/ignition setup, lambda concept, compression ratio, boost pressure, exhaust gas recirculation, load control strategy, combustion chamber design and charge motion have to be designed properly for each fuel. While some parameters are comparably straightforward to vary, others are difficult. Since internal combustion engines have a repetitive combustion process where the cylinder charge runs through a closed high-pressure process (compression-combustion-expansion), this cylinder charge has to be replaced for the next process (exhaust, intake). One advantage of ICEs versus stationary thermodynamic machines such as turbines is that the intermittent combustion process makes very high combustion peak temperatures possible, without exceeding material

[2] https://www.aramis.admin.ch/Texte/?ProjectID=49517

[3] https://www.bfe.admin.ch/bfe/en/home/news-and-media/press-releases/mm-test.msg-id-97292.html

[4] Hydridization means that two energy converters are combined. For powertrains, the usual combination is an internal combustion engine and an electric motor. This gives the possibility for load-shifting, recuperation and local pure-electric driving. Whether hybridization makes sense or not, depends heavily on the vehicle mission. Long-haul applications have a very limited potential for hybridization while other use cases, like excavators, can profit a lot.

temperature limits. One drawback is that the control of process parameters is rather complex, especially for the gas exchange.

Classically, gas exchange is controlled by opening and closing gas exchange valves at the right moment. Since the process is repetitive, the classical gas exchange mechanism is mechanically coupled to the engine’s crankshaft, which synchronizes the process. Unfortunately, such a direct mechanical coupling is very inflexible. There have been a lot of attempts to bring flexibilities to the gas exchange, none of them has found their way to mass-produced heavy-duty engines. In the passenger car engine sector, a number of approaches is mass-produced. However, none of these solutions does it without a mechanical coupling to the crankshaft. So, the solutions still rely on a camshaft but bring some degree of freedom by either switching cam profiles of modifying them by a mechanic or hydraulic interlink. Unfortunately, such mechanical approaches are not very flexible and they still rely on a camshaft with the need of a mechanical coupling and a proper lubrication, which is very demanding for the engine’s lubricant because of high contact pressure levels.

A better approach would be a pure electronic coupling of the valve actuation to the crankshaft position. Many attempts have been made to bring such systems to maturity but they showed a lack in safety/robustness, costs, or energy demand. In the recent years, Empa and etavalve have developed a new approach for a safe, robust, low-cost electrohydraulic valve actuation mechanism with a low energy demand through hydraulic recuperation. The system has proven to work on a comparably simple passenger car engine [21–26] and this project aims at transferring this approach to heavy-duty engines with a special focus on fuel-flexibility.

By using a fully variable, electro-hydraulic valve control on the commercial vehicle engine, this project aims at quantifying the potential of this flexibility in terms of increasing efficiency and making an engine (more) compatible for different fuels. In the framework of the P&D project discussed here, the basic setup for a fully variable electrohydraulic valvetrain (VVT) is being developed and implemented. Its potential will be screened for the high-reactivity fuels Diesel and HVO. In the aforementioned R&D project "FlexComb"[2], which bases on the hardware developed in this P&D project, the potential of a VVT in a heavy-duty engine for the low-reactivity fuels methane and methanol as well as the potential for non-classical combustion concepts will be investigated.

The main purpose of this project is to design an electrohydraulic VVT on a FPT serial production diesel engine for industrial applications. The smallest engine of the FPT range, the F1C (see Figure 1), has been chosen as the experimental platform. In principle, this engine is not in the focus to be made compatible for future renewable fuels but it is much more economical to perform demonstration and research projects at an early phase of innovation on an energy converter which is not too large. The findings can then, in a later stage, be transferred to systems in the upper power ranges.

Summary of the two main motivating points:

1. Maximize efficiency of the compression-ignition combustion engine in classical and hybrid-electric configuration by adding flexibility to the gas exchange process (this P&D project, for high-reactivity fuels Diesel and HVO). Additionally other effects like enhances thermal management can be beneficial.
2. Adapting the system for the investigation of alternative fuels (methane, methanol) and alternative combustion processes based on the same hardware basis (separate R&D project).

In such a complex chemical-physical system as an internal combustion engine, it is not possible to assess the full potential of a fully VVT in all its aspects in this P&D project. As a comparison: fully flexible electronically controlled common rail systems, a way to shape injection for high-reactivity fuels, were invented in the 1990 with ETH Zürich being one of the main contributors. Still today, new ways to take advantage of this flexibility are being introduced as for example on-demand pressure-amplification / pressure-shaping in the injector itself. However, this P&D project aims at

- Showing that it is possible to design and build a fully flexible electrohydraulic VVT for a commercial diesel engine with a flat combustion chamber roof, vertically standing gas exchange valves.
- Showing that it is possible to integrate additional features in such a valvetrain, such as establishing an engine brake function without the need to introduce additional acturators.
- Showing that it is possible to design a fully flexible electrohydraulic VVT in a way that the energy demand for the valvetrain itself is minimal; this should be achieved by introducing hydraulic recuperation of potential energies stored in the valve springs while they are compressed.
- Finding possible ways to introduce additional flexibilities, e.g. by introducing valve-individual lifts (this point was initially not part of this project but the project team decided to facilitate this option after the results of the initial design loops).
- Finding possible ways to simplify the system, initially invented for a spark ignition research engine, towards more realistic parameters for a potential industrialization. This includes the design of a concept with a low effort for the hydraulic supply.
- Demonstrating the functioning of the system on a fired F1C engine on an engine test bench.
- Screening of the energetic potentials such a system gives for a compression ignition engine.

All in all, the main purpose of this P&D project is to establish a hardware platform which is suitable for a further efficiency increase of heavy-duty internal combustion engines and to demonstrate/quantify possible future ways.

1.3 Objectives

Within this project, the following targets are envisaged:

- Build-up a fully flexible electrohydraulic valve train for an FPT F1C engine (4 cylinders, 3 litre displacement). This engine is currently produced in a diesel and a CNG version and powers numerous commercial vehicles (e.g. in vehicles from Iveco, Fiat, Fuso).
- Build-up a rapid prototyping control system capable to control the engine, including the VVT system.
- Perform experimental research on Empa's engine test bench to precisely quantify the advantages of the system in terms of efficiency, pollutant emissions and other aspects like thermal management.
- The definition of an exact goal for efficiency improvement is difficult at this stage, it will be quantified in detail within the project by combining experiments and simulation for the use case addressed here. Literature states, that the following goals may be realistic:
    - Increase full load torque across the engine's speed range by around 5-15% by optimizing exhaust valve opening and intake valve closing [27], a very strong low-end torque increase by 40% is reported in [28]
    - Efficiency increase of around 2-4% at moderate loads while keeping the classical diffusion-controlled combustion mode [27–30]
    - Even efficiency increase are possible by applying new combustion modes such as premixed charge compression ignition (PCCI) [31] or reactivity controlled compression ignition (RCCI) [32] - with a strong decrease in the engine's NO_x emissions which, in turn, reduces the AdBlue consumption as well. Such new combustion modes will be addressed in a separate R&D project.
    - Up to 10% fuel consumption improvement during heating up phase (untill ATS light off)

The following research questions are envisaged:

- Is it feasible to build a heavy-duty diesel engine with a high flexibility (regarding gas exchange, EGR, injection) and which efficiency benefits can be achieved?

- What are the optimal powertrain configurations for different vehicle types and different missions, taking advantages of a VVT engine like cylinder deactivation, skip firing, friction reduction by lift-on-demand, etc.
- Assess efficiency-increase and CO_2 reduction potentials for commercial traffic using conventional Diesel and also HVO as a fuel.

2 Description of facility

As mentioned above, this project uses the FTP F1C as a prototypical experimental platform for a heavy-duty engine. This is the smallest heavy-duty-type engine from FPT and used in vehicles like the Iveco Daily or the Mitsubishi Fuso. The comparably small F1C engine was chosen to keep the hardware and fuel costs as low as possible but the transferability of the project findings to larger heavy-duty engines (such as the NEF and Cursor series of FPT) is explicitly kept in mind.

2.1 F1C Engine

Table 2 lists the main parameters of the serial-production FPT F1C engine and Figure 2 shows its full load performance.

Relevant for this P&D project is the fact that gas exchange valves of this engine are camshaft-operated without any flexibility in terms of camshaft phasing or valve lift. The whole valve train system is to be replaced by a new fully variable electrohydraulic valve train.

Table 2: Specifications of the serial-production FPT F1C diesel engine

Engine name	FPT F1C
No. of Cylinders	4 in line
Combustion	Diesel, CI
Control System	Bosch EDC17
Injection System	Bosch Common Rail
Turbo Charger	Garrett eVGT
Bore x Stroke , Displacement	95.8 x 104 mm , 2999ccm
In-cylinder emission reduction	High-pressure EGR
Valve configuration	4 per cylinder
Valvetrain	Camshaft operated, no flexibility
Torque / Power	430Nm / 129kW

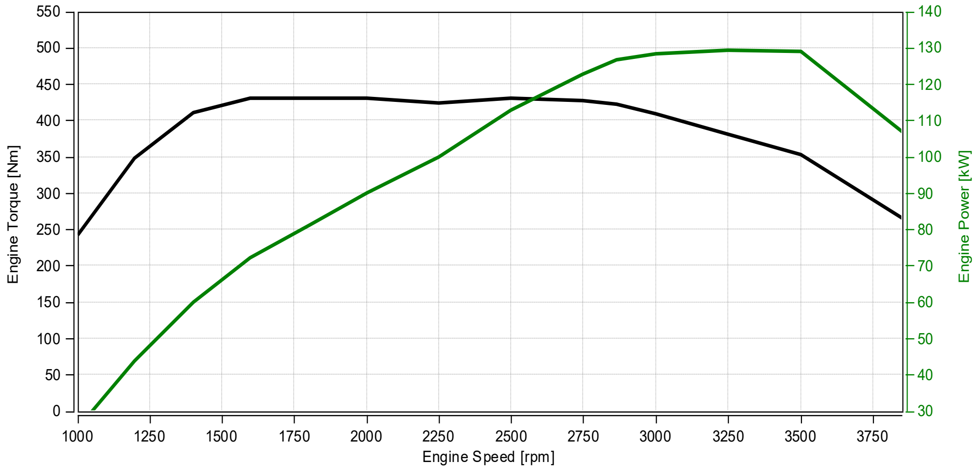

Figure 2: Peak torque and peak power characteristics of the used serial-production FPT F1C Engine

As a first and major step, the engine control unit (ECU) of the serial-production engine has to be replaced by a so-called rapid prototyping system. Serial-production ECUs are designed to fulfil the task to control and diagnose an engine and the ATS but they are not built to add new features. This is why the project team has decided to completely skip the serial-production ECU and replace it with a high-performance rapid prototyping system, based on a dSPACE Microautobox (MABX). The used MABX has a multitude of inputs, outputs and CAN buses, microprocessor-based as well as FPGA functionalities. However, the basic control functions of the serial-production ECU have to be transferred to the MABX. To do so, the serial-production configuration of the engine was first operated on the engine test bench and the engine and the ECU behaviors have been characterized.

2.2 Characterization of the Serial Production Engine

The experimental characterization of the serial-production engine is the reference for the later project steps. FPT has built-up the basic engine with a fully instrumented cylinder head in Arbon. This engine was put in operation first on a test bench in Arbon and its proper operation was checked before the engine was set up at Empa's test bench in Dübendorf. Figure 3 show the fully instrumented engine on the Empa test bench. In view of the need for future experiments with alternative fuels, a new fuel flow measurement and conditioning unit was installed on the test bench (Figure 4).

Table 3 lists the main specifications of Empa's test bench on which all the experiments are performed and Figure 5 shows a sketch of the instrumentation.

The results of this characterization are discussed in chapter 3.

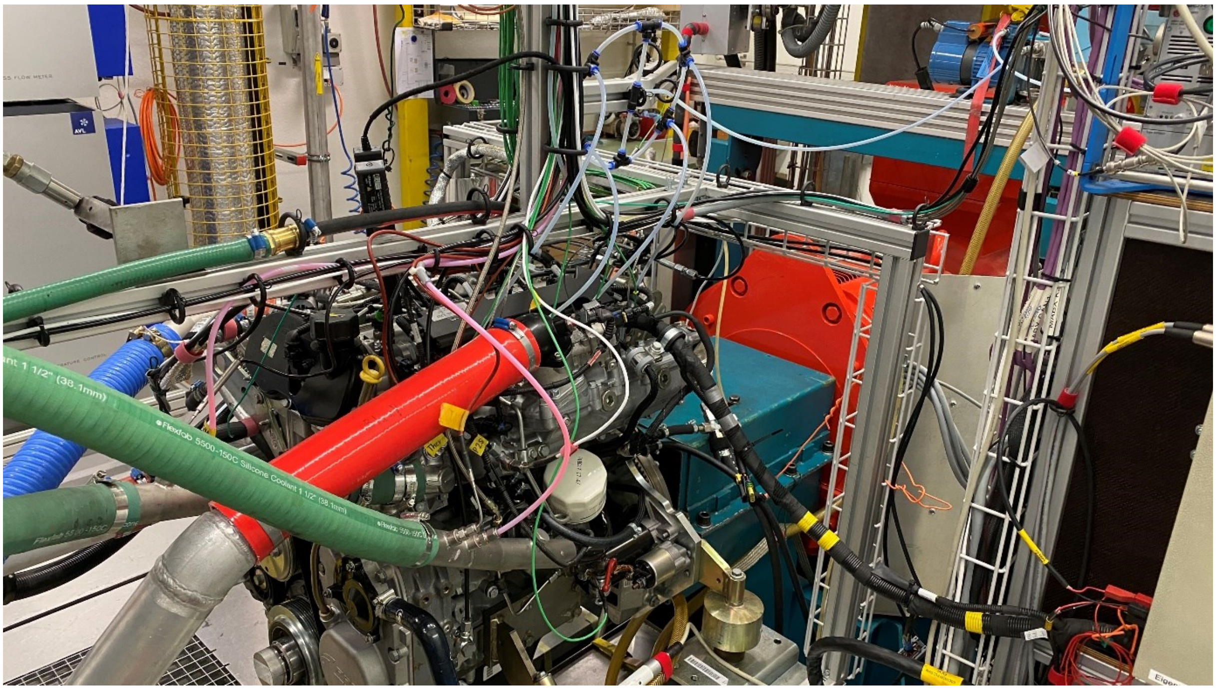

Figure 3: FPT F1C Engine on Empa's test bench

Figure 4: Fuel-flexible fuel flow measurement and fuel conditioning unit

Table 3: Main specifications of the engine test bench

Test Bench Name	Empa P3
Test Bench Type	Schenck Dynas, asynchronous machine
Automation system	SRH STARS
Torque Measurement	GIF torque measurement flange
Cylinder Pressure Indication	Kistler KiBox, cylinder-individual piezoelectric sensors
Emission Bench	Horiba Mexa 7400D, certification-grade measurement of CO, CO2, NO, NO2, THC, O2
Fuel Flow and Conditioning	AVL 735S FlexFuel, including Fuel temperature and pressure conditioning units
Combustion Air Supply	Humidity-controlled
Combustion Air Measurement	ABB Sensyflow P

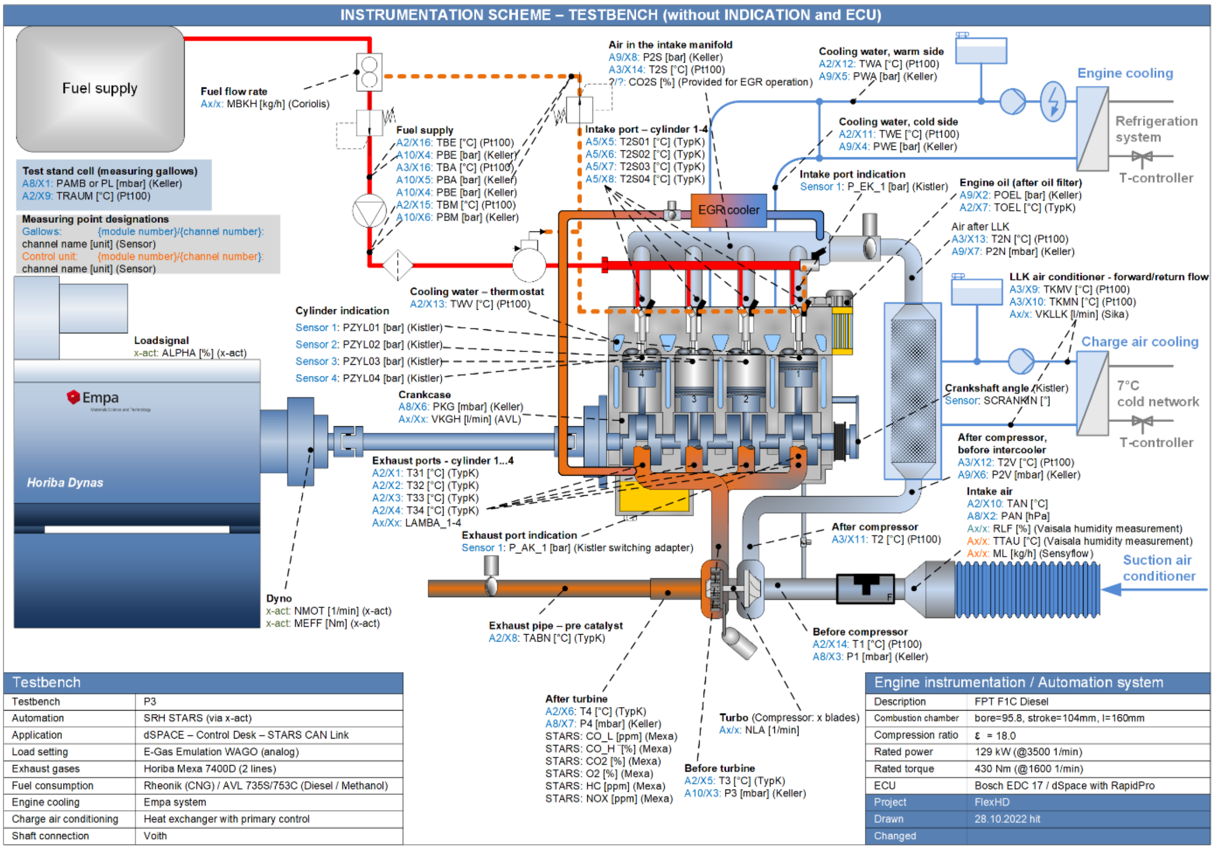

Figure 5: Schematic of the testbench and engine instrumentation

3 Procedures and methodology

The design and production of the variable valve train, the buildup of a rapid prototyping control environment as well as the buildup of a simulation environment are the key tasks in the initial phase of this project.

3.1 Design of the Variable Valve Train (VVT) System

The VVT system has been derived from the original Empa VVT valve train "Flexwork", which was successfully developed and operated for a classical spark ignition engine with a roof-top cylinder head desig. However the new construction "FlexHD" needed a lot of additional and partly unforeseeable engineering work. One reason is that this project deals with a diesel base engine and such engines have a flat cylinder head with perfectly vertical gas exchange valves. This, together with the need to hold a rather large injector in the center, gives a very tight space for the actuation mechanics for a fully variable valve train.

This engineering work was done mainly with the state-of-the-art industrial use Multiphysics 1D-imulation tool (Siemens Simcenter AMESim) and the design was done using 3D-CAD/FEM Software (Solidworks).

Typically, new steps were modeled and simulated first in AMESim and then half parallel the feasibility and realization was proven in Solidworks. For example feasible dimensions in terms of diameters and masses were fed back to the simulation.

The typical procedure is top-down: starting with simplified model elements, then proving with sophisticated near real model, for example:
- start with simple check valve model with simple "diode" behavior,
- later: detailed model with parameterization derived from the design execution (masses, geometries, spring stiffness, flow forces, dampening, etc.),
- then: if not working satisfactory adjust design parameters (diameters e.g.), simulate again.

AMESim also has the capability to simulate the generation of pressure and suction waves in the actuation fluid lines. This feature became more important as the found activation layout led to very high short term flows with the "flight time" of the valves being in the region of 2 milliseconds.

For specific part analysis the Solidworks FEM tool and for specific flow analysis questions the Solidworks tool "Flow" were used .

Manufacturing: The system is being manufactured in in the prototype workshop of FPT in Arbon, assisted by external companies for dedicated tasks. Some typical hydraulic parts (solenoids, check valves e.g.) will are being tuned and delivered by etavalve and electronics/sensor parts are designed/acquired by Empa.

3.2 Buildup of a Rapid Prototyping Engine Control Platform

For a fully flexible valve train design, there is no standard control hard- and software available from a Tier 1 supplier. For this reason, an own solution is being developed. The work necessary to build-up such a system can be summarized as follows:

- ✓ Definition of the control system requirements and selection of appropriate hardware components.
- ➢ Setup of the control system hardware and implementation of a control structure to operate the engine in its series production configuration. Comparison to the engine operation behavior with the production engine control unit.

- ❖ Stepwise adaption and extension of the engine control structure to include new actuators and sensors of the variable valve train, the water injection or the port fuel injection (some of these features are necessary for the FlexComb R&D project).
- ❖ Derivation of a supervisory control concept allowing the intuitive calibration for various engine configurations, fuels, and combustion concepts.

The development and calibration of an engine control unit with all its functionalities is a challenging and time consuming task. We therefore simplify it as much as possible. The control structure is designed to operate the engine on a test bench in steady-state. Any tuning towards fast transient operation as well as the implementation of extended safety features are neglected. Transient processes (such as the effect of hybridization) will be tackled numerically instead. Still a number of challenging tasks remain:

- ✓ The air path, consisting of a turbocharger with variable turbine geometry, high-pressure exhaust gas recirculation, and an intake throttle, needs to be controlled to accurately set the amount of EGR and the pressure in the intake manifold.
- ✓ A fuel pump and a pressure release valve have to be simultaneously actuated to control the rail pressure for the direct-injection of high-reactivity fuel.
- ✓ Up to 12 injectors need to be actuated depending on the engine crank-angle and with a precision of only few to less than a microsecond.
- ➢ The variable valve train contains eight solenoid valves and 16 lift sensors, all of which have to be actuated or evaluated depending on the engine crank angle.
- ➢ The complete engine contains a large number of actuators which often affect a number of engine performance parameters. The development of a strategy to intuitively operate it with various fuels and combustion concepts will be challenging.

Based on the identified control tasks, suitable hardware components were selected. Figure 6 shows a schematic of these components, interconnected to an engine control unit. It is based on the *dSpace* rapid control prototyping system *MicroAutoBoxII*, which consists of a real-time capable processor and a field-programmable gate array (FPGA), both with digital and analog interfaces. The FPGA is used to evaluate and generate crank-angle based signals and the processor is used for the time-based control and evaluation. A number of *dSpace* actuator drivers, referred to as *RapidPro* units, are used to operate all the actuators.

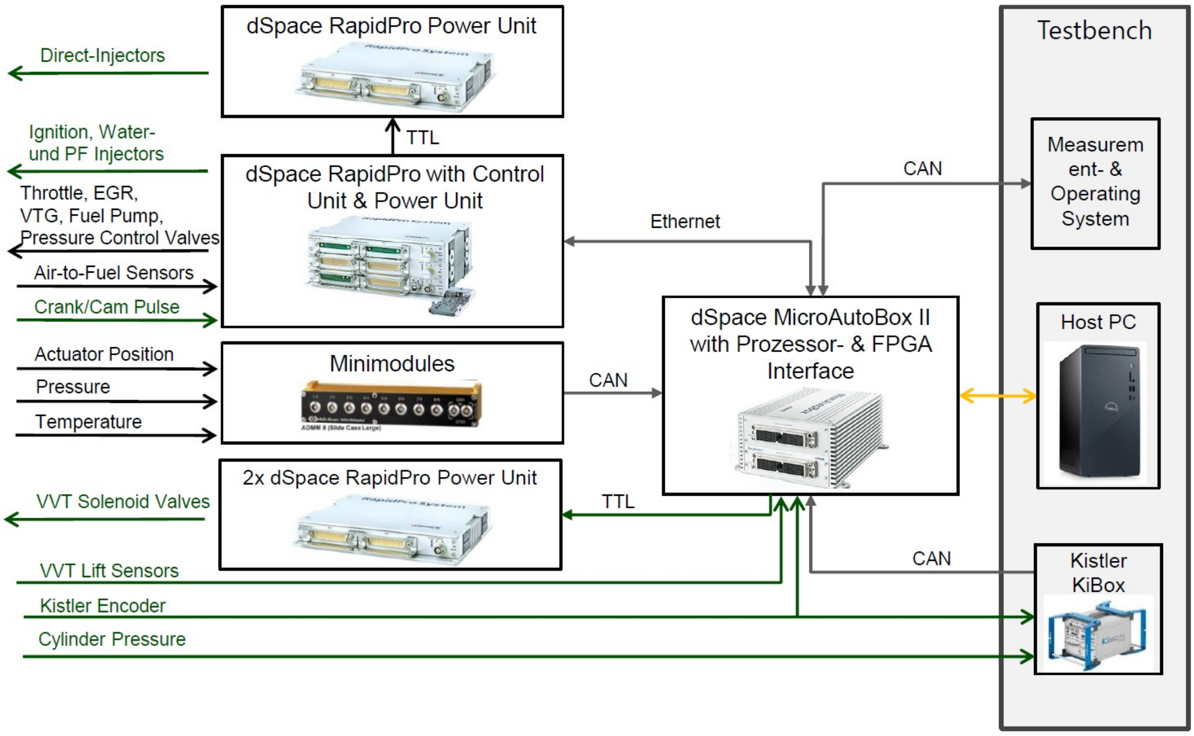

Figure 6: Hardware components selected to build an own engine control unit, consisting of a rapid control prototyping unit with a FPGA, connected to various actuator drivers and sensor evaluation modules. Green signals are crank-angle based, black signals are time-based.

A special feature of these *RapidPro* units is that they can directly generate crank-angle synchronized signals, used e.g. for the actuation of the injectors. Therefore, the control of the engine in its series production configuration can be realized without the use of the FPGA. Hence, to replace the series production engine control unit, we only have to develop software for the real-time capable processor.

3.3 Possible Combustion Strategies with VVT

Based on methodologies and tools described in the previous subchapters, the VVT will be put in operation and be optimized for different operating points as well as for the optimization of the full load behaviour. This P&D project focuses on classical diffusion-controlled combustion and will contribute to:

- Increasing the full load torque across the engine's speed range by around 5-15% by optimizing exhaust valve opening and intake valve closing [27].
- Increase efficiency of around 2-4% at moderate loads while keeping the classical diffusion-controlled combustion mode [28], [33], [30].

Examples of strategies to be implemented can be seen in Figure 7.

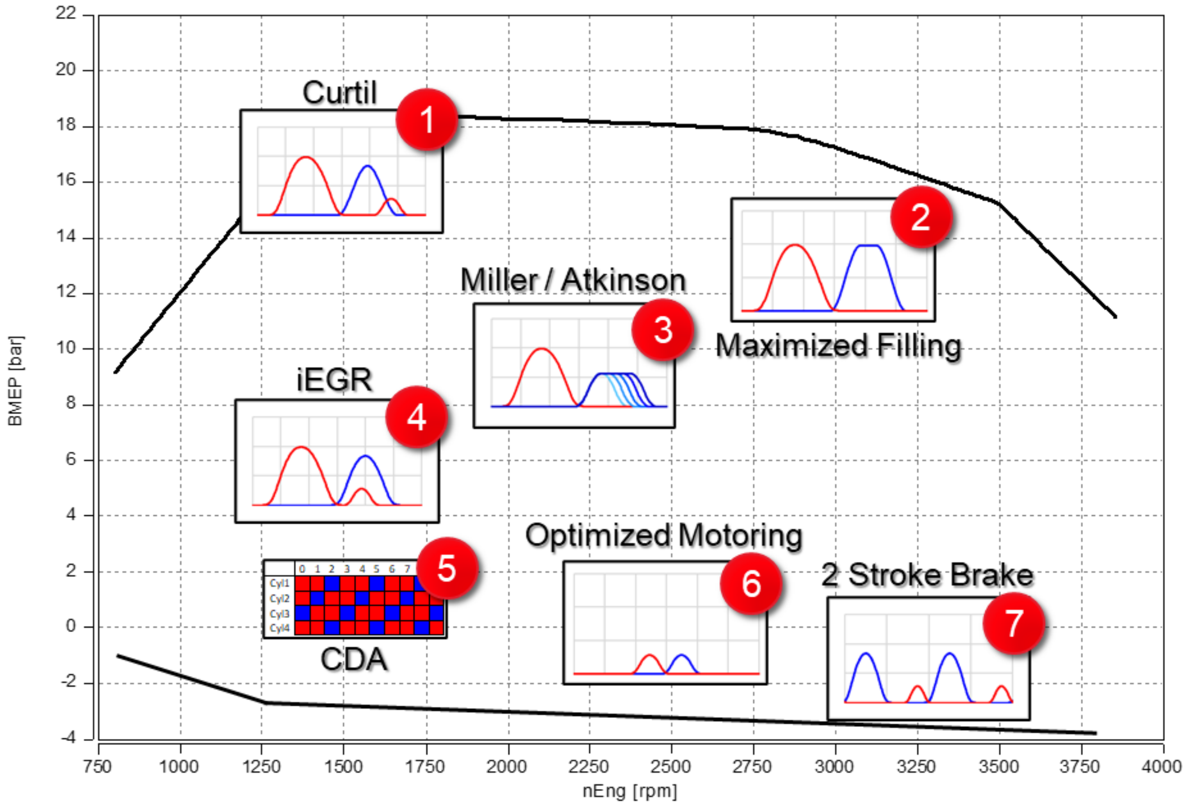

Figure 7: Possible engine operation modes, enabled by VVT

Seven different valve lift strategies were identified and will be investigated during the P&D project. A combination of the strategies can even allow alternative combustion modes as example Premixed Charge Compression Ignition (PCCI) what could be of interest for the separate R&D project.

1. Increase of low-end torque thanks to the so-called Curtil effect: The exhaust valve is opened again during intake stroke for a short time. This allows depending on the pressure waves in the exhaust manifold an increased virtual displacement. Different from other points along the maximum torque of the engine, the low-end torque is limited by available air and not by exhaust temperature or peak pressure.
2. Maximized filling at high engine speed: thanks to the capabilities of the VVT, valves can be closed faster and depending on the engine speed optimized for the inertia of the fresh air. This allows potentially higher air mass in the cylinder in the high speed, high load area of the engine map and therefore an improved tradeoff between power and efficiency.
3. Efficiency increase due to flexible valve lift and phasing: with variable valve train, the lift of the valve can be controlled and will be opened only as far as needed. Whereat with a conventional camshaft, the valves are fully opened also for low engine speed range. Also, it will be investigated, how external EGR and Miller cycle compete in terms of best BSFC during NO_x/Soot trade off.
4. Internal EGR for low loads: A reopening of the exhaust valve during intake stroke or a negative valve overlap allows a precise amount of internal EGR. This can be an enabler to keep the exhaust gas temperature as high as possible with reduced NOx emissions. The dilution of the combustion gas in combination with Miller timing is a possible enabler for PCCI combustion over a wider engine load range (to be investigated in a separate R&D project).

5. Cylinder deactivation (CDA) for lowest load: The fully flexible VVT system will allow dynamic cylinder deactivation for minimized fuel consumption with maximized exhaust gas temperatures by keeping the NVH emissions on an acceptable level.
6. Optimized delivery in motoring conditions: Long motoring phases are cooling out the aftertreatment system, leading to temporary high emissions in fired mode afterwards. With VVT, an optimal air mass flow can be set to minimize the cooling of the after treatment system, but to keep the turbine spinning on the desired level.
7. Engine brake: thanks to the capabilities of the VVT, a high performant two stroke engine brake can be implemented with limited additional effort. This is an important feature for heavy duty engines.

4 Activities and results

4.1 Design of the Variable Valve Train (VVT) System

The application of the Flexible Valvetrain for Heavy Duty (HD) engines brings up several challenges. One main design goal is to build a robust and still simple (and thus cost efficient) solution. Under this prerequisite a maximum of system capabilities and variability was searched to increase the attractivity of the solution and still give a maximum flexibility for this project, for the parallel R&D project FlexComb as well as for a further application at FPT.

Simplicity
According to these goals the team decided to work with one solenoid actuator per pair of valves only (meaning one solenoid for the inlet and one for the exhaust side of a cylinder). This in minimum allows common operation of a valve pair.

Engine brake capability
On today's Heavy Duty engines the so called «exhaust gas braking» or «compression braking » was improved a lot during the last decade by introducing special (and complicated) cam control mechanisms. The engine is being used as an «energy consuming compressor» and relieves the friction brakes during long or strong breaking phases. One highly sophisticated system is shown in Figure 8.

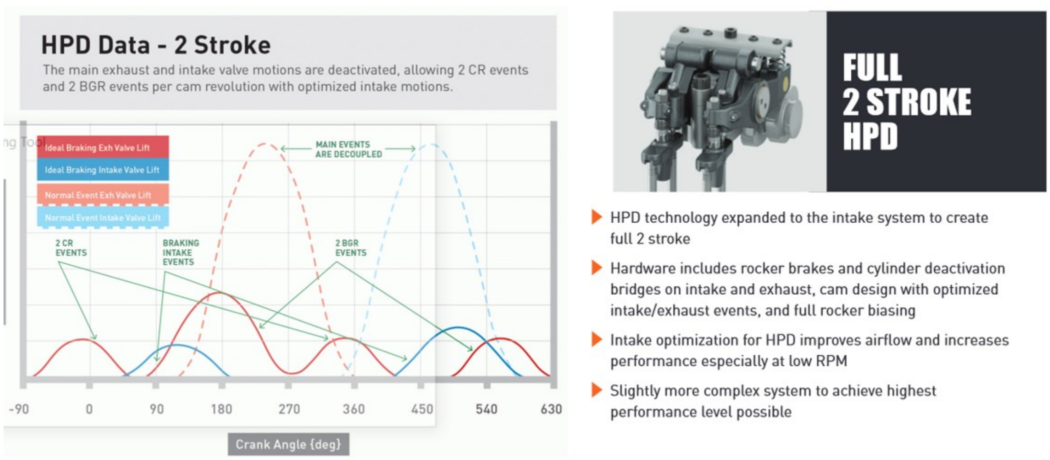

Figure 8: Principal of state of the art compression brake system on HD engines showing its complexity (source: Jacobs Vehicle Systems, 2-stroke High Power Density brake)

Achieving the same functionality with the new valve train would be highly appreciated. The difficulty to overcome here is the ability of the exhaust valves to open towards the end of a compression stroke to deload the cylinder pressure. To verify this capability of the FlexHD system the braking work (BMEP) was simulated in the 1D simulation tool «Simcenter AMESim» with a simplified engine cycle. The simulation showed which cylinder pressures would have to be overcome to achieve a certain braking work. Accordingly the system was laid out on the hydraulic side for cylinder pressures up to 30 bar – with about 500 bar on the hydraulic side (about 250 bar in normal non braking function). Figure 9 and Figure 10 show the in-cylinder pressure situations and the resulting brake torque levels, respectively.

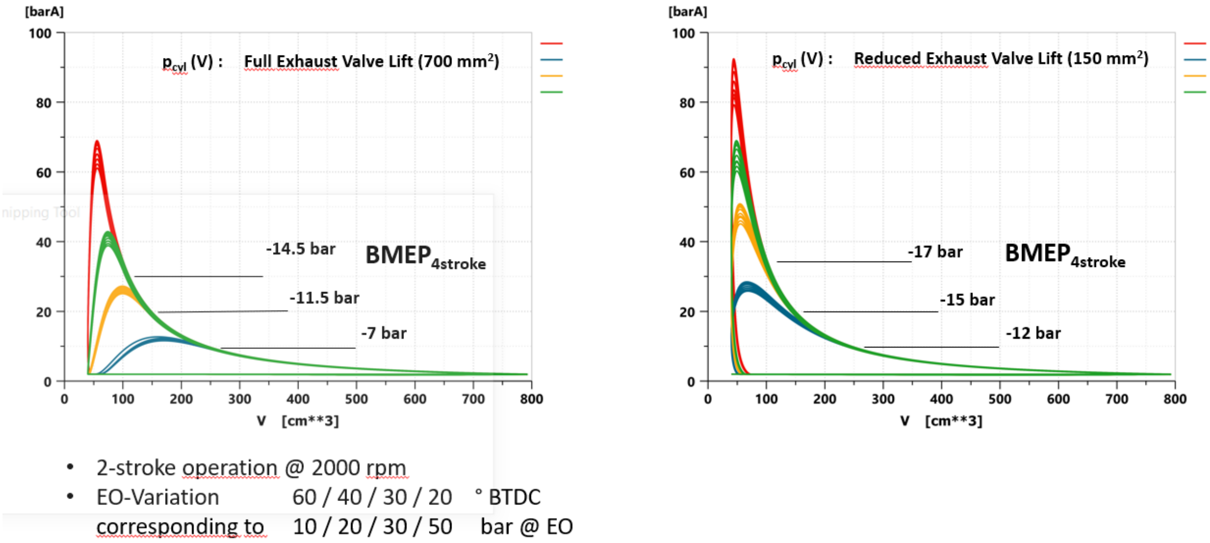

Figure 9: Simulated braking work (in brake mean effective pressure BMEP) in 2-cycle operation with FlexHD valve train (curves for 2 bar abs exhaust back pressure)

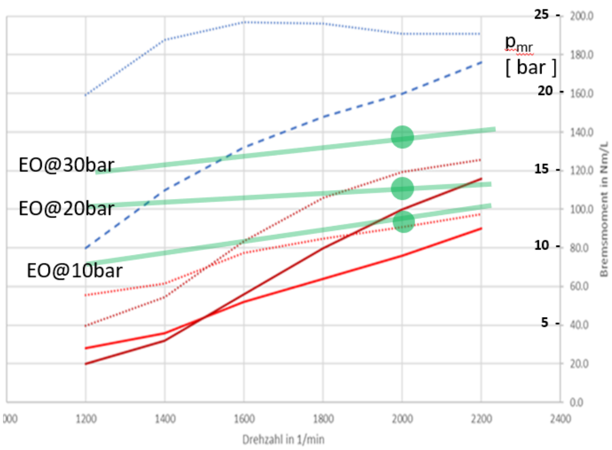

Figure 10: Simulated braking work resp. specific torque of the FlexHD-system (green) in comparison to various todays HD compression brake solutions (red and blue)

Space restrictions

One of the most challenging space restriction is the fact, that on HD engines all valves are placed parallel to the cylinder axis around the central injector (direct injection) or the central ignition system. The high compression ratios and central piston bowl with quench zone typically do not allow any angular arrangement (on the test engine the distance from piston crown rim to cylinder head is only 0.8 mm when the piston is at top dead center).

To cope with this difficulty in a first approach a rocker arm was designed which allows the arrangement of the hydraulic drive piston in some distance to the valves. Rocker arms are the standard solution on cam driven engines. Usually there is one rocker arm per valve. For FlexHD a specific rocker arm has been designed and optimized by FEM that spreads the force of the solenoid driven actuator to the two single valve stems. The additional equivalent mass of this rockerarm corresponds to less than 20% additional mass which would result in an acceptable 10% longer valve "flight" (movement) time.

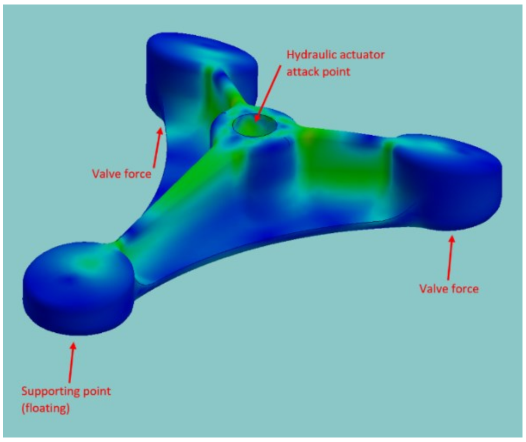

Figure 11: FlexHD VVT variant for the F1C with a rocker arm

Chosen solution without rocker arms

As an alternative solution, a variant with two single actuator pistons (instead of the rocker arm and one central drive piston) was investigated. In this case the two actuator pistons are hydraulically controlled by the central solenoid valve but the lift control is done by separate worm drives. Getting rid of the rocker arm gives the additional advantage to eliminate side forces on the gas exchange valves. This not only reduces friction but also omits the need to lubricate the contact areas. A lubrication with a camshaft solution in no problem as lubrication oil is anyway widely spread across the contact areas of the camshafts. The electrohydraulic solution, however, leaves the cylinder head basically oil-free and omitting the need for a valve shaft lubrication simplifies the overall system.

Figure 1 shows the tight chosen solution from a top-view. The space restrictions between the fuel injector in the center and the gas exchange valves (they are below the blue screw heads) are clearly visible.

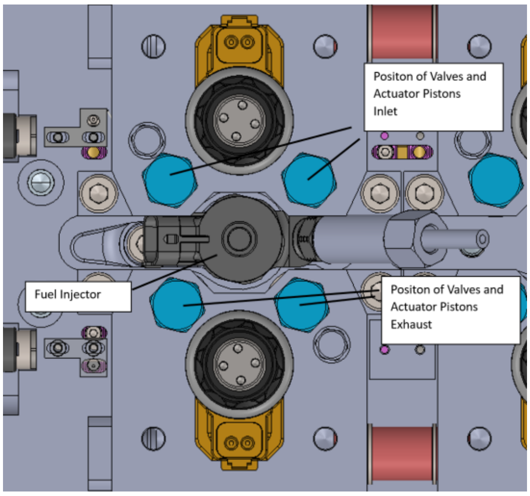

Figure 12: Top view (in cylinder axis) showing the very narrow space between the injector and the gas exchange valves

Worm drives, which are very precisely turned by stepper motors, control the slanted edge pistons. This solution allows individual lift control or even complete deactivation of one of the valves of a pair. This solution with valve-individual-control was chosen by the project team (see Figure 13), as it offers additional swirl control possibilities and demonstrates best the system capabilities. In so far the feasible but less flexible solution with a special rocker arm was overruled.

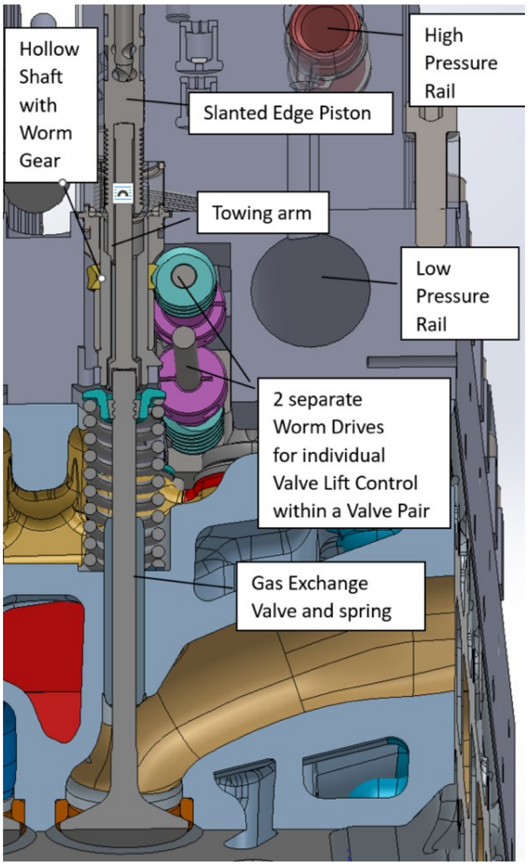

Figure 13: Cross-section through the plane of the gas exchange valves

Unification of inlet and exhaust side
The control robustness of the hydraulic system was laid out in detail with the 1D multiphysics tool AMESim. In comparison to the Empa's earlier FlexWork system the closing response on the solenoid has been optimized.
Both sides «inlet» and «exhaust» were designed to work according the same lift control system, which is a novelty (usually, the exhaust side has to guarantee opening versus comparably high cylinder pressure, while the intake side does not have this problem). This will allow working with the same pressure on both sides which means that the system needs only one high-pressure hydraulic pump. The very steep closing ramps will be of advantage on both sides: on the exhaust side near TDC and on the inlet side for controlling the air mass with a minimum of losses.

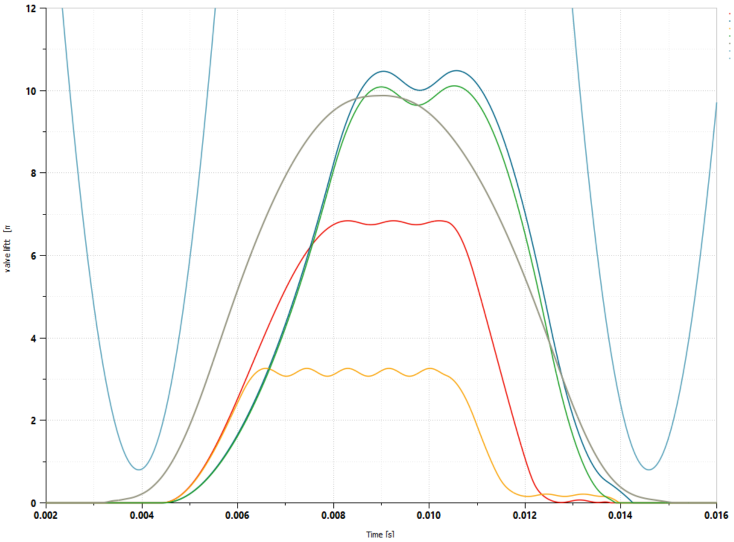

Figure 14:Valve lift curves vs. time at nominal engine speed [grey : camshaft-driven serial-production solution, light blue: piston position relative to the valve in closed state (just shifted in time to see the gradients), red/yellow FlexHD (partial lift of 7 mm/ 3 mm), blue/green FlexHD (maximum lift against 13 bar in-cylinder pressure)]

Lift measurement
It was a challenging task to find a fast and compact lift measurement device which also copes with the space restrictions and the temperature levels present in the cylinder head of a running engine. A compact solution was found which uses a chip integrated circuit sensor – developed originally by CSEM – which does not need a magnetic counterpart. It only needs teeth on the actuator pistons (Figure 15). This sensor allows better than 0.05 mm lift resolution and is able to follow the high valve velocities of up to 10 m/s. Remark: in a serial-production design, simplified sensors or position switches would be needed – this precise sensor setup is only deeded for R&D.

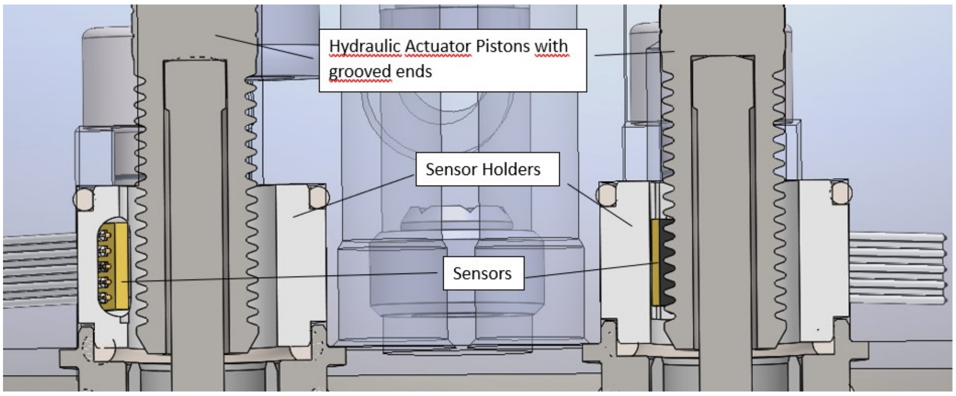

Figure 15: Lift measurement setup using a sensor-chip (yellow) and a teeth-counterpart on the actuating piston

General design

The general design was laid out as a base plate with eight nearly identical actuator blocks mounted on top (Figure 16). The base plate is designed in aluminimum and serves as carrier for the large low pressure (LP) channels as well as the lift adjustment means, but it also seals the bottom part of the cylinder head.

This layout keeps the possible demands of a serial-production solution in mind meaning for example that the elements can easily be exchanged or serviced.

As the high pressure (HP) will be substantially high (up to 500 bar) particular in engine brake mode it is conducted within short steel pipe pieces between the actuator blocks.

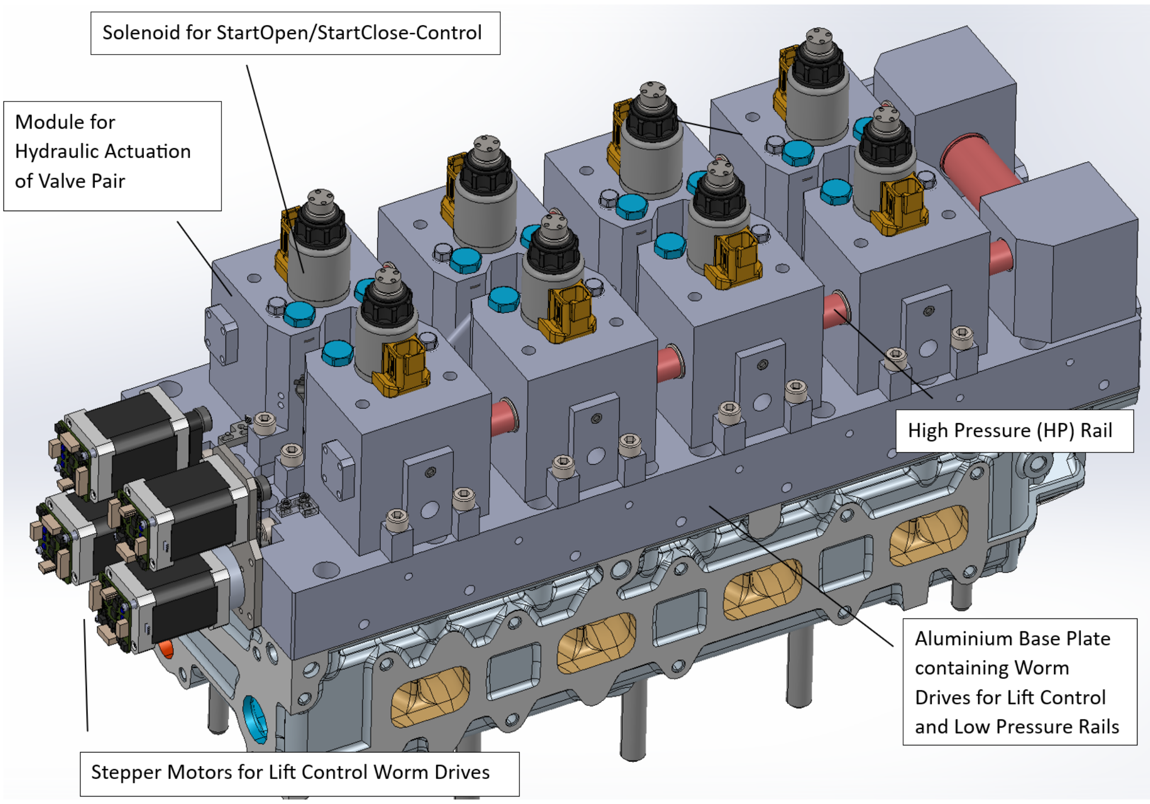

Figure 16: Actual design with a base plate and modular actuator blocks.

4.2 Characterization of the Serial Production Engine

As a reference, the serial production engine has to be characterized at Empa in its actual state (i.e. serial-production engine control, no changes in components). In week 42/2022, the full characterization of the serial production engine has been completed. Afterwards, a measurement data analysis and engine characterization was conducted. As an example, Figure 17 and Figure 18 show high-resolution data from the indication measurement (i.e. values are measured versus the engine's crank position). Figure 18 focuses on the combustion phase with two pre-injections and one main injection event. In addition, it shows the calculated heat release analysis which is an important basis for later, when the influence of the valve control on combustion will be studied.

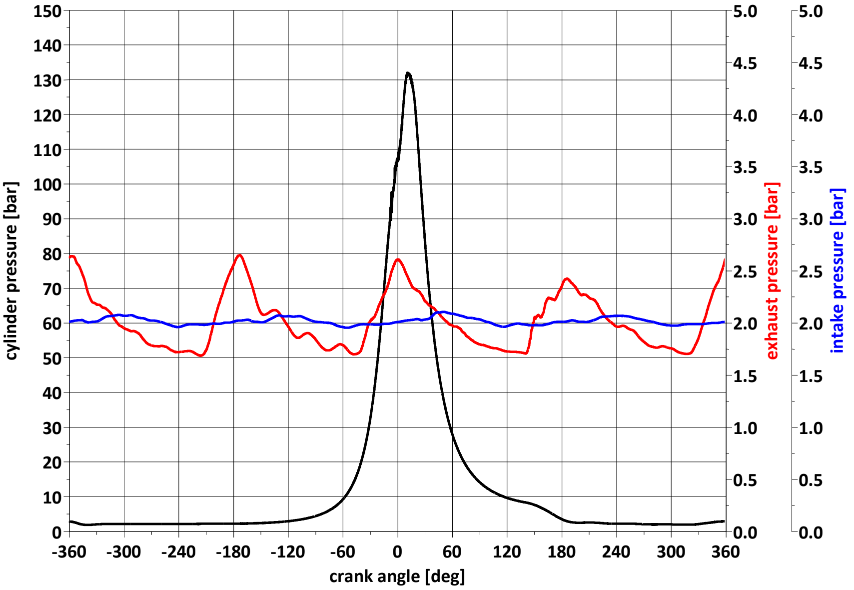

Figure 17: Example of the measured cylinder, intake- and exhaust port pressures versus the engine's crank angle

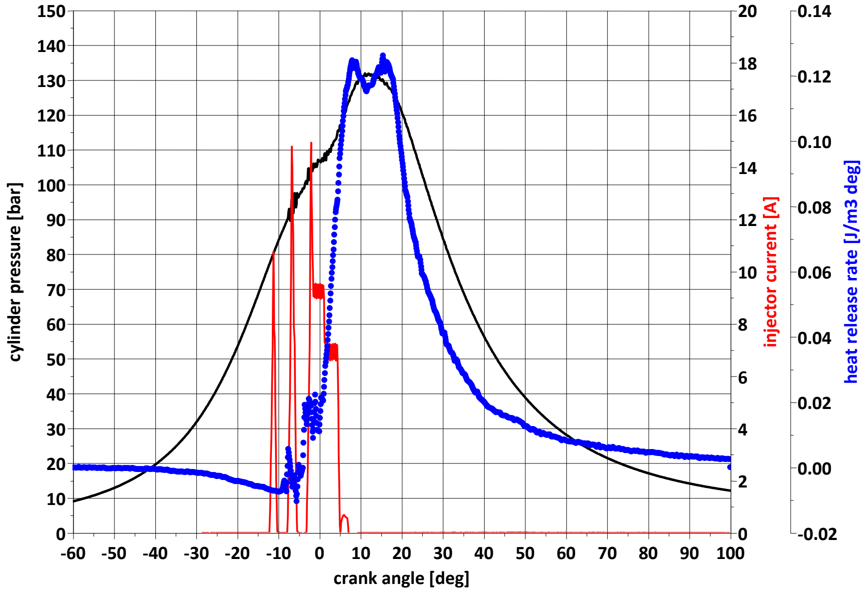

Figure 18: Example of the measured cylinder pressure, the measured injector current and the calculated heat release rate.

Figure 19 shows the measured fuel flow across the whole engine map – from very low load up to the engine's full load torque.

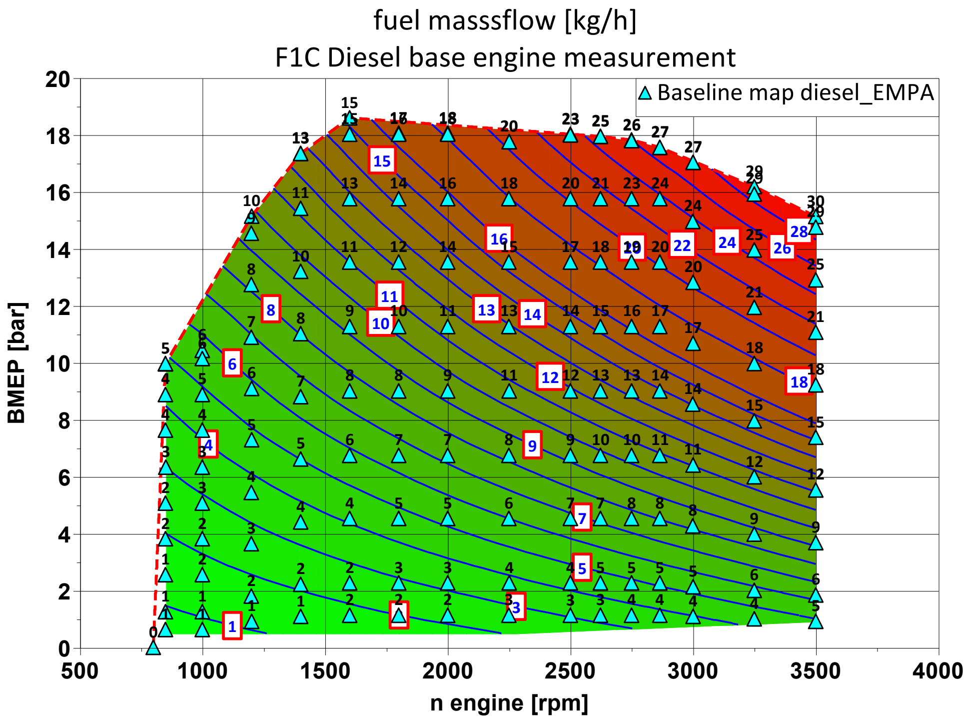

Figure 19: Measured fuel flow map (the triangles represent all measurement points).

With this experimental campaign, the engine which will be drastically modified later, has been fully characterized in its serial production state.

4.3 Operation of the Engine with the Rapid Prototyping System

Once the engine was fully characterized with the series production ECU, the next step is to replace and reproduce the engine behavior with the own control environment, based on rapid prototyping control (RCP) hardware. The components depicted in Figure 6 have been acquired and set up as shown in Figure 20. With this setup, every engine sensor and actuator previously connected to the series-production ECU, is now connected to the RCP unit and available for the own engine control development.

With the objective to first re-create the engine operation behavior of the series production ECU, a control structure close to the one implemented in the series production ECU has to be developed. Together with FPT, the control structure illustrated in Figure 21 was identified and implemented as a real-time process. A torque set-value, related to the load demand, is used together with the engine speed to read set-values for the rail pressure, the fresh air mass flow, the boost pressure, the indicated mean effective pressure (IMEP), and the center of combustion (CA50) out of calibration maps. These set-values are then used in a high-level control structure to derive the injector actuation, the reference currents for the rail pressure actuators and the reference positions for the air path actuators. The injector actuation is derived for each cylinder individually. Feedback-control is used to achieve the desired IMEP and CA50. Rail pressure and air path actuators are then feedback-controlled to these reference values.

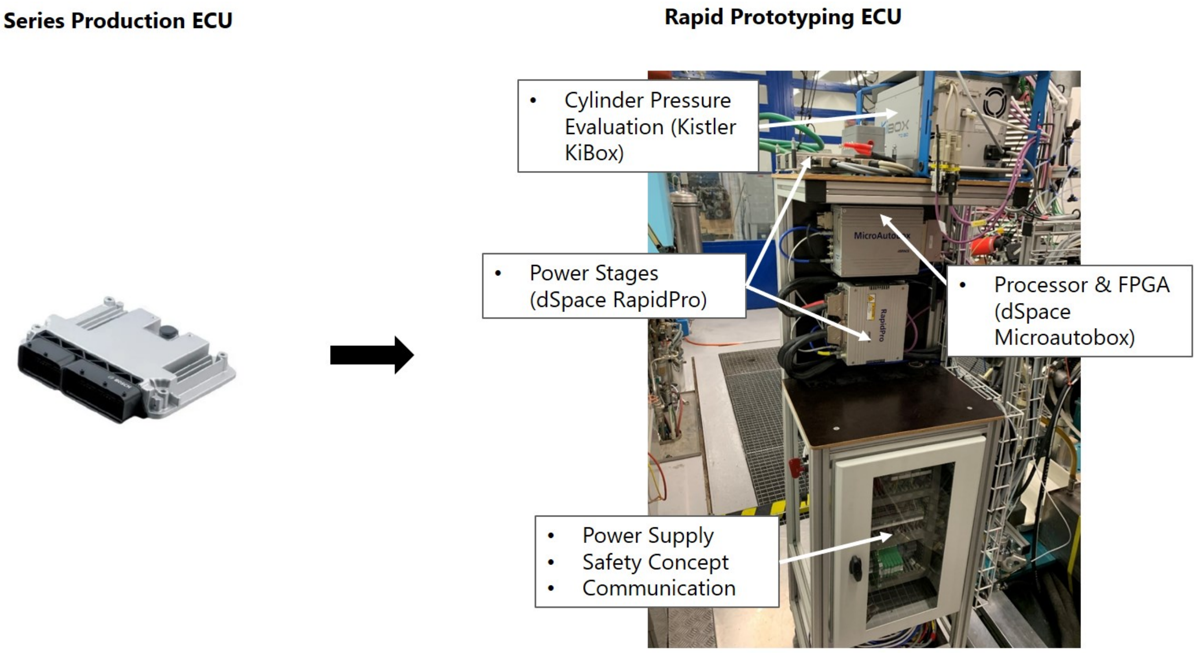

Figure 20: Replacement of the series production ECU with an own rapid prototyping ECU consisting of the components depicted in Figure 6.

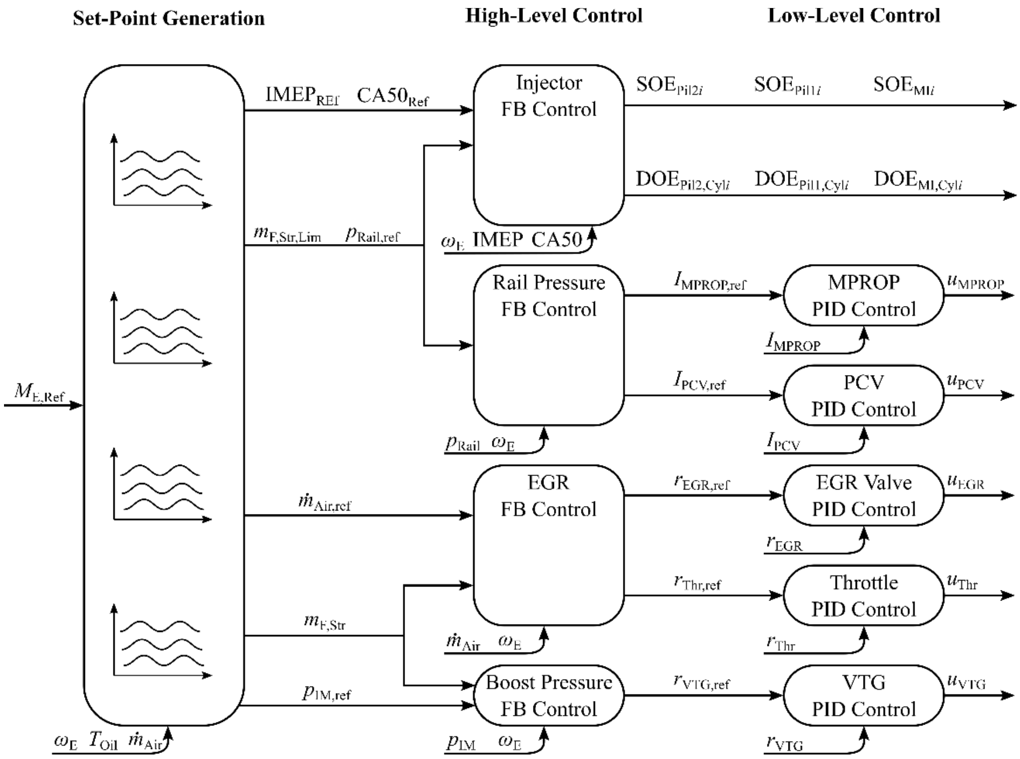

Figure 21: Initial control structure, designed to operate the engine in its series production configuration.

This software structure was implemented and parameterized in the beginning of the year 2023. A challenging task was the development of a common rail pressure controller, able to track the reference pressure fast and accurately using two actuators simultaneously.

After several iterations of parameter tuning, a full characterization of the engine with the RCP control unit (referred to as "own") was conducted. The derived results were then compared to the measurement data derived with the series production ECU. As an example, Figure 22, shows a comparison of the engine efficiency. As illustrated in the bottom left plot, the achieved efficiency is nearly identical for any measurement data point of the engine map. The mean absolute error is 0.07%$_{abs}$ only. At an engine speed of 2750 rpm at full load, the largest discrepancy in efficiency is measured. For this operation point, Figure 22 shows the recorded data of the engine operated with the series production ECU in black and the data of the engine operated with the RCP ECU in blue. A comparison of the illustrated data reveals that every measured value is nearly identical. The discrepancy of 0.5%$_{abs}$ in efficiency is assumed to be the result of a series of small differences in air path and combustion parameters.

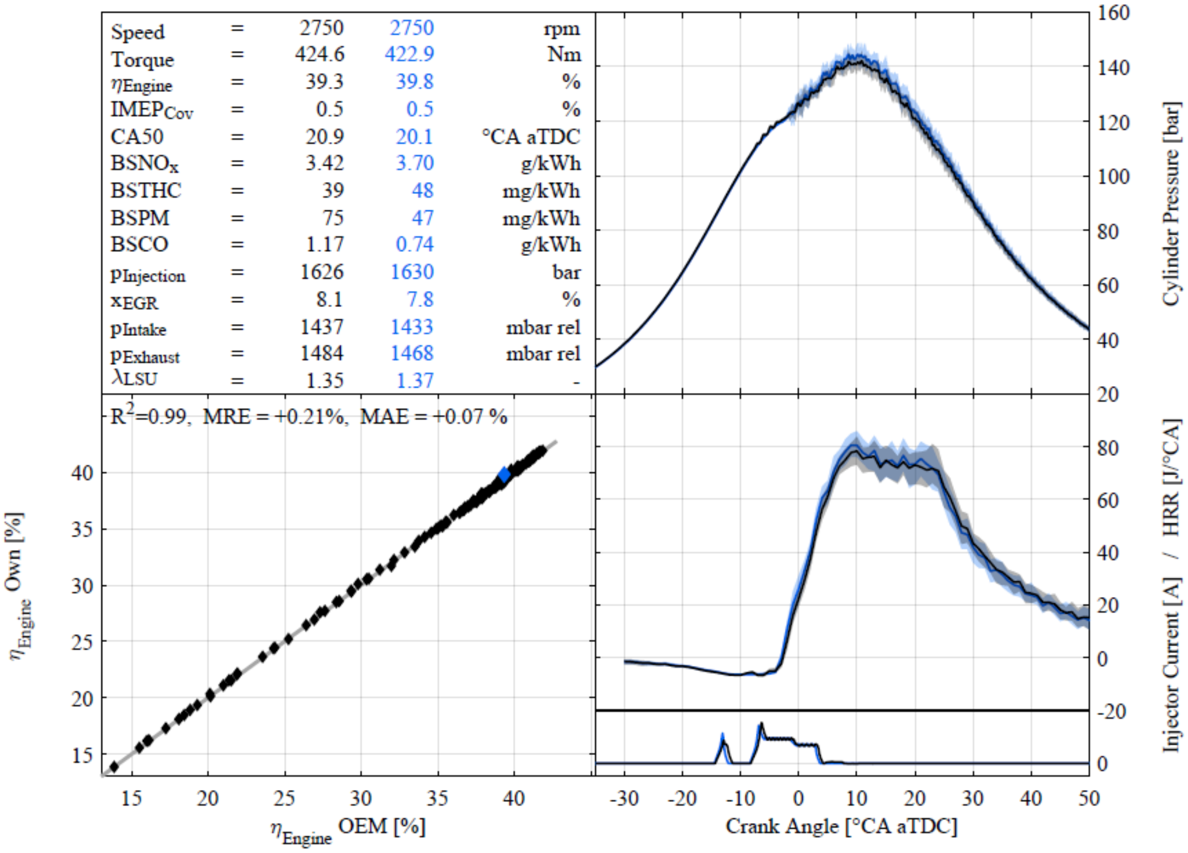

Figure 22: Comparison of the engine efficiency achieved the own ECU (blue), compared to the engine efficiency achieved with the series production ECU (black). The bottom left plot shows an efficiency comparison of all measurement data points, the remaining three plots compare the two data points with the largest efficiency discrepancy.

As for the efficiency, Figure 23, shows engine-out NOx emission of both the setup with the series production ECU and the RCP (own) ECU. While the trends are still very similar wit an R^2 value of 0.96 and a mean absolute error of 0.13g/kWh, individual discrepancies can take higher values. Again, the operation point at which the largest difference occurs is shown in more detail. Here, the discrepancy presumably originates from a difference in the injected fuel mass for pre-injections.

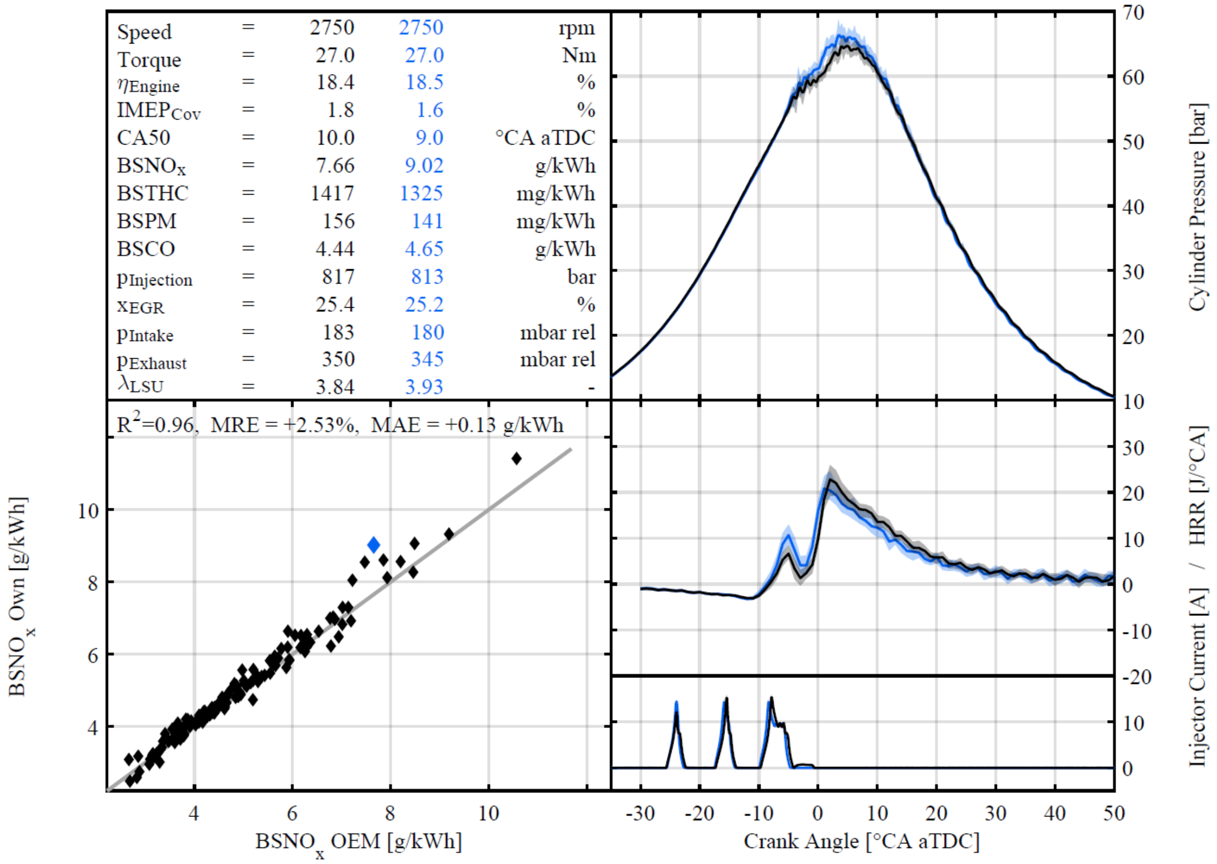

Figure 23: Comparison of the engine-out NOx-emission levels achieved the own ECU (blue), compared to the NOx emissions achieved with the series production ECU (black). The bottom left plot shows a NOx emissions comparison of all measurement data points, the remaining three plots compare the two data points with the largest NOx emission discrepancy.

The complete evaluation conducted shows that the engine operated with our RCP ECU can reproduce the engine operation with the series production ECU with a satisfactory level of accuracy. We have therefore demonstrated our hardware and software adaptions do not limit the engine performance in any way. Also, we have set the perfect pre-conditions for the functionality development and commissioning of the variable valve train.

5 Evaluation of results to date

5.1 View of FPT

FPT is glad to be part of the FlexHD project as an industrial partner. The discussions in the last months about the VVT system design were highly interesting and led also to animated debates within the company.

Unfortunately, CFD simulations are no longer possible on our side of the team due to staff departures. At the moment, we do not see an urgent need of engine simulations and therefore this topic will be handled with low priority.

FPT is looking forward to seeing the system running on the F1C engine and demonstrating the anticipated benefits in the coming months on diesel and afterwards with renewable fuels.

5.2 View of Empa

The project runs well from Empa side. The serial-production engine could be successfully characterized, the rapid-prototyping system could be set-up and programmed, the engine could be successfully operated with the rapid-prototyping system. We have no doubt that the project will progress content-wise as planned.

5.3 View of etavalve

Etavalve had a lot of challenges to convert the initially in the FlexWork project developed valve train to the needs of Heavy Duty Engines which are: the narrow arrangement of the 4 gas exchange valves per cylinder in the cylinder head, the need to open the exhaust valves against high in-cylinder pressure, and the expectation of a competitive (=strong) inherent compression brake function (which functionality was verified by a simplified simulation of hydraulics and engine cycle).

By looking for a design variant without rocker arms we found a solution for individual valve lift control (capable to part or complete deactivation of one valve of a pair) – while the number of control solenoids stays constant. This solution was reviewed and highly appreciated by the project team as it enlarges possibilities of influencing swirl/turbulence (also with respect to the following R&D project), may further improve the hydraulic efficiency and rises the attractivity of the new system in general.

We are now focusing on finishing the drawing set rapidly with additional manpower while production of parts at FPT already has started.

6 Next steps

The next step is to create production drawings of the VVT (etavalve). The VVT system will then be manufactured by FPT Motorenforschung in Arbon. The assembly and first test of the VVT system in unfired configuration will then be performed by etavalve and Empa.

Once this will be done (estimated for early 2024), the extensive experimental phase will begin.

7 National and international cooperation

None (other than the close cooperation between the project partners).

8 Publications

None yet.

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