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Design and experimental development of a compact and efficient range extender engine

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HIGHLIGHTS

- New concept of compact, clean and fuel efficient range extender engine.
- Developments through CFD simulation and experiments.
- Significant step forward in comparison to the current 4-strokes.
- Weight: −35%, brake efficiency: +6%, heat rejected: −18%, thermal load: −40%.
- Cost effective technology for CO_2 reduction in transportation.

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ABSTRACT

The paper reviews the design and experimental development of an original range-extender single-cylinder two-stroke gasoline engine, rated at 30 kW (maximum engine speed: 4500 rpm). The goal of the project is to get most of the benefits of the two-stroke cycle (compactness, high power density, low cost), while addressing the typical issues affecting the conventional engines of this type. Among many recent similar propositions, the peculiarities of this engine, besides the cycle, are: external scavenging by means of an electric supercharger, piston controlled scavenge and exhaust ports (no poppet valves), gasoline direct injection (GDI), and a patented rotary valve for the optimization of the scavenging process, of the loop type. Lubrication is identical to a conventional four-stroke engine, and the rotary valve, connected to the crankshaft, helps to improve the balance of the piston reciprocating forces, yielding an excellent NVH behavior. It should be noted that, except the patented rotary valve, all the engine parts are standard automotive commercial components, that don't require any specific expensive technology. In fact, the originality of the engine consists in the optimum combination of existing well assessed concepts.

The scavenging and combustion systems of the engine are developed in the first phase of the project, including the construction and the experimental testing of a prototype. In the second phase, the air metering system of the prototype is completely modified: the piston pump is replaced by an electric supercharger, and engine load is now controlled by the supercharger speed, without throttle valve.

The new engine is compared to a standard 4-stroke engine, developed in a previous project for the same application. The main advantages of the two-stroke engine may be summarized as follows: lower weight (−35%), higher brake efficiency (+6%, on average), less heat rejected (−18%), lower thermal and mechanical loads within the cylinder (−40%). The only concern, that will be addressed in a future phase of the study, is the compliance with very low NOx limits: in the worst scenario, the 2-stroke engine could be forced to adopt a well assessed but expensive after-treatment device.

1. State of the art

One of the most critical challenges of recent electric cars is the driving range achievable with the current battery technology, which allows the vehicle to store only a small fraction of the

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Nomenclature

Acronyms

BDC	bottom dead center
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
CCD	charge control device
CFD	computational fluid dynamics
EGR	exhaust gas recirculation
GDI	gasoline direct injection
HCCI	homogeneous charge compression ignition
IMEP	indicated mean effective pressure
MBT	maximum brake torque
NVH	noise, vibration, harshness
OEM	original equipment manufacturer
SPL	sound pressure level
TDC	top dead center

energy provided by conventional fuels, such as gasoline or diesel. An effective way to address the so called "range anxiety" is the adoption of a range extender, that is a small internal combustion engine designed to recharge the traction batteries when their available energy content drops below a specified threshold [1]. The range extender is also a practical solution to further issues. As an example, the range extender enables a more efficient use of heating and air-conditioning functions when the vehicle stops, thus helping to further reduce CO_2 emission [2].

The basic requirements for the range extender are:

- peak power sufficient to allow the car to reach a target highway speed (typically, 120 km/h), with empty batteries;
- compactness and lightness, in order to permit an easy and not expensive installation on a conventional vehicle;
- excellent fuel efficiency, to maximize the benefits on CO_2 reduction of the electric vehicle;
- low pollutant emission levels, to meet stringent regulations;
- excellent NVH behavior: ideally, the driver should not be able to tell when the combustion engine is running;
- low cost.

For vehicles needing a power higher than 40–50 kW, a range extender can be directly derived from a mass production engine. Conversely, for city cars requiring less than 30 kW, even the smallest existing automotive engine is not suitable. Apparently, the easiest solution is to convert engines, already existing for other applications (motorcycles, small gen-sets, etc.), into range extenders. However, the engineering cost for these conversions would be not much lower than a development from scratch. Moreover, a specifically developed engine allows the designer to select more suitable technologies and solutions. This is the reason why some important players of the automotive industry, not only OEMs, decided to develop their own Range Extender.

As a first example, Lotus Engineering [3] developed a 3 cylinder, naturally aspirated, 1.2 l, 4 stroke engine, able to deliver a maximum power of 35 kW at 3500 rpm. The engine weight, without generator and related electric/electronic parts, is about 56 kg.

In the GETRAG range extender [4], the number of cylinders and the engine displacement are reduced to 2 and 0.9 l, respectively, while the target of 45 kW at 3500 rpm is achieved by means of a turbocharger. In this solution the engine is connected by a 2 speed gearbox to the differential and it is also able to provide mechanical power for the vehicle traction and not only for the generation of electric current. The engine weight is almost identical to the Lotus solution (55 kg).

The two-cylinder 4-Stroke layout was selected also by Mahle for their prototype [5]: the engine is naturally aspirated, and it reaches 40 kW of maximum power at 4000 rpm. Besides a very low weight of the engine, 50 kg, Mahle also claims an excellent best specific fuel consumption of 240 g/kWh.

Another compact two-cylinder, naturally aspirated unit is proposed by FEV and KSPG [6]. The power target of 30 kW at 4500 rpm is achieved with a lower displacement (800cc). Differently from Mahle, FEV decided to adopt an in-line layout, and to use the coupled electric motor to balance the inertia forces.

In parallel to conventional solutions, AVL and FEV are developing some prototypes based on the rotary engine technology [7,8]. While AVL developed a 250cc engine, able to deliver 15 kW at 5000 rpm, FEV opted for a larger capacity (295cc), achieving 18 kW at 5500 rpm. These solutions are much more compact of an equivalent 4 stroke, and they have the indisputable benefit of very low vibrations. However, the proposed prototypes don't seem to introduce any particular innovation to the conventional rotary engine technology, which is still penalized in terms of pollutant emissions and high specific fuel consumption. Moreover, reliability and performance of this technology are directly related to the expensive manufacturing process of some key parts; this issue makes the production costs increase, being the predictable market volumes of such systems quite low, compared to standard automotive figures.

Micro gas turbines are interesting propositions too [9], but they appear to be still immature for an immediate application, being their main challenges not entirely solved.

4-Stroke Diesel engines are normally discarded as range extenders, because of their low power-weight ratio, poor NVH characteristics, as well as for the high cost of their exhaust after-treatment systems.

2. Two-stroke engines?

The two-stroke cycle, with a new specific design, represents an unconventional but not exotic alternative to 4-Strokes. The main reason of interest for this type of machines is the double cycle frequency, allowing the designer to either draw a very compact and light unit for the given power target, or limit the maximum rotational speed, with ensuing advantages in terms of mechanical efficiency, noise and vibrations.

Recently, the modernization of the two-stroke engine is a quite hot research topic worldwide, so that it would be impossible in this paper to review all the relevant propositions. Only the most similar to the current project will be presented here, whereas for a more complete overview, one can refer to [10].

A 2-Stroke engine can easily share many technologies and components with a Spark Ignition (SI) passenger car engine. Abandoning the crankcase pump, the lubrication system (oil sump, pump, internal passages) can be the same. Moreover, a commercial high pressure gasoline direct injection system (GDI) can be installed also on a 2-Stroke. Finally, a 2-Stroke prototype can be constructed on the basis of an existing 4-Stroke, modifying only the valves actuation strategy, as done by some researchers [11–12].