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Teze disertační práce

Hybrid Vehicle Powertrain with Range Extender

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1. General Introduction and Overview

1.1. Current State of Contemporary Transport System

Transport has become a major sector of the national economy and plays an essential role in the contemporary world, which depends completely on it. In its traditional meaning, the current transport system relies on energy derived from fossil fuels. Without doubt, one of the most significant achievements of modern science is the invention and subsequent development and innovation of the internal combustion (IC) engine as a primary power source for all different kinds of vehicles. In particular, motor vehicles make possible the free movement of people and goods all around the world, and therefore contribute to the social development and economic growth of modern society. [27, 50]

The human population is growing at a fast rate, which is also being reflected in the growth of the number of passenger vehicles. These numbers are still rising quickly with the continual process of world urbanisation and globalisation. On the other hand, this significant number of motor vehicles has a negative impact on the natural environment and human life and leads to many problems. The main reason is hidden in the high reliance of the present transport system on fossil fuels. The atmospheric pollution caused by emissions from burned petroleum products leads to poor air quality (air pollution), changes in the Earth's climate, global warming or exhaustion of crude oil resources.

1.2. New Strategy for Low-Emission Mobility

Nowadays, modern human society is striving for a sustainable future. Transport and mobility are essential for anticipated sustainability. However, in the view of a longer-term perspective, the current system for personal transport does not correspond to this idea. The reasons for that have been already mentioned, i.e. the total energy supply for the sector comes mainly (approx. 90%) from fossil fuels (limited source) and the harmful emissions from burning them. That is why a new, more favourable for economic development and more environmentally friendly transport model has to be developed and introduced. It is necessary to focus on efficient, safe, clean, and smart mobility and, at the same time, outsmart future obstacles like oil scarcity, traffic congestion, reduction of CO_2, pollutant emissions, etc.

The new European strategy for low-emission mobility was approved in July 2016 in order to ensure Europe's competitiveness and responsiveness to the incessantly changing transport and mobility demands. The new EU legislation is an important step forward in the effort to successfully reduce GHG emissions and the total energy consumption. It is very important to develop new technologies to improve the fuel efficiency of conventional vehicles.

In recent years, research and development in the automotive industry has been focused on efforts to improve transportation efficiency, safety, and cleanliness. Different solutions were proposed as alternatives or more likely as a supplement to conventional motor vehicles, such as hybrid and electric vehicles.

1.3. Summary and Global Aims of the Thesis

The internal combustion engine is the most commonly used power source in motor vehicles, and the situation probably will not change significantly in the near future. However, further measures are needed to increase the overall efficiency and fulfil new, stricter and more demanding emission standards.

It is essential to push forward the research process of engine and powertrain systems and to continue the search, design, and development of new solutions for a wide range of applications ready to achieve new goals. An important step is the development of innovative, functional, and reliable technologies for engine aftertreatment, fuel systems, air/fuel mixture (cylinder charge) formation, etc. The development process has to be flexible and adapt quickly to continuously changing requirements and demands. This can be achieved by the utilisation of the experience and knowledge gained in the design and development of IC engines in combination with a wide range of advanced technologies, available resources and development capabilities, as well as advanced and efficient computer-aided design approaches and methods based on analysis and simulation. This will help to develop new innovative ICE and powertrain concepts for the future, e.g., alternative fuels and hybrid ones.

The continual process of electrification of vehicle powertrain systems leads to the implementation of different hybrid-electric technologies. In modern hybrid electric vehicles (HEVs), which are becoming more and more popular, IC engines are also the main option for a primary power source. In these vehicles, the IC engine is joined together with an electric generator, an electric battery, and an electric motor. The utilisation of the IC engine in automotive hybrid systems requires a different manner of design, control, and operation in comparison with that of conventional motor vehicles (MVs). The IC engine can run in a high-efficiency range for a longer time period (steady-state) and usually there is no need for a fast (transient) change of operating mode. Generally, these IC engines are not designed and developed separately for this application. They are often based on conventional IC engine series. However, it is desirable to continue with research and development in order to achieve an improvement in the overall efficiency. All effort is focused on the transition to fully EVs. In any case, vehicle electrification still presents a huge technical challenge with a lot of questions and unknowns, and the future course of this process remains, for now, uncertain. [27].

2. Current State of Knowledge

2.1. Electrification and Hybridisation as Alternative

2.1.1 Modern Electrified (Electric and Hybrid) Vehicles

The most common conventional motor vehicles (MV or CMV) powered by an internal combustion engine (ICE) rely on a highly energy-dense petroleum-based (fossil) fuel as an energy carrier. It offers excellent performance together with a great operating range (mileage or travelling distance). Despite this fact, the CMV has, from today's point of view, some significant weaknesses and disadvantages, such as insufficient fuel economy and a not negligible environmental impact from harmful exhaust emissions. [27]

In contrast, electrified propulsion systems are supported by electrical energy coming from electrochemical or electrostatic energy sources (electric storage batteries). They use a minimum of one electric machine as a traction motor for full or partial propulsion of the vehicle. The most common alternative type of vehicle, i.e., electric vehicles, offers some advantages over the CMV. In particular, there is higher energy efficiency and a lower environmental impact (measured on a local scale, see 1.1.2). In comparison with CMV, the overall performance of the EVs is much more limited, especially the operating range, time needed for energy renewal (battery recharge), overall weight and cost. The reason for this is hidden in the significantly lower energy density of bulky and heavy electric batteries. [27]

A hybrid vehicle (HV) is one that has more than one powertrain and uses a combination of two different types of energy sources for propulsion (no more than two, due to the rising complexity). Different feasible concepts are available, but the most common are solutions using IC engines and electric motors or fuel cells and electric motors. According to the particular powertrain architecture, both power sources can supply one or two independent propulsion systems (e.g., series vs. parallel HV).

2.1.2 Issues of Hybrid Powertrain Units with Range Extender

Definition of Range Extender, Reasons for Introduction, Concept Description

These days the interest in alternative fuel vehicles is growing rapidly. In particular, battery electric vehicles (BEVs), which also belong to this category, are becoming again more and more popular for different reasons. Since the very beginning, more than a century ago, the available technology, manufacturing processes, and human knowledge have changed significantly. Thanks to these prerequisites today, it is possible to develop and produce far better and more reliable electric-powered vehicles with significant improvements in performance, efficiency, and travel (driving) range.

Anyway, the range autonomy of pure EVs is still one of the major disadvantages and obstacles to great success, together with the higher price. BEVs have a limited range, i.e. they can travel less distance in comparison with conventional vehicles. It does not depend only on the vehicle's speed, trip distance, track profile, weather conditions, etc., but also on the usage of heating and climate control, lighting, and any other vehicle equipment on-board powered by the electric battery. In addition to the insufficient strength of the battery systems, the electric infrastructure for charging EVs is very sparse and needs an improvement. A refinement of the battery technologies to lower the price, reduce the weight, and increase the capacity. However, this is a long-term process requiring further research and time.

An interesting and more accessible solution to the issue of outsmarting the limited driving range can be achieved by a discreet modification of the pure battery-electric powertrain. The electric vehicle is supplemented additionally with an auxiliary power unit (APU, a secondary power source), commonly called a Range Extender (REx), which is used exactly to extend the reachable travel range to a more acceptable limit by supplying the battery system with electricity on the road. This solution allows reducing the total capacity of the electric battery to the minimum needed for a specific use (e.g., urban operation) and thus reducing the price and weight of an electric vehicle. The remaining energy needs (e.g., occasional extra-urban operation) of the vehicle are covered by the range extender. Thus, the newly emerged concept of an electric vehicle with an extended travel range represents a distinctive type of hybrid powertrain. The main difference compared to the conventional types of hybrid vehicles is the primary energy source, which here is the electric battery, and the propulsion is purely electric.

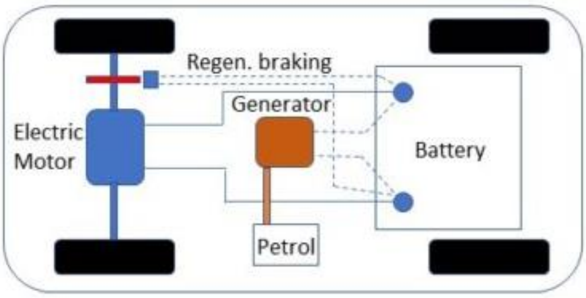

Fig. 1 A scheme of extended-range electric vehicle EREV

REx consists of a secondary fuel-based power source (usually a small heat engine as a fuel convertor) that drives a mechanically connected electric machine (operating as an electric generator – EG) in order to supply (charge) the battery system of the vehicle and the electric motor with electricity. The unit transforms the chemical energy from the fuel, which is released as heat energy during combustion, into mechanical energy that is afterwards transformed into electrical energy by the generator. There is a variety of different types of thermal engines, but the present doctoral dissertation is focused on reciprocating ICE. There is no mechanical link between the ICE and wheels and it can be installed anywhere. [34]

Description of Operating Principles of EV Powertrain with REx

The vehicle architecture (layout) is very similar to that one of the series and plug-in hybrids, with all its advantages and disadvantages. It is clear the role of the REx unit is to increase the EV travel range to a more acceptable level when it is necessary. It runs only when the battery has reached a certain critical level of charge, and then it helps the vehicle get to a charging station for recharging the battery. However, in most situations, this device serves only as a safety measure to eliminate range anxiety (i.e., to stay broken down with a flat battery).

In fact, the EREV is an electric vehicle, but at the same time, it is also a hybrid electric vehicle based on the series powertrain layout. The primary power source (primary mover) is the traction electric motor and electric battery, whereas the secondary is the auxiliary power unit (APU) – the range extender, which means the pair of IC engine-electric generator. If there is enough energy stored in the battery system, the EREV operates as a pure electric vehicle. The APU is then activated in a situation when the battery is almost flat (depleted). It is reasonable to operate the vehicle mostly in the electric mode, which requires a regular battery recharge from an external source (e.g., a charging station or wall power plug) at a time when the vehicle is not in use (at night, during work day, etc.). The battery system must be designed to provide power for daily driving (a range of ca. 50 km), but at a price as possible. According to the latest data, the daily travel distance in European countries averages from 40 km (in the UK) to 80 km (in Poland or Spain). This yields a suitable BEVx configuration – a small vehicle with a small storage battery (allowing lowering the cost, as well as the weight) with a capacity sufficient to cover daily driving in pure electric mode. The APU, a backup energy source, will be involved in case of emergency to reach a charging station or to ensure occasional longer journeys. It is clear that it presents an excessive weight at the most of the time. That is why the REx unit should be small, light, and affordable. Most of the time the vehicle runs in a pure electric mode and the operation is very quiet and comfortable. That is why a significant emphasis is also placed on the noise and vibration properties. [34, 52, 64]

General Requirements for Range Extender Unit

A competitive range extender unit for an electric vehicle should meet all requirements and demands. This is a much more complex issue than it appears because it is not just about driving. The electric energy from the storage covers all the vehicle. As a result, the vehicle range varies significantly. The range extender unit can significantly affect the range of vehicles.

***Specific Requirements and Characteristics for Range Extender Unit*:**

• **size and dimensions** – small and compact, allowing optimal installation in electric vehicle; mostly single and twin configurations, but also three-cylinders; inline, V-type, flat; displacement up to 1,0 litre;

• **weight** – as low as possible, usually around 50 to 60 kg, since most of the time it is only an unnecessary weight. Depending on the EREV concept, the vehicle is equipped with a REx to extend its range without changing the battery system, or the capacity of the battery is reduced and a REx unit is installed, when the total weight (smaller battery + REx unit including cooling and controlling system) should be lower that of the initial BEV battery;

• **cost** – low as possible, for development and production – up to 1000 Euro per unit; simple and proven technologies;

• **output performance** – in general limited – narrow speed range, but optimal for REx application, around 20 kW to 35 kW at a constant speed to ensure battery recharge and travel range extension; (maximum output performance is provided by the electric drive only); easy start end stop;

• **efficiency** – as high as possible; optimised with regard to required power, low fuel consumption and emissions;

• **emissions** – depending on the concept, the REx is not expected to operate frequently in start-and-stop conditions (during real-world or legislated driving cycles). Therefore, proper thermal management of the engine and exhaust system is needed to control the emissions;

• **superior NVH characteristics** – quiet operation, low vibrations (balance of inertia forces), noise insulation and dampening;

• **optional equipment** – selected at a client's request. [29, 31, 39, 60, 61]

2.2. Internal Combustion Engine for Range Extender Unit

Since the fuel converter in a REx unit can operate in its optimal efficiency area, independently of vehicle speed (due to the lack of mechanical connection), almost all heat engines, even those which were historically unsuitable for vehicle propulsion, can be used. Various engine concepts have been considered and discussed, such as piston engines, rotary engines, gas turbines, fuel cells, etc. However, considering all the criteria and requirements, the most suitable option for the REx unit for EVs appears to be the reciprocating internal combustion engine, more precisely, the conventional naturally aspirated four-stroke spark-ignition (petrol) engine. It is undemanding, simple in design and cheap. The limitations coming from the general requirements, especially the development and manufacturing costs, do not allow the use of the latest advanced technologies applied generally in the automotive industry in terms of improving efficiency, e.g., downsizing, downspeeding, diesel or alternative fuel engines, direct fuel injection, optimisation of the combustion process and charge exchange, friction reduction etc. The implementation of this type of ICE implies a number of issues and challenges.

2.3. Concepts of Range Extenders with Internal Combustion Engine

Various small IC engines are suitable for REx application. A lot of them are more or less explored, and the results and conclusions are presented in research articles and reports. A lot of different engine and vehicle concepts have already been created. Some of them are commercially introduced on the market or prepared for production. For example, the BMW i3 REx, Chevrolet Volt, Mazda MX-30 or the Nissan Note e-POWER. A brief overview of some existing range extender concepts shows specific features and issues related to the design of the range extender units with internal combustion engines.

Every automotive manufacture uses its approach to the subject of range extenders, however several common analogies can be found. All engines are naturally aspirated and use a simple and proven technique - simple port fuel injection and valvetrain systems with two valves per cylinder. The power outputs are in the range up to around 40 kW. All concepts strive to achieve similar objectives – minimise the fuel consumption, friction, noise, and vibration.

Most of the projects focused on IC engines for a range extender and the range extender itself have been conducted within research and development activities and studies aimed at exploration and definition of the issues and to presenting some solutions to them. These proposals have been made according to the knowledge and experience of the individual manufacturers. Since there are a lot of requirements, most of the proposals use simple and proven technologies in order to find an optimal solution for this specific task. This in turn excludes solutions and technologies targeted at improving the overall efficiency of the engine, which are financially expensive. The final solution implies compromises between all requirements, leading to one or more optimum operating points.

2.4. Summary

The ICE for a REx unit is a specific type of engine. Since it has to be adapted to a lot of diverse requirements, it differs from other types of engines used for propulsion of conventional motor vehicles – in design, size, operation and control. As a modular unit connected in series, REx can be utilised in various vehicle types, allowing improving of their operating range. This may lead to better acceptance of electric vehicles from the customer side, reducing the negative effect of EV limitations. In the meantime, it will be interesting to see if the battery technology will evolve progressively and thus offer a more attractive ratio between capacity, weight, and price, which will make this solution meaningless.

3. Goals and Methods

The engineering design process (not only in the automotive industry) is a complex, demanding, and challenging process that constantly asks for new solutions. Therefore, to ensure higher productivity and competitiveness, it is important to explore new ways to improve the steps of design process - from the idea and initial design proposal, through prototyping and testing, to the production and market launch of the product. Often, the proposal and design of a new product do not start from scratch. The development process is usually based on the design and engineering knowledge and experience gathered over the years.

3.1. Goals of Doctoral Dissertation

Designing a new ICE is not a simple task, even one for a REx unit. It may look easy because it is just a small engine, but the opposite is true. This is due to quite different requirements and operating conditions, which open new possibilities in design and operation. In this case, it is the ability to run the engine at a single or two operating points. The design of an ICE requires a much more complex analysis and design approach, sometimes even asking for completely new design solutions, almost from scratch. In many cases, however, the ICEs found in the REx units use proven solutions from series production with some adaptations.

This leads to the choice of a general focus of the doctoral dissertation on the design of internal combustion engines for range extender units using available cylinder units. It aims to find appropriate solutions offering an acceptable trade-off between the operating characteristics and efficiency and the engine package and design (size, weight). This can be accomplished by means of different:

– mechanical design of IC engine components and subsystems, aided by parametric CAD modelling techniques, thermodynamic analyses of the engine cycle, structural analysis (calculation of stresses and strains), and so on;

– reducing (optimisation) the weight, size and volume of ICE unit;

– optimisation of design and operating properties of REx units and HEV layouts.

Regarding these general goals, **the particular practical objectives of the present doctoral dissertation are defined as follows**:

– examine, identify, or determine the power demands for an EREV using a suitable approach (measurement, calculation, or simulation);

– examine, identify, or determine the power of a REx IC engine suitable for this vehicle using a suitable approach (measurement, calculation, or simulation);

– suggest a suitable design workflow for the initial phase of the design process, aiming at an increase in productivity using the tool from the previous step;

– suggest a suitable approach, method, model, or tool for quick initial (conceptual) design of the ICE, its mechanical systems (components) during the first phase of development;

– create (develop) and implement the model or tool using the software systems and equipment available;

– test (validate) the developed method and workflow on the IC engine design;

– provide a preliminary design proposal of the ICE, including initial analysis and verification, respecting the requirements, which will serve as a basis for further design stages.

3.2. Methods

In the field of mechanical engineering design (but not only), it is possible to observe a distinction between traditional analytical calculation methods and modern computer-aided technologies (CAx). The general view is that traditional analytical calculations are becoming less important in the design of mechanical components since the available modern CAx methods (designing/analysing) seem to offer more options and accuracy while requiring less time and work. Mostly, this is true, but it is still necessary to retain a basic understanding of the engineering problems (physical nature) and their solutions, which usually analytical methods provide the best. It might seem that the analytical methods are less accurate for some tasks, or in some cases, they may seem a little obsolete, but they have their merits. This provides prerequisites for the implementation of new designing approaches by combining (integrating) analytical calculations with virtual design methods/models directly in the CAx environment in order to obtain a more flexible solution for design.

The doctoral dissertation aims to propose and provide a suitable approach for solving design problems in the field of mechanical engineering using traditional calculation methods in combination with parametric CAD modelling techniques, thus connecting the design intent and engineering knowledge.

Therefore, the **suggested method** involves:

– preparation of a model for the preliminary calculation of IC engine parameters (main dimensions, kinematic and dynamic properties, etc.);

– preparation of a model for the initial design proposal of the IC engine cranktrain components by applying traditional analytical and empirical calculation methods and models for designing and dimensioning (incl. initial strength analysis, etc.);

– preparation of parametric three-dimensional CAD models of the IC engine cranktrain components using modern parametric CAx modelling techniques.

An integration of all these prepared models is used to:

– gain the best from both worlds, including a feedback between them (from calculation to design and vice versa),

– design and optimise the parameters of the IC engine and its cranktrain, and

– obtain a preliminary design proposal of the IC engine cranktrain, providing a basis for further consideration, decision-making or detailed design of units.

By using pre-prepared models of the engine components and knowing only some input parameters of the engine, it is possible to complete the initial design steps and tasks, obtaining as a result a preliminary engine design proposal. It might seem that the analytical methods are not very accurate for some tasks or in some cases they may seem a little obsolete, but they have their merits.

Because the main focus is directed at the ICE for REx units, the suggested method will be applied (tested) to the mechanical design of the IC engine, and in particular to the design of cranktrain components. However, this approach is practically intended to be versatile and applicable in the design process of other mechanical systems as well. The method strives to conduct critical engineering calculations relatively quickly with sufficient accuracy and precision and to provide direct feedback on the design, aiming to increase productivity in the initial stage of the development process. It can be considered as a preliminary stage before the use of more advanced simulation-based design methods (simulation-driven design).

4. Internal Combustion Engine Design

4.1. Internal Combustion Engine

The conventional reciprocating internal combustion engine (RICE) remains the most popular power source used all around the world in all kinds of motor vehicles and, in the near future, the situation will obviously not change significantly. After more than 130 years of evolution, there is a widespread belief that internal combustion engines have already reached their limits and there is a little room for future development, but the opposite is true. The ICE, their design, processes, operation, as well as all individual technologies, have been continuously improving over the years. However, extra measures are needed in order to increase the overall efficiency and fulfil new emission standards, which are becoming more and more strict and complex. It is necessary to search for new solutions to these challenges effectively in order to achieve significant enhancements in performance, efficiency, power density, weight and size, as well as gas emissions of the ICEs. These development objectives can be achieved by the implementation of new modern technologies, materials, processes, and design methods while still using the gained experience and knowledge. For example, advanced knowledge-based, analysis and simulation-based design approaches, methods and techniques assist the further improvement and optimisation of the ICEs during the entire development process. [27, 36, 50]

The continual process of electrification of automotive powertrain systems, which has already been carried out, has led to the implementation of different hybrid-electric technologies. In modern hybrid electric vehicles (HEVs), which are becoming more and more popular, ICEs are also the main option for a primary power source. In these vehicles, the IC engine is joined together with an electric generator, an electric battery and an electric motor. The next stage in vehicle drivetrain electrification is the utilisation of a larger-capacity energy storage electric battery together with external recharging from the electric power grid, which involves the use of plug-in hybrid (PHEV) technologies. The use of ICEs in automotive HEV and PHEV propulsion systems requires a different manner of control and operation in comparison with that of conventional motor vehicles (MVs). In these hybrid systems, the IC engines can operate in a high-efficiency mode for a longer period of time (steady-state), and thus, they do not need to change the operating mode fast and frequently. Generally, these ICEs are not designed and developed specifically for this application. They are frequently based on the conventional series-production ICE with appropriate modifications. However, additional research and development are still required in order to achieve an improvement in the overall efficiency. The pure electric vehicle is the final stage in vehicle electrification.

Vehicle electrification still presents a huge technical challenge with a lot of questions and unknowns, and the future course of this process remains, at this point, uncertain. [27, 36, 50]

4.2. Preliminary Engine Design – Process Workflow

4.2.1 Main Parameters – Initial Description and Preliminary Proposal

The cylinder bore B, the piston stroke S, the crank radius R and the connecting rod length L are common parameters outlining every reciprocating ICE. Since the relationships (proportion) between them predetermine the overall character of the engine, they have to be considered during the design process from the beginning. [13, 14, 15, 16, 17, 18, 36, 45, 80]

The considered process for a preliminary (initial) design proposal of a new IC engine and its mechanical subsystems begins with the resolution of four essential engine specifications, which predetermine its character and behaviour. They have a significant effect on the design, size, performance, and operating properties of the engine. All these parameters depend on the particular engine type and application.

Firstly, it is found out what value of total **displacement volume** the IC engine needs in order to generate a specific amount of power. The displacement presents the volume of the engine cylinders swept (displaced) by the pistons (without the volume of combustion chambers). Secondly, it is necessary to specify a finite **number of cylinders** into which the total volume will be distributed. After that, the **dimensions of the cylinders** have to be determined. The geometry of each engine cylinder is defined by two values, which are the bore B – the diameter of the cylinder; and the stroke S – the distance travelled by the piston between its two end positions (TDC and BDC). Finally, the **arrangement of the cylinders** in the engine frame (block) is specified by selecting a suitable engine layout (configuration). Since all parameters have a combined effect, they should be considered in a complex manner. A trade-off between all parameters should be made to determine the optimal B/S ratio. [17, 18, 36, 45]

4.3. Engine Component Design and Construction - Key Points

To design a new IC engine, it is desirable to use reasonably all the experience and knowledge obtained in engine building over the years. Usually, IC engines of one type are characterised by similar typical design features as a result of the objective way of evolution. For this aim, it is necessary to study all the characteristic features of the particular engine type or to select an appropriate existing engine as a sample and basis for designing the new one.

Before starting the design process, it is useful to collect all the available relevant data: parameters and properties of the designed ICE in order to have a better idea about the requirements, as well as of the sample ICE in order to have stable input data for initial design activities and thermodynamic analysis. The most common of them are listed below:

– type of engine – spark-ignition (petrol), compression-ignition (diesel);

– type of cylinder filling (charging) – natural aspiration, supercharging (forced induction);

– type of mixture preparation – external (carburettor, port injection) or internal injection) for petrol, pre-chamber or direct injection for diesel;

– compression ratio – ε [–];

– excess air coefficient – λ or α;

– maximum (rated or peak) power – P_e [kW];

– rated engine speed – n [min^{-1}];

– number of cylinders – i;

– arrangement of cylinders;

– cylinder bore (diameter) – B or D [mm];

– piston stroke – S [mm];

– bore-to-stroke ratio – $x = B/S$ [–];

– connecting rod length – L [mm];

– crank radius – R [mm];

– design ratio – $\lambda = R/L$, [–];

– engine displacement volume – V_z [dm^3];

– **mean piston speed** – c_s [dm^3];

– **mean effective pressure** – p_e [MPa];

– power per litre volume – P_e/V_z [kW/dm^3].

The displacement of the IC engine required to achieve a specific power can be obtained from a preliminary calculation, engine proposal or thermodynamic analysis.

Design and Construction of Cranktrain Components. The doctoral dissertation presents, an overview of some common approaches to the design of mechanical components (piston, connecting rod, crankshaft, engine block) of the IC engine cranktrain (in a first approximation), which are used afterwards in the suggested method for a preliminary design proposal. In a first approximation, most of the design dimensions of the components can be determined according to the statistical data and practical experience.

At this moment, it is also important to determine initially (theoretically, e.g. using two approaches) the masses of crankshaft components, which are necessary to determine the inertial forces and moments acting in the mechanism. Next, it is possible to carry out an analysis of kinematics and dynamics properties, estimation of the friction in the engine, etc.

Conclusion. The design and development of a new ICE is an extremely complex and demanding task. In essence, it is a multidisciplinary process that connects almost all fields and disciplines of mechanical engineering, such as statics, kinematics, dynamics, heat transfer and thermodynamics, fluid dynamics, material science and material strength, design, acoustics, manufacturing, etc. The doctoral dissertation focuses on the first stages of the development process – the engine concept study and design, including the selection of basic conception, initial thermodynamic calculation, initial mechanical calculation, determination of engine displacement and configuration, and preliminary conceptual design.

5. Simulation of Electric Vehicle with REx

Analysis of the entire vehicle is a quite complex and demanding task. It involves advanced modelling and simulation of the vehicle systems from the vehicle concept, its dynamics and control, powertrain and drivetrain, etc. The aim is to study, propose, evaluate, and optimise vehicle driving characteristics, performance (acceleration, deceleration, etc.), fuel economy and emissions (driving cycles, real-drive cycles), transmission dynamics (gears, shifting, control), drivetrain dynamics (torsional vibrations, weight distribution, tyre traction, etc.), and engine and powertrain control systems and strategy. [32, 33, 42, 68]

There is a wide range of simulation software that can be used to perform various vehicle analyses and studies at different system levels during the design process. In the following example, it is GT-SUITE from Gamma Technologies, which is a versatile multi-physics modelling and simulation tool with many capabilities focused on the automotive industry. An initial analysis and comparison between a traditional pure battery electric vehicle (BEV) and an electric vehicle equipped with a small range extender (REx) has been carried out, using a simple simulation model to explore the vehicles' properties. [16]

Vehicle model description – There are several possible layouts for an EV, but only the most common one is considered and explored by the selected simulation model. The vehicle is equipped with an electric powertrain, including a battery system for supplying electricity and a single traction electric motor that drives the wheels through a drive shaft, gears, and differential. The powertrain is next extended with a REx unit, consisting of an IC engine, an electric generator, and a controlling unit. The layout is similar to that of series hybrids.

Main vehicle parameters have been retrieved from the BMW i3 series electric car. This is due to the general availability of this electric vehicle, the existence of both purely electric version and electric one with a range extender, as well as the availability of numerous independent research, measurements, and data. The simulation models are adjusted roughly to correspond to the characteristics of the BMW i3 vehicle. Because the simulation and optimisation of EVs is not a main goal of the doctoral dissertation, the simulation model used is not calibrated or verified in any way, and the results are only provided as an example. [58, 75, 76] The BMW model i3 is the most popular and widely available electric vehicle, having been produced since 2013 in various versions. There are two main options: a pure electric vehicle (i3) and an electric vehicle with a range extender (i3 REx). They are powered by an electric motor with a maximum power of 125 kW or 135 kW (for Sport variants), supported by an electric battery with a usable capacity of 18,8 kWh (60 Ah), 27,2 kWh (94 Ah), and 37,9 kWh (120 Ah). The overall real-driving range varies from approximately 130 km to 260 km for electric versions, and 240 to 330 km for the REx versions. The average energy consumption based on real driving data is around 17 kWh/100 km (13 kWh/100 km in WLTP). [57]

The BMW i3 REx is equipped with a range extender unit. The electric generator, with a peak power of 26,6 kW at 5000 min^{-1} is driven by a twin-cylinder, four-stroke, naturally aspirated spark-ignition engine W20K06U0 with a displacement of 647 cm^3 which produces a power of 28 kW at 5000 min^{-1} and torque of 55 Nm at 4500 min^{-1}. The compression ratio of the engine is 11,6. The vehicle's range can be increased by 120 – 150 km by using a fuel tank with a capacity of 9 litres of petrol. The total weight of the REx unit is 120 kg. [57]

Using a simplified simulation model, three different configurations have been examined:

	BEV 60 Ah	BEV 94 Ah	Rex 60 Ah
Vehicle weight [kg]	1270	1320	1390
Battery weight [kg]	230	280	230
REx weight [kg]	-	-	120
Electric motor power [kW/rpm]	125/4800	125/4800	125/4800

Tab. 1. The specification of the considered electric vehicles

Firstly, the model is used to calculate the traction power demand to run a specified driving cycle. The computed results show that the average power that a BEV with a 60 Ah battery needs to travel on the NEDC cycle is 4,1 kW and 6,6 kW on the WLTP cycle. For the BEV with a 94 Ah battery, which is 50 kg heavier, it is 4,2 kW and 6,7 kW, respectively. The BEVx equipped with a 60 Ah battery and range extender (an additional 120 kg) requires on average 4,4 kW in NEDC and 6,9 kW in WLTP. The peak power demand varies from 34 to 43 kW.

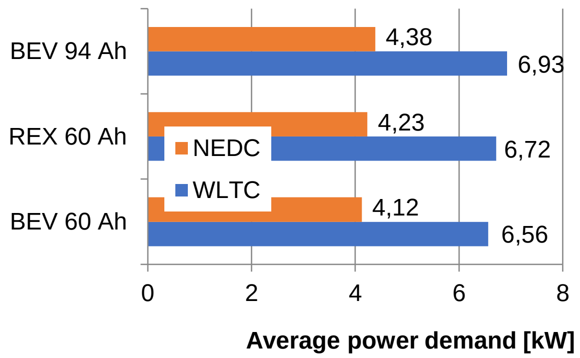

Fig. 2 The average traction power demand

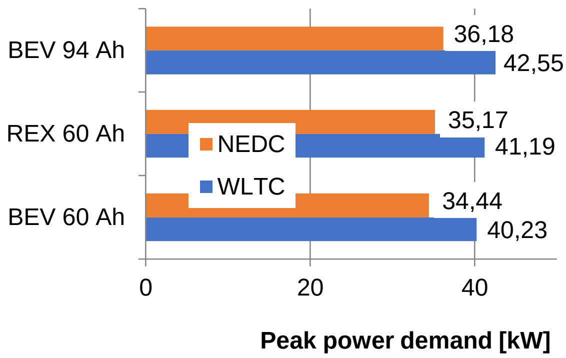

Fig. 3 The peak traction power demand

The analysis shows the differences in reachable electric range just by changing the size of the battery and the contribution of using a range extender instead of increasing the battery size. This quick study also reveals some preliminary parameters of the range extender unit. For simplicity, a single simulation model is used to perform all analyses. The vehicle parameters are modified in each case. In the pure EV, the IC engine is turned off. [16]

The overall EV range is estimated by performing the specific driving cycle a few times in a sequence until the electric battery is fully discharged. The results show that by increasing the capacity of the battery from 18,8 kWh (60 Ah) to 27,2 kWh (94 Ah), i.e., adding an additional 50 kg of weight, the EV can drive 65/53 km more in the NEDC/WLTP accordingly (i.e., +53 %).

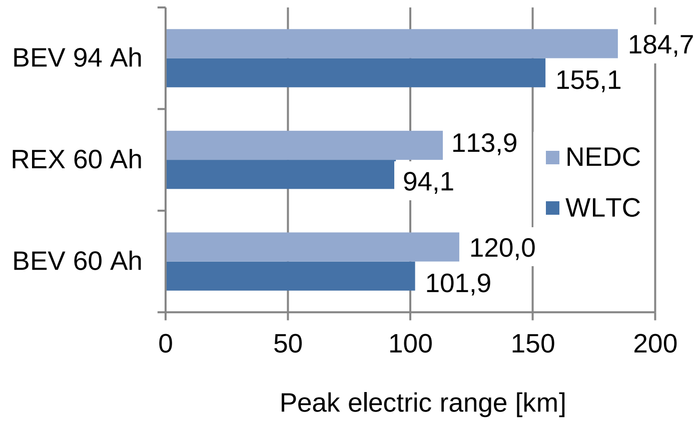

Fig. 4 Vehicle electric range

One more important question appears here: what amount of power does the IC engine in the REx unit have to generate and how the engine operation should be controlled: when to start/stop it in order to guarantee an appropriate extension of the range. The preliminary results indicate that an engine with an output power of about 20 kW to 30 kW has to be enough to ensure an acceptable extension for the vehicle segment. For this model example, only one engine operating point is used (power of 20 kW). Obviously, it is important to develop a more advanced control strategy for the range extender (e.g., more than one operating point).

Since the parameters and maps of the IC engine are unknown, the simulation model is simplified, and the IC engine is represented by simple mechanical components that simulate its function just by applying torque and speed to a rotating shaft. In the electric mode, the state-of-charge (SoC) of the battery is set to 100% (fully charged). The simulation runs the vehicle in the specified driving cycle a few times until the battery is completely depleted (fully discharged). In the REx mode, the REx starts when a specific battery SoC is reached. The total vehicle range is presented in the graph below.

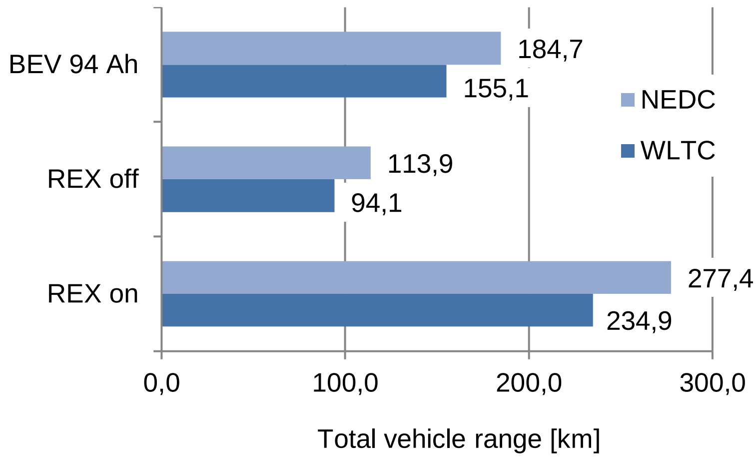

Fig. 5 Comparison of the total vehicle range

The model example shows roughly what amount of power is needed to extend the vehicle's range. A 20 kW IC engine can provide an approximately 50% longer travel range in both NEDC (+93 km) and WLTP (+80 km) compared to the BEV 94 Ah.

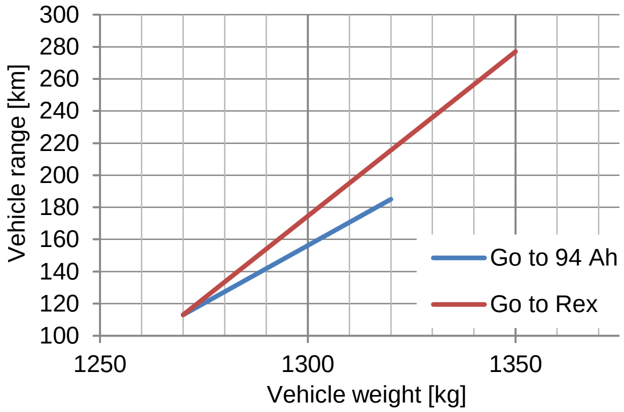

Fig. 6 BEV vs. EREV Range Comparison

The results confirm the fact that EVs with REx have great potential, and it is noteworthy to pay more attention to this viable solution for the future of personal mobility. An important factor for further decision-making is the relationship between the vehicle range and vehicle weight. It is important to decide at the beginning if it is worth it to go for a higher capacity (heavier) battery or for a REx unit solution (additional finite weight) in terms of added range, weight, and cost. This implies a requirement for the REx unit to weigh as little as possible. Or at least, the weight of the small battery and REx unit should be lower than that of the higher capacity battery. The optimisation of the weight and cost of every solution is challenging. Of course, there is always a trade-off between the available means and particular requirements.

6. Simulation of IC Engine for Range Extender

When designing a new ICE, it is essential to obtain an overall view of its performance in the initial phase of design. Proper dimensioning of an ICE is important with respect to its particular use. For this aim, various simulation studies are carried out in order to predict the gas flow, combustion process, heat transfer, and overall engine performance before the development of a prototype engine that can be tested and measured. Since the IC engine is a very sophisticated machine, computer simulation can be an extremely complex and demanding assignment. The simulation is not only limited to the analysis of the engine thermodynamics, combustion process, and performance but can also include analyses of emissions formation and aftertreatment, friction, lubrication, and cooling, as well as mechanical systems (cranktrain, valvetrain and timing, balancing), acoustics, etc. With the use of an appropriate calibration of the simulation models, the results could correspond with reality.

Following the intended design workflow, the simulations at this stage of the design process are used to obtain results from an initial engine analysis. These results are essential for the initiation of the mechanical design of the engine and its components. The aim in our case is to find preliminary optimum operating points of the REx ICE regarding the performance expectations and to predict the course of cylinder pressure and loading forces. Since this is an intermediate step in the workflow, the doctoral dissertation is not primarily focused on advanced simulations and optimisation of engine parameters.

Twin-cylinder IC Engine for Range Extender Unit for Electric Vehicle

A plain simulation model presenting an inline twin-cylinder engine, which follows the specifications of the REx engine developed at ŠKODA AUTO a.s., is used to perform some sensitivity analyses of the IC engine parameters and to examine the effect of some of the parameters on the engine performance and characteristics. For this aim, a pretty simple, but useful tool is utilised. Concept Builder from Lotus Engine Simulation allows the user quickly to understand and set the initial parameters of a specific engine configuration according to the requirements and to prepare a simulation model. The resulting model considers the dimensions of the cylinders, intake and exhaust systems, as well as the parameters of the gas flow through them. In addition, the simulation model uses different sub-models, such as the combustion model for describing combustion and heat transfer processes, etc. The code of the simulation programme is based on known engine theory and Lotus Engineering experience and could serve as a good starting point for the IC engine development process.

As previously stated, the REx unit has to meet a variety of requirements. Most of its characteristics depend directly on the IC engine itself, such as efficiency, fuel consumption, emissions, cost, assembly size and weight, NVH properties, etc. This calls for a compact and highly efficient ICE, which in turn contradicts its complexity and cost. Various research studies have shown that the most suitable engine for this particular application is the spark-ignition naturally aspirated engine because of its simplicity and undemanding, low-cost design.

At first, three essential parameters have to be set in order to prepare simulation models: the number of cylinders, engine displacement needed to generate the target power together with the specific engine speed. The main engine parameters of the inline twin-cylinder engine designed in ŠKODA AUTO a. s. are presented in Tab. 2.

Parameter	Unit	Value
Engine type	[-]	Naturally aspired, spark-ignition
Engine layout	[-]	Inline-twin
Fuel type	[-]	Petrol
Injection type	[-]	Multi-point port injection
Ignition interval	[°]	0 - 180
Bore, B	[mm]	74,5
Stroke, S	[mm]	91,6 (original 76,4)
Bore/Stroke ratio, ξ	[-]	0,813 (1,230)
Number of cylinders	[-]	2
Cylinder displacement	[cm^3]	399,3
Engine displacement	[cm^3]	798,6
Crank radius, R	[mm]	45,8
Compression ratio	[-]	12

Connecting rod length	[mm]	137
Connecting rod ratio	[-]	0,33

Tab. 2 Main engine parameters of inline twin-cylinder engine designed in Škoda Auto a.s.

Considering all the data and assumptions, the newly proposed engine has to deliver around 30 kW of power at mid-range engine speed, ca. 4000 min^{-1}. From the physical point of view, a more important quantity is the mean piston speed c_s, which in this case equals to 12,2 m/s. It can be assumed that the specific fuel consumption at that operation regime could be around 240 g/kW^{-1}.h^{-1} and the engine volumetric efficiency of around 90%. These requirements, data and assumptions give an estimation of the displacement volume of 800 cm^3. The model example corresponds with the sample engine.

Simulation study of twin-cylinder IC engine for REx: The displacement needed to generate a desired amount of power is already known (roughly), so the purpose of the following simulation study is to analyse three design cases. Following the intended design workflow and considering the reference REx ICE from Škoda, this study compares several configurations in terms of cylinder geometry, focusing on a range of operating and design parameters.

Engine Parameters and Operating Conditions. For the design and proposal of a new ICE, respecting the physical limitations (constraints), it is advantageous to apply gained experience, generalised by the use of similarity rules (geometric, kinematic, thermodynamic). It is common to use quantities (i.e., BMEP) independent of the ICE size (i.e., engine displacement), which facilitates the comparison of different engine variants.

Similar engines are assumed to have identical types of fuel, combustion systems, and charge exchange systems. The ICEs are intended as two-cylinder, spark-ignition, naturally aspirated, with four valves per cylinder. The compression ratio is set to a higher value of 12:1. The mean piston speed c_s is assumed to be equal for similar engines.

Considering the sample engine and expected performance and operating conditions as: power target of 30 kW, number of cylinders i_v = 2, mean piston speed c_s = 12,2 m/s and BMEP p_e = 1,1 MPa, we can obtain a bore size of 75,4 mm, which corresponds with the specifications of the sample engine.

In the following simulation studies, various operating and design parameters of the ICE are considered and tuned, aiming to find preliminary favourable settings or identify some trends in performance, efficiency and design. An objective could be a reduction in fuel consumption, which could be important for frequent operation of the REx unit (although it is not a priority parameter). A reasonable steady-state operating point respects the preliminary power requirement of 30 kW. A further complex optimisation of parameters is still needed.

For the considered model example of an ICE intended for a REx unit, several ICE design case studies can be examined. The aim is to highlight and summarise some important findings from this initial (theoretical) part of the design process, which are important for further decision-making. The design case studies considered include studies of:

1. of small ICEs for REx – the effect of the engine size (displacement volume)
2. of small ICEs – effect of the piston stroke size (by identical cylinder bore)
3. of small ICEs with identical displacement volume (with different B/S ratios).

Design Case Study 1 presents a comparative study of three similar small ICEs with different sizes of displacement volume (V1, V2 and V3). All 3 engine variants are considered as "square" (bore is equal to the stroke). The mean piston speed c_s is set to 9,9 m/s (an equivalent to 4000 min^{-1} for 74,5 mm stroke), whilst the connecting rod ratio λ to 0,33. All the conditions for similarity between the engines are fulfilled, and they can be compared correctly.

	Unit	V1	V2	V3
ICE Total Displacement	[cm^3]	421,5	649,5	947,7
ICE Cylinder Displacement	[cm^3]	210,8	324,8	473,9
B/S (ξ) Ratio	[-]	1	1	1
Bore - B	[mm]	64,5	74,5	84,5
Stroke - S	[mm]	64,5	74,5	84,5
Mean piston speed	[m/s]	9,93	9,93	9,93
Operating Speed	[min^{-1}]	4620	4000	3527

Tab. 3 Main parameter of engine configurations

All engine variants are compared under conditions of equal output and mean piston speed (as a single operating point). Since not all variants can fulfil the power target of 30 kW (due to the limited c_s and lower operation speeds), they are tested at a lower power of 20 kW.

	Spec. power P_v [kW/dm^3]	**Speed n** [min^{-1}]	**FMEP** [bar]	**BMEP** [bar]	**BSFC** [g/kWh]	**Br. Therm. Eff.** [%]	**Mech. Eff.** [%]	**Vol. Eff.** [%]
V1	47,5	4620	1,44	12,3	243,3	34,4	89,6	97,8
V2	30,8	4000	1,36	9,2	255,3	32,8	87,1	76,9
V3	21,1	3527	1,31	7,2	268,0	31,2	84,6	62,7

Tab. 4 Main parameters of considered ICE configuration, target 20 kW

For identical mean piston speed and brake mean effective pressure (i.e., $c_s.p_e$ = const.), all 3 engine variants will be loaded similarly by mechanical forces, whereas the thermal loads will rise with the size of the cylinder bore. The power density (specific volumetric power) decreases with the bore (displacement) size. The larger displacement results in a higher amount of power that an ICE can generate. The higher the displacement, the lower the speed needed to reach the selected power target. To achieve lower power targets for the REx (less power), the ICE has to be run in partial (low) load areas. This handicaps the overall ICE effectiveness due to non-optimum operation conditions, as it is obvious from the results: the volumetric efficiency drops significantly with the displacement, which is caused by engine regulation. That is why the overall performance in terms of fuel consumption and efficiency gets worse with the increase in displacement. On the other hand, as the engine displacement rises, FMEP drops due to the increasing size of the bore and decreasing operating speed. This can favour the NVH properties of ICE. Larger engines seem not to be very suitable for REx applications (power vs. size vs. weight ratio). We should remember that for the initial power target (30 kW), the situation will probably turn around and larger engines could perform better. It should be noted that an ICE with a displacement of around 1000 cm^3 could already be a full-featured vehicle engine, which probably no longer makes sense. The proper selection of the ICE size is essential. For the REx, it is important that the ICE displacement is set appropriately regarding the power target, engine load, NVH, efficiency, lightness, and compactness.

Design Case Study 2 is focused on a comparative study of a few small ICEs which differ by the size of the piston stroke. For this analysis, all engine variants have an identical value for cylinder bore (74,5 mm), and the size of the stroke is determined from B/S ratios from a selected range. The mean piston speed is set to 12,2 m/s (equivalent to 4000 min^{-1} for 91,6 mm stroke) and the connecting rod ratio λ is 0,33.

	Unit	S1	S2	S3	S4	S5
ICE Total Displacement	[cm^3]	464	541	666	799	1083
ICE Cylinder Displacement	[cm^3]	232	271	333	399	541
B/S (ξ) Ratio	[-]	1,4 (0,714)	1,2 (0,833)	0,975 (1,026)	0,813 (1,230)	0,6 (1,667)
Bore - B	[mm]	74,5	74,5	74,5	74,5	74,5
Stroke - S	[mm]	53,2	62,1	76,4	91,6	124,2
Connecting Rod Length - L	[mm]	79,8	93,1	114,6	137,4	186,2
Mean piston speed	[m/s]	12,2	12,2	12,2	12,2	12,2
Operating Speed	[min^{-1}]	6878	5895	4791	3996	2948

Tab. 5 Main parameter of engine configurations

The engine displacement volume gets smaller with the increase of the B/S ratio (from long to short stroke). As the stroke of the piston shortens, the operating speed of the engine variants rises, which negatively impacts the friction losses and fuel efficiency and can cause serious NVH issues. results under similar conditions (single point) – power target of 30kW, mean piston speed of 12,2 m/s, bore of 74,5 and BMEP of 11,3 bar are presented below.

	Spec. power P_v [kW/dm^3]	**Speed n** [min^{-1}]	**FMEP** [bar]	**BMEP** [bar]	**BSFC** [g/kWh]	**Br. Therm. Eff.** [%]	**Mech. Eff.** [%]	**Vol. Eff.** [%]
S1	64,7	6878	1,77	11,3	254,7	32,9	86,5	93,7
S2	55,5	5895	1,65	11,3	252,6	33,1	87,2	92,9
S3	45,0	4791	1,53	11,3	250,1	33,5	88,2	92,0
S4	37,5	3996	1,43	11,3	249,4	33,6	88,7	91,7
S5	27,7	2948	1,31	11,3	247,8	33,8	89,6	91,1

Tab. 6 Main parameters of considered ICE configuration, target 30 kW

In this case, the common trends in ICE design are present as well. The power density decreases with the displacement size. The shorter the length of the piston stroke, the higher the operating speed, which has a negative effect on efficiency. Obviously, with the rising piston stroke (and displacement), i.e., with the decreasing operating speed, fuel consumption and friction losses improve. All engine variants have to withstand similar mechanical forces because of identical mean piston speed and BMEP ($c_s.p_e$ = const). The thermal loads will also be similar because of the constant value of the cylinder bore. So, the proper selection of the piston stroke is also a common task. Considering the bore size as identical, the stroke can significantly affect the engine's behaviour and performance but also the engine size in terms of displacement volume, weight, and overall dimensions. The ICE size and weight are crucial for the REx unit system, so a proper decision on the piston stroke length has to be made. Again, the decision is a trade-off between target power, engine load, NVH, efficiency, lightness, and compactness.

Design Case Study 3 presents a comparative study of five small ICEs with an identical size of cylinder displacement but a different cylinder shape. The displacement is maintained at a constant value while the geometry of the cylinders (i.e., bore and stroke) varies according to B/S ratios from a selected range. The operating conditions remain similar. In this case it is not possible to comply with all similarity conditions because the B/S ratio is not retained the same, the mean piston speed and brake mean effective pressure are kept at constant values.

	Unit	B/S 1	B/S 2	B/S 3	B/S 4	B/S 5
B/S (ξ) Ratio	[-]	0,600 (1,667)	0,813 (1,230)	1,000 (1,000)	1,199 (0,834)	1,400 (0,714)
ICE Cylinder Displacement	[cm^3]	399,1	399,3	399,1	399,3	399,6
ICE Total Displacement	[cm^3]	798,3	798,6	798,2	798,6	799,2
Bore - B	[mm]	67,3	74,5	79,8	84,8	89,3
Stroke - S	[mm]	112,2	91,6	79,8	70,7	63,8
Operating Speed	[min^{-1}]	3265	4000	4590	5181	5741
Piston speed c_s	[m/s]	12,2	12,2	12,2	12,2	12,2

Tab. 7 Main parameter of engine configurations

Clearly, the shorter-stroke engines ($B/S > 1$) operate at higher speeds, which would lead to higher mechanical friction losses, wear or NVH issues. The larger-bore would favour the cylinder charge exchange, volumetric efficiency, final performance and also the time for charge formation and combustion at TDC. The larger-bore would lead to higher thermal loads.

B/S (S/B) ratio	Speed n [min^{-1}]	Br. power [kW]	IMEP [bar]	FMEP [bar]	BMEP [bar]	BSFC [g/kWh]	Vol. Eff [%]
0,600 (1,667)	3265	25,6	13,15	1,35	11,8	238,4	91,2
0,813 (1,230)	4000	30,0	12,73	1,43	11,3	243,7	89,6
1,000 (1,000)	4590	30,0	11,3	1,50	9,8	249,9	80
1,199 (0,834)	5181	30,0	10,27	1,57	8,7	257,2	72,9
1,400 (0,714)	5741	30,0	9,54	1,64	7,9	275,0	70,3

Tab. 8 Results for single point, Pe = 30 kW, c_s = 12,2 m/s

The BSFC gets better with the increase of piston stroke and the decrease of operating speed. The friction losses are negatively affected by the operating speed. All engine variants (excl. B/S1) are capable of achieving the power target. It is obvious that the higher operating speeds will result in a much higher amount of power (for shorter-stroke variants). Therefore, to reach the required power target, these configurations should operate under part-load (non-optimal) conditions, leading to a worsening of characteristics. The result has shown that reciprocating IC engines with similar displacement, but different cylinder geometry will differ in their way of operation, which comes from their nature. Here again, it is evident that the cylinder bore and piston stroke are essential parameters that can significantly change the ICE behaviour. The shorter-stroke ICEs don't seem very suitable. [36, 61, 62]

Conclusions. This chapter does not aim to offer a comprehensive solution for the REx ICE. It tries to offer rather a brief overview or guideline generalising, to a certain extent, the findings of the REx ICE's design and parameters. It could serve as a basis for further research. The presented simulation studies focus on the analysis of a model example of a REx ICE. The aim is to explore the ICE parameters and find preliminary favourable settings.

This is a simple computer simulation of a virtual engine at an early stage of design, and many of the parameters have to be appropriately selected. The presented studies are more of a specific sensitivity analysis of the engine size (displacement) and cylinder shape (bore, stroke) to the performance, rather than an ordinary engine cycle simulation. The presented results are unique for the considered REx ICE model example, design case studies, particular conditions and assumptions. However, the outlined trends in the effects of the parameters on the ICE nature and performance are fairly common in theory and practice.

The results successfully identified some trends and operating areas. It can be concluded that the shorter-stroke or square engine variants should be more suitable for higher required output powers (and higher loads) when they can operate with better efficiency. And vice-versa, the longer-stroke variants benefit from lower power output targets. It is good to remember that engine efficiency and fuel consumption (which were emphasised) do not have the highest priority during the design of a REx IC engine. So, it is all about a trade-off between all engine characteristics, vehicle type and architecture. If a shorter-stroke engine comes out better in terms of package dimensions or weight, it could be preferred to a longer-stroke configuration at the expense of efficiency and fuel consumption. So, a square or a shorter-stroke configuration with a displacement of around 600 cm^3 can be pointed out as a suggestion for a starting point. The results are in line with the REx engines already available.

Suggestions and Recommendations for Future Research. A more complex multi-objective and multi-parameter optimisation is desirable in order to refine the discussed parameters of the REx ICE with respect to not only overall efficiency, performance, and operating characteristics, but also to the physical design of its subsystems and components. To refine the simulation results, it is appropriate to extend the applied simulation models with more advanced modelling features and techniques with an emphasis, first of all, on predictive modelling capabilities (combustion, knocking, friction). A proper calibration of the models with real data is very essential. This will provide more realistic, accurate, and trustworthy results.

It should not be forgotten that the overall size and weight of the IC engine for REx are decisive parameters that could limit the choice of parameters and decision-making process and thus affect the final solution, i.e., the engine's character and performance. Therefore, a significant opportunity for the creation and providing of a conceptual IC engine proposal is the application of a complex modelling approach which involves an interconnection (coupling) of fast 0D/1D cycle simulations directly with parametric 3D design and FEA methods and also aims to provide feedback from the simulation to the design and vice versa. This will improve, for example, the heat transfer analyses and modelling by obtaining a more accurate cylinder thermal field and wall temperatures using 3D geometry and finite element models, or by transferring the results from engine cycle optimisation directly into the parametric 3D design proposal of the engine, thus maintaining the links between individual design stages.

7. Practical Application of the Designed Approach

The proposal and design of a new IC engine usually (or rarely) do not start from scratch, but always use the current state of technology, knowledge, and experience. Therefore, an objective of the present doctoral dissertation is also to suggest or develop a suitable method, model, or tool for quick initial (conceptual) design of mechanical systems at an early stage of design. It should strive to connect design intent and engineering knowledge in order to use, maintain, extend, and share intellectual property. Since the main focus is the ICE for a REx unit for hybrid powertrains, the suggested method is applied (adapted) to this field, in particular to the design of the engine cranktrain. However, the approach is intended to be versatile and to be used in the design of other mechanical systems as well. The aim of the tool is to provide a complete preliminary design proposal, using intuitively all knowledge and experience gathered over the years of development, including initial analyses or verifications with respect to specific requirements. This proposal will serve as a basis for the next design activities.

In the field of mechanical engineering, it is possible to observe a distinction (often artificial) between traditional analytical design methods and modern advanced computer-aided technologies (CAx). The general view is that analytical design approaches are becoming less important. In addition, it seems that modern computer-aided design and analysis methods (approaches) offer more options and accuracy, requiring less time and effort. In most cases, it is true, but it is still necessary to retain a basic understanding of the specific problems and their solutions, which usually analytical methods provide the best, thus avoiding the use of the trial and error approach for solving them. This provides a prerequisite for the implementation of approaches that combine and integrate analytical calculation methods directly into the CAx environment in order to obtain more flexible and faster solutions to the design problem. It might seem that the traditional analytical methods are not very accurate or suitable for some tasks, or in some cases, they may seem a little obsolete, but they have their merits.

Parametric Modelling Approach in CAD

Over the last few decades, computer-aided technologies (CAx), like computer-aided design (CAD), computer-aided engineering (CAE), or computer-aided manufacturing (CAM), have become an integral part of the development process in all fields of mechanical engineering. They involve a wide application of computer-based design tools, aiming to support and assist designers and engineers in every task of the development process. CAx systems are focused on simplifying, optimizing, and facilitating design process workflows with the goal of increasing productivity and improving design and manufacturing quality and accuracy. Lying at the heart of virtual product development, these software design tools allow the creation of a complete virtual three-dimensional model (digital prototype or digital twin) of the designed mechanical component or system. They use advanced design, modelling, and analysis techniques while reducing time and cost for completion due to a more efficient and optimised workflow.

The utilisation of parametric CAD modelling techniques in virtual design is very common nowadays, and many capabilities are implemented in modern CAD software systems. A parametric CAD model consists of a set of geometrical features, dimensional and geometric constraints, and is controlled by a set of parameters, expressions, and relations. Using parametric models during early-stage development is essential for preparing a flexible representation of the designed entities (components and subsystems), including their physical characteristics (material properties), size (dimensions), and shape (geometry). Furthermore, using these representations, it is possible to conduct a preliminary estimation of the mass and inertia properties, which are crucial for the overall design and operating characteristics of the designed unit. Parametric models make it possible to respond quickly to the design requirements and to make the right decisions and modifications directly and more easily.

In order to improve the speed and flexibility of the suggested designing method, it is necessary to work with geometrically optimised (simplified) CAD models. This requires removing complicated geometric elements from components and replacing them with more simple shapes, while retaining all the important cross-sections. Using simplified CAD models means considering fewer details, but this also allows much easier parameterisation and modification of the components, making the model lighter and faster to regenerate. Because the desired output from this stage is a preliminary design concept of the ICE cranktrain, the parametric modelling approach has to achieve a sufficient ratio between accuracy and speed. The parametric CAD models of the individual ICE components and their assemblies have to provide an initial idea of themselves and the engine subsystems, while also being able to respond to design changes during the initial design phase.

In contrast, by using traditional CAD modelling techniques, the designer's effort is focused on creating more detailed (accurate) design proposals, including different technological and manufacturing features. Due to the complexity, this prevents the use of parametrisation and makes greater demands on making changes and improvements to the design. Two-dimensional drawings of the ICE unit and its individual components reflecting the design changes can also be generated from the parametric three-dimensional CAD models.

7.1. Practical Implementation of Method

For a practical implementation of the intended design method, the individual relations and equations can be programmed, depending on the available SW equipment, either directly into parametric CAD models or into a utility tool. The aim is to link the analytical design calculations with the CAD models in order to control the geometry. Once the basic input data is entered, the analytical model performs a quick calculation, providing a solution, which is transferred directly to the CAD model. So, combining analytical design approaches with parametric CAD techniques allows the creation of CAD models of individual components, which are updated according to the computations and thus reflect the design changes.

The proposed analysis-driven method for parametric design can be divided into a few individual steps: define the design intent (describe the problem, design parameters and constraints), prepare the initial design proposal using pre-prepared analytical calculations and parametric CAD models, optimise this proposal according to the requirements.

7.2. Description of the Workflow

The considered designing process starts with a specification of the design intent, including a summary of available data for the newly designed ICE and clarification of the specific application with relevant requirements and demands. Once an idea of the performance expectations is obtained, the engine displacement needed to generate the required amount of power can be roughly estimated. The process continues with the decisions about the number of cylinders, engine layout, bore-to-stroke ratio, and connecting rod length.

The ICE calculation model, which uses mathematical relations and equations, can be filled with already known data and used to perform initial design activities. The calculations are done in a spreadsheet in MS Excel. The ICE model includes a summary of all parameters, a preliminary estimation of the masses of the cranktrain components, a calculation of kinematic and dynamic properties, etc. The model can also contain calculations for initial strength analysis of the components (analytical submodels). After entering all the needed data, all the output quantities are calculated. Then the data can be transferred (updated) to a prepared CAD model of the ICE cranktrain (allowed by the Excel analysis in Creo Parametric).

The first design proposal obtained is optimised in several steps, aiming to minimise the weight of components while the stresses in critical areas are kept within reasonable limits. The entire process runs inside Creo Parametric using the Optimisation feature and the connection to the calculation model in Excel and exchanging data between the both programs.

The final result is a preliminary design proposal of the ICE and its cranktrain, optimised in a first approximation by means of analytical calculations. Thus, the designers have at their disposal a complex solution in which they can find important data and context for the newly designed engine. This initial design proposal can serve as a basis for the subsequent detailed design of the individual components, for package (size, weight) and installation analyses, etc.

The proposed analysis-driven design method is applied to the model example of a twin-cylinder inline ICE intended for a REx unit. It shows that the chosen approach has good potential for application in practice. The performed computations show that the effectiveness of the designing method depends on the particular way of implementation and applied SW tools, their flexibility and “speed”. For the used utilities, it can be concluded that the model computations run fast enough (in Excel), but the regeneration of CAD models in Creo during the optimisation process is quite time-consuming. So, using an alternative CAD system or method of building models may yield better results. Therefore, it is necessary to find a better practical way to implement the method in order to get the best of it.

In summary, the considered analysis-driven design approach allows us to prepare a preliminary design (conceptual) proposal of the ICE components (at first approximation) by applying analytical calculation models proven over the years. As a suggestion for enhancement of the considered method, an advanced numerical (FEA) simulation aimed to verify or refine the initial (analytical) design solution can also be performed as an intermediate step. This will make the design process a two-step process with two independent approaches.

Various design studies can be performed using the pre-prepared parametric CAD models of the particular internal combustion engine and its components. Depending on the specific design level, the CAD model can be extended to the entire range extender unit. The package analysis is the most important, as it can provide a better idea of the IC engine or REx unit dimensions, weight and mounting space requirements.

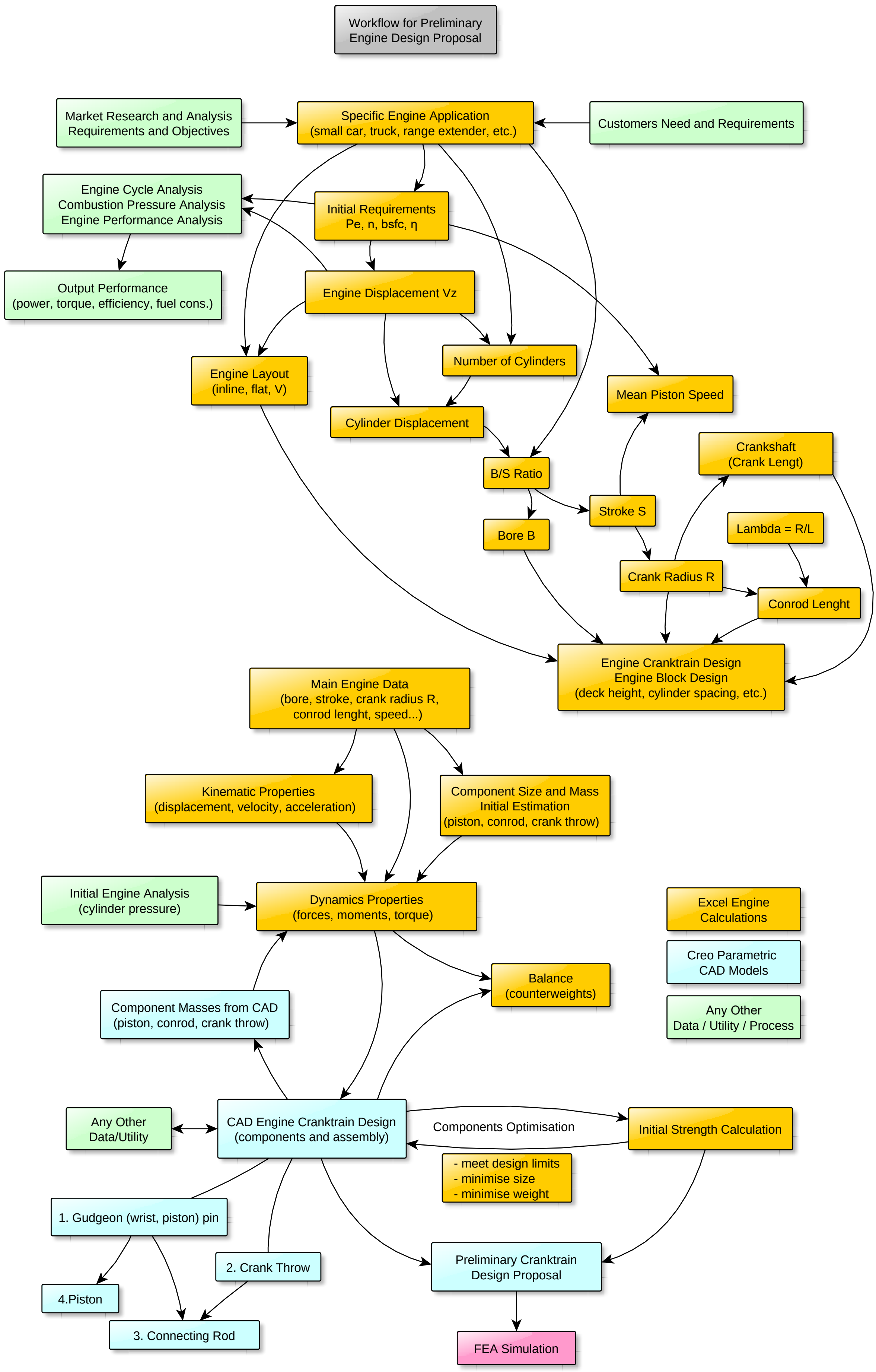

Fig. 7 Overview of suggested workflow for preliminary cranktrain design proposal

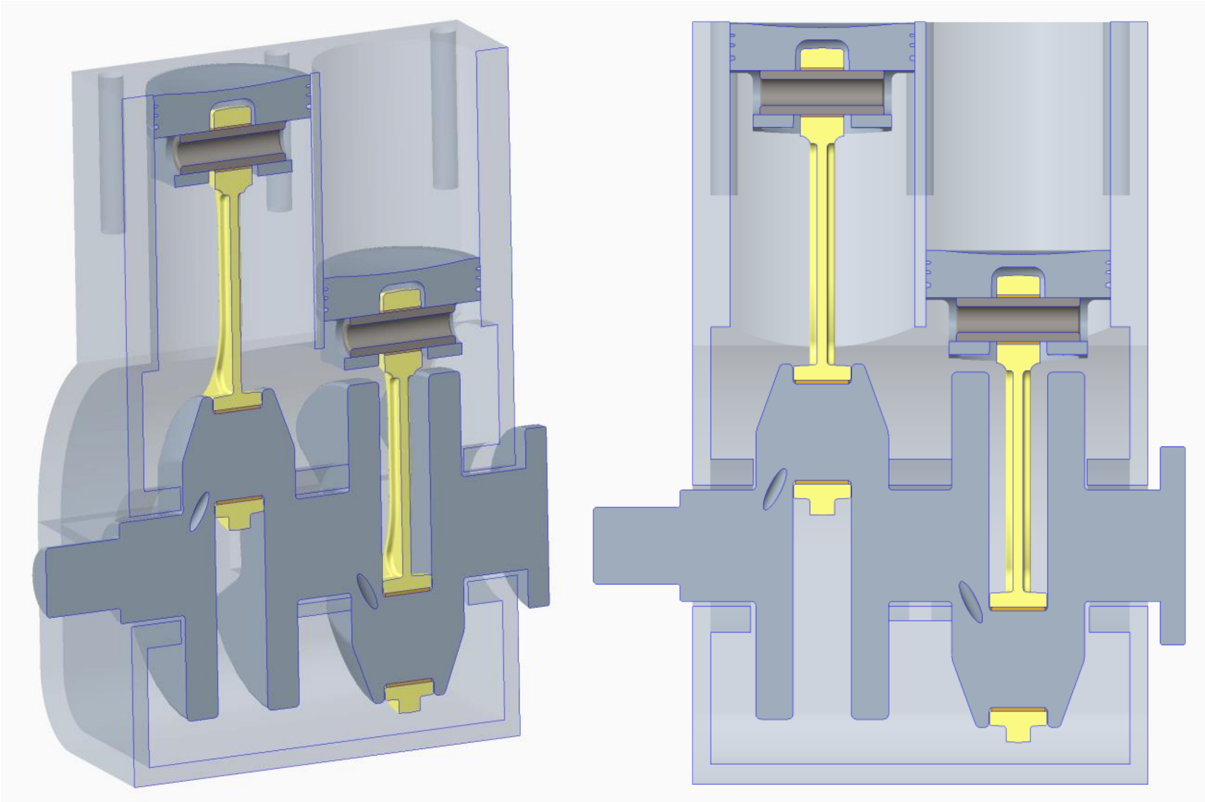

Fig. 8 Illustration of parametric 3D CAD model of twin-cylinder engine

8. Final Thoughts

8.1. Conclusions, achievement of objectives and contribution

Modern society and the transport system are evolving very quickly. This brings a lot of issues and questions. The main reasons for that are the growing human population, the increasing number of vehicles, growing energy demand, as well as the dependence of transport on fossil fuels, whose resources are limited in nature, and last but not least, the effect of transport on air pollution and CO_2 emissions.

Modern human society is striving for a sustainable future, for which mobility is essential. However, from a longer-term perspective, it appears that the current system for passenger transportation is not leading to the desired target. This is the reason why a new, more environmentally friendly transport model has to be introduced, aimed at efficient, safe, clean, and smart mobility, which at the same time outsmarts current and future obstacles like oil scarcity, traffic congestion, reduction of CO2, and pollutant emissions.

Various attempts aim to reduce dependence on fossil fuels and carbon emissions by involving the use of cleaner and safer energy. In recent years, research and development in the automotive industry have focused on improving the efficiency, safety and cleanliness of transport. Many different solutions have been proposed as an alternative or as a supplement to conventional motor vehicles, such as hybrid and electric vehicles.

The development process should be more flexible and adapt quickly to requirements and demands. This can be achieved by using the experience and knowledge gained in a combination of a wide range of latest advanced design technologies as well as modern computer-aided approaches. This will help to develop new innovative engines and powertrain concepts for the future.

Nevertheless, the internal combustion engine is the most commonly used power source in transport, and this situation probably will not change significantly in the near future. In any case, further measures are needed to increase efficiency and fulfil new and stricter emission standards. It is therefore essential to push forward the research, design, and development of ICE and powertrain systems and to continue the search for new technical solutions.

The electrification of vehicles has led to the implementation of various hybrid-electric powertrain solutions in which the ICEs are also the main option for the primary power source. However, their utilisation requires different ways of design, control, and operation. All efforts are focused on the transition to fully electric vehicles, but vehicle electrification still presents a huge technical challenge, and the future of this process remains uncertain.

Compared with conventional vehicles, the limited autonomy range of pure electric vehicles still remains one of the major disadvantages and obstacles to great success, together with the higher price. Refining the battery technologies for higher capacity, lower cost, and weight is a long-term process that will take more time and research.

The range extender unit presents an accessible solution to these issues. It involves a discreet modification of the pure electric powertrain, which is equipped with an auxiliary power unit used to extend the travel range to a more acceptable limit by supplying the EV system with electricity. This solution, e.g., allows reducing the total capacity (thus weight and cost) of the electric battery. Other energy needs are covered by the range extender. The dissertation presents a suitable approach for quick identification of the power demands of an EREV, i.e., vehicle simulation [16]. A comprehensive simulation study of the parameters of the IC engine for REx, which successfully identified the areas of optimum values, is presented [15, 17, 61].

The design of an ICE for a REx unit for EV is not a simple task due to completely different requirements, design and operating conditions. The overview of available REx ICE shows that in some cases, they use proven solutions from series production, while in others they require a more complex design approach, even asking for quite new design solutions.

Development is a complex, demanding, and challenging process that constantly asks for new findings. The design of a new ICE usually does not start from scratch but is always based on the current state of knowledge and experience. It is necessary to search for new ways how to enhance the individual design phases, aiming at better performance. A goal of the dissertation is to determine the potential of a suitable designing method aiming at an increase in productivity. Next goal involves suggestion and description of an appropriate design workflow, which is to be applied at the beginning, covering every single step.

That is why the doctoral dissertation aims to explore ways to enhance the individual steps of the design process and to improve productivity, thus obtaining the desired results faster. Traditional design approaches were chosen as an instrument to meet the goals.

This doctoral dissertation suggests and presents a theoretical and practical development of a suitable method (or a model) for quick preparation of conceptual design proposals of mechanical components and systems during the early phase of development. The aim of this tool, in our case, is to provide a preliminary design proposal of ICE components and subsystems, using intuitively all the knowledge and experience gathered over the years, including an initial analysis or verification, while respecting the specific requirements and demands. It can serve as a basis for further design stages. The designing method also involves the need for a suitable workflow to carry out initial engine design tasks with better productivity.

The main interest of the doctoral dissertation is focused on the IC engine for the range extender unit. Hence, the suggested design method is applied to the proposal of the engine cranktrain and its components. A significant contribution of the approach is the intention to be versatile and to be applied in the design process of other mechanical systems as well. It strives to perform critical engineering calculations relatively quickly with sufficient accuracy and to provide direct feedback on the design, aiming to increase productivity in the initial stage of the development process. It presents a step before advanced simulation-based design methods.

The suggested approach for an initial conceptual design of the IC engine is based on the application of traditional analytical and empirical calculation models used for designing and dimensioning the IC engine components in combination with parametric three-dimensional CAx modelling techniques and approaches. Using an ICE calculation model and virtual 3D models of the IC engine components, it is possible to complete the initial design tasks and obtain a conceptual design proposal. Today, it might seem that the analytical methods are not very accurate for some tasks, or in some cases, they may seem a little obsolete, but they still have their merits (retain a basic understanding of the specific problems and their solutions).

The designing method has been successfully tested on a model example of an IC engine suitable for a range extender unit. The design study of the IC cranktrain presented shows that the suggested design method has good potential for application in engineering practice. Moreover, it can be used for educational purposes. Through the use of an integration of both analytical and parametric CAx models, a preliminary virtual design solution can be prepared while maintaining an awareness of the physical nature of issues. The effectiveness of this design tool, however, depends on the method of implementation and the software tools used (here MS Excel and PTC Creo). The prepared calculation model can run fast enough, but the regeneration (update) of CAx models during the optimisation process is rather time-consuming. Thus, an alternative way of implementation is desirable in order to improve the speed and flexibility of the designing tool.

8.2. Suggestion for Further Research

The following themes, directions, or expansions can be considered as further areas (topics) for research in the field of internal combustion engines for range extender units for EV:

– complex multi-objective and multi-parameter parametric studies, sensitivity analyses and optimisation of the IC engine parameters and thermodynamic cycle; calibration of models;

– application of advanced predictive simulation models and approaches; FEM models;

– enhancement and extension of the suggested method with FEM numerical methods;

– methods for assessment of the mounting system of the range extender units in the vehicle, dynamics and vibrations of REx units;

– methods for optimising hybrid vehicle layout – design, optimisation, and control;

– thermal management of the range extender unit, including analysis and assessment of emission system and vehicle heating systems;

– methods for assessment of IC engine start/stop (on/off) operation aimed at fast-changing load and speed in order to reach quickly the optimum operating point;

– considering the low-cycle fatigue and wear of the cold engine.

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Abstrakt

Disertační práce se zabývá problematikou pohonných jednotek s prodlužovačem dojezdu pro hybridní vozidla. Zaměřuje se zejména na spalovací motory využívané v těchto jednotkách a jejích návrhem. Vzhledem k tomu, že bateriová elektrická vozidla stále používají těžké, objemné a drahé baterie, které nabízejí velmi proměnlivý, v některých případech nedostatečný dojezd, představují pohonné jednotky s prodlužovačem dojezdu rozumné řešení těchto problémů. Prodlužovače dojezdu jsou pomocné pohonné jednotky, které přeměňují energii ukrytou v palivu na energii elektrickou. Pro pohon elektrického generátoru se používá většinou specifický typ spalovacího motoru. Prodlužovač dojezdu umožňuje ne jenom prodloužit dojezd vozidla, ale také zmenšit kapacitu baterie (tedy i její velikost a hmotnost), tím že dodává systému dodatečně elektrickou energii. Vzhledem k tomu, že spalovací motor není ve většině případů přímo spojen s koly vozidla, je možné jej provozovat v bodech (oblasti) s optimální účinností a spotřebou paliva. Tím, že spalovací motor bude pracovat pouze v jednom nebo dvou provozních bodech, lze také zkoumat nová a inovativní konstrukční řešení. Toto naopak vyžaduje vhodné návrhové nástroje, metody a přístupy, které umožní rychle a efektivně dosáhnout stanovených cílů. Disertační práce se zaměřuje také na tuto problematiku a předkládá možnou metodu navrhování s využitím analytických výpočtových modelů a parametrických modelovacích technik v CAD.

Abstract

The doctoral dissertation examines issues related to range extender units for hybrid vehicle powertrains. In particular, it is focused on the internal combustion engines utilised in these units and their design. Because battery electric vehicles still use heavy, bulky and expensive batteries, that provide a varying, and in some cases, insufficient driving range, the powertrains with range extender present a reasonable solution to these issues. The range extenders are auxiliary power units that convert the energy hidden in fuel into electric energy. They use a distinctive type of IC engine to drive an electric generator. The range extender also allows us to reduce the capacity of the battery, thus its size and weight, by supplying the system with electricity. Since in most cases, the internal combustion engine is not connected directly to the wheels of the vehicle, it can be run at points (operating range) with optimum efficiency and fuel consumption. Operating the IC engine at only one or two makes it possible to explore new and innovative design solutions. This in turn requires suitable design tools, methods, and approaches, which allow us to achieve the objectives quickly and effectively. The doctoral dissertation also focuses on this topic and presents a possible design method using analytical calculation models and parametric CAD modelling techniques.