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Essam Shehab, Peter Ball, Benny Tjahjono  
*Editors*

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Dr Essam Shehab, Dr Peter Ball and Dr Benny Tjahjono

Cranfield University  
Cranfield  
Bedfordshire  
MK43 0AL  
UK

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## **MODULAR LIGHTWEIGHT COMPONENTS FOR PERIPHERAL E-MOBILITY SOLUTIONS**

Matthias Heinicke  
Stefan Lüdecke  
Gerd Wagenhaus

Institute of Ergonomics, Manufacturing Systems and Automation  
Otto von Guericke University  
Magdeburg  
Universitätsplatz 2, 39106 Magdeburg, Germany  
matthias.heinicke@ovgu.de

### **ABSTRACT**

Based on a comprehensive prototype, the researchers at the Otto von Guericke University systematically investigate components and system solutions within a project regarding the interplay of electric vehicles and range extenders. In consideration of the electric vehicle, named Editha, different operating strategies for the use of range extenders in the predominant application field of electric mobility were tested. The principal objectives of the project are to determine appropriate operating strategies for the use of a range extender and operating characteristics for an optimal system configuration of existing or future engine technology in combination with the respective generator technology. Thus, sensible and expedient combinatorics with regard to weight and performance criteria arises. This project aims at gaining an overall understanding of the interplay between automotive and alternative energy generation based on the prototype and the exemplary design of both power trains.

**Keywords:** e-mobility, range extender, operating strategies.

### **1 INTRODUCTION**

Reviewing the current state of research and the areas of missing knowledge, the project aims at designing a lightweight range extender for electric automotive operation. This is against the backdrop of ever increasing numbers of electric vehicles commercially available. Accordingly, the resolution of previously limited range gains currency regarding the satisfaction of customer demand in terms of the range of these vehicles. Thus, range extenders represent a corresponding solution by removing one of the major hurdles in terms of market and customer acceptance in the field of electric-mobility applications. In this context, a comprehensive market research was conducted to show what applications in the field of electric mobility come into consideration as regards building up a range extender.

The basis for further research is the project Editha (Wagenhaus et al. 2012). Due to its minor curb weight and its specific construction, a Smart was chosen as starting product for the e-conversion. In consequence of the redesign, the previous power train is dispensable. The research vehicle is a battery electric vehicle using an individual DC motor with a fixed gear ratio for each wheel of the rear axle. At this, each electric motor is located in the immediate vicinity of the rear wheel and can be individually controlled by its own motor controller as well. Thus, the Editha project points out a transition from vehicles with central engine to hub wheel electric engines. As a complementary system to the existing electric vehicle, industrially manufactured components, both immediately available parts and at a prototype stage, were evaluated as appropriate for range extenders (Section 2.2).

Range extenders provide the opportunity to combine the advantages of both an internal combustion engine and an electric power train (Section 2.1). Thus, the issues of battery technology

can be circumvented (Fischer 2009). Consequently, a range extender represents a worthwhile type of propulsion technology as a transition from the internal combustion engine to the electric power train. The combination with electric drives enables fulfilling legal regulations in terms of pollutant emissions as well as realising a drive train at minimum costs (Münkel et al. 2011).

A comprehensive review of potential components for designing a range extender systematically offers several configurations (Münkel et al. 2011). The focus of the investigations is a serial electric drive with respect to the use of a range extender as well as its evaluation in operation (Kampker et al. 2012). This assessment is addressed in the context of two alternatives, on the one hand considering the possibility of replacing a portion of the electric battery through the integration of a range extender in a vehicle. Alternatively, a modular range extender represents a technology testing platform in terms of a trailer-range extender. Taking into account the research carried out and the test vehicle Editha, this investigation is used to create a flexible solution for a technical implementation of a range extender in or at the existing vehicle.

## 2 DESIGN OF THE RANGE EXTENDER

### 2.1 Operating Strategies for Range Extenders

In this section the requirements and operation strategies are specified. In parallel hybrid drives, the internal combustion engine transmits the operating power via clutch and gear box to the wheels directly. An additional electric drive is integrated in the power train. Accordingly, this offers the possibility to combine the power distribution between the combustion engine and the electric drive (Münkel et al. 2011). Apart from that, a serial hybrid drive in terms of a range extender enables an exclusively propulsion and recuperation of a vehicle by electric drive motors. An additional combustion engine (range extender) only actuates a generator directly feeding the electric battery (Kampker et al. 2012, Tschöke 2012, Münkel et al. 2011). Thus, a range extender represents an additional energy source to extend the electric range out of the traction battery. Accordingly, it generates electric energy on demand in order to actuate the electric drive motors or charge the battery (Tschöke 2012, Kampker et al. 2012).

Parallel hybrid drives imply more weight of the entire drive system due to the permanent redundancy of power trains. Thus, the proposed concept contains a serial range extender that is designed as trailer. Furthermore, it is assumed that the range extender operates in fixed operating points and feeds maximum electric power into the electric vehicle. Furthermore, the range extender, more precisely the loop of combustion engine and generator, operates separately.

Moreover, the following aspects have to be considered in terms of a trailer-range extender:

1. Manual switch in the vehicle for ON and OFF (master switch)
2. Overload protection as regards traction battery (battery shutdown, master switch OFF)
3. Either charging on range extender or mains (locking of range extender during mains connection)
4. Charging even in stand-by of the vehicle (car parks and is closed, range extender charges – particularly concerns 2)
5. Implementing petrol meter as regards range extender in cockpit display
6. Display in the vehicle if range extender operates
7. Warning display that range extender does not work but manual switch is ON (range extender not operating due to fault)
8. Defined discharge status of the traction battery to start range extender (no start if battery has full charge)

Several critical states have to be considered additionally. With respect to a recuperation of both drive motors and simultaneously charging via range extender, an overload of the traction has to be prevented. Hence, a range extender necessitates a specific operation point offering reduced electric power to the battery. A range extender should enable a continuous feeding of the battery during normal operation and, thus, significantly extend the maximal range of the electric vehicle.

Apart from a reliable and stable operation of a range extender, several additional requirements pertain in this context (Larminie and Lowry 2003). The main requirements of an combustion engine

used as range extender focus on minimum fuel consumption, compact design and inconspicuousness in terms of vibrations and noise (Münkel et al. 2011). The combustion engine has to be as fuel-efficient as possible in order to increase the operating distance of the range extender significantly. Moreover, legal and technical constraints regarding maximum weight and size of a trailer-range extender apply. In addition, the range extender should be environmentally compatible in terms of exhaust gases to confirm the sustainable claim of the Editha project. Thus, a petrol engine is preferred as opposed to a diesel engine (Helmers and Marx 2012).

## 2.2 Design of crucial Parameters

The requirements of an internal combustion engine as a range extender differ significantly from a combustion engine used in a parallel hybrid drive. The required power is in the range of 15 to 30 kW and, thus, considerably low (Münkel et al. 2011). Furthermore, the transient behaviour of the combustion engine is irrelevant due to the fact that the engine actuates the generator in a steady-state operating point. Hence, the operating range of the combustion engine is confined to charge the battery in an appropriate operating point (Fischer 2009).

Based on preliminary considerations of operating strategies, an appropriate set-up of the range extender occurs. Due to a potential range extender directly feeding Editha, specific requirements in terms of merging two different power trains arise. In this context, the precise energy and power demand of Editha has to be estimated. Moreover, a simplification of design is required. Accordingly, several components installed in Editha are also used for the range extender's design due to reasons of standardisation. This concerns both the planetary gear and the controllers as well as the drive motor that can be used as generator as well. Figure 1 illustrates the chosen configuration and the efficiency factors of all components in per cent. In consideration of the efficiency of Editha's power train (Wagenhaus et al. 2012), an appropriate connection of the range extender is necessary. Therefore, an electric link from the range extender between controller and drive motor is proposed. However, a direct feed-in of the battery implies an decreased efficiency due to an additional energy transformation.

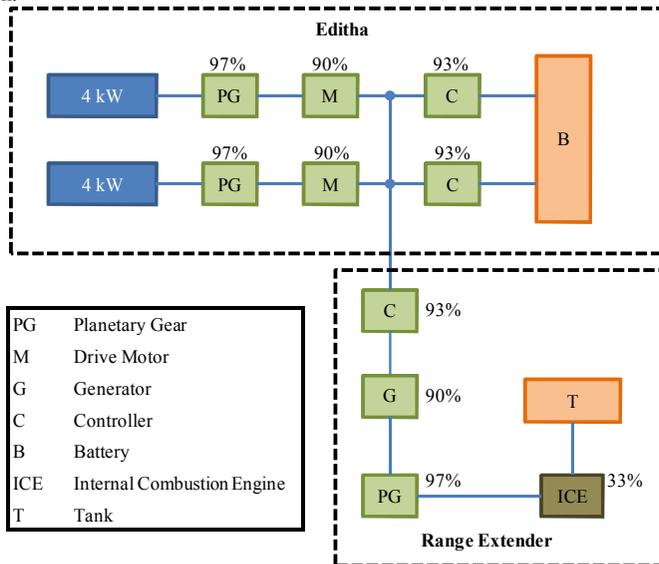


Figure 1: Interplay of Editha and Range Extender.

With respect to the mechanical energy output of Editha needed for an average speed of 80 km/h, an electric power of twice 5 kW has to be offered by a potential range extender. Due to further energy

losses during operation, a continuous driving operation of Editha necessitates an electric power of 11 kW provided by generator, thus a mechanical power of 13 kW provided by internal combustion engine. In addition, the legal towing capacity of Editha is confined. As a result, the maximal weight of a trailer-range extender is limited to 150 kg. Consecutively, an appropriate combustion engine was chosen with regard to both performance and weight criteria. The selected twin engine offers 45 kW mechanical power. In consideration of the weight of 35 kg and consuming 5,2 l petrol, this compact combustion engine meets all requirements (Section 2.1).

### **3 DETECTION OF THE ENGINE MAP**

#### **3.1 Engine Test Bench**

In consideration of the design and set-up of operating strategies of range extenders, the knowledge of the specific power generation and fuel consumption of the internal combustion engine need to be addressed. Thus, characterisation of the operational performance and development of the characteristic engine map in terms of consumption necessitate a measurement of the range extender internal combustion engine on an engine test bench.

The engine operating point is defined by its speed-torque characteristic. The entirety of all potential operating points generates the engine map in a two-dimensional representation. Within this characteristic engine map the scope of operation of an internal combustion engine is confined by the full-load curve as well as the minimum and maximum speed (van Basshuysen and Schäfer 2012). An engine map can consist of the specification of discrete values in individual points. In the presence of a large number of individual values over the entire operating range, lines of equal characteristics can be drawn by interpolation. Lines of constant power result in hyperbolas. Common engine maps pertain the specific fuel consumption. Lines of equal specific fuel consumption represent isolines. For each possible combination of speed and torque, the resulting specific fuel consumption can be read from the engine map. Usually, several operating points are possible with different fuel consumption for a certain required engine power (van Basshuysen and Schäfer 2012). Thus, the target is to operate an engine in ranges with the lowest specific fuel consumption.

An engine test bench for determining the properties of an internal combustion engine consists essentially of a electric dynamometer loading the combustion engine and a sampler measuring the supplied amount of fuel. For the determination of the operating performance of an internal combustion engine, it is connected by a rigid coupling to an electric dynamometer. The fuel supply is carried out directly by use of the sampler. Moreover, this enables the measurement of absolute fuel consumption regarding a specific load case of the internal combustion engine at a defined time interval.

#### **3.2 Detection and Analysis of the operational Properties**

Operating properties of the internal combustion engine were measured and developments of the characteristic engine map as regards to: consumption, parameters of the speed, torque and absolute fuel consumption were an integral part of the dynamometer tests. In a first step, the coarse measurement of the internal combustion engine was conducted. Accordingly, the parameters to be varied, here values of speed and torque, were divided in different measuring points within a predefined scheme over the entire operating range of the internal combustion engine. In this context, the scheme of measuring points defined an incremental variation of the torque with a fixed speed. Starting at the lowest possible speed of the internal combustion engine the torque is raised gradually up to its maximum. Subsequently, an increase in speed to the next higher level to be examined is realised in accordance with a settling time of the test structure. Furthermore, for each of the individual measuring points a detection of absolute fuel consumption occurred using the sampler. The successive raising of torque within a fixed speed avoids an influence on individual measuring points in terms of an incurred system status caused by the thermal impact of previous measurements. In consideration of the defined thermal ramp-up during conducting the series of measurements, this procedure ensures a reproducibility of the measurements. Regarding the intended steady-state operational behaviour of the engine as a range extender, a thermal ramp-up is essential to represent the future system behaviour.

The measurement started at the lowest revolution speed acceptable to the tested engine. This occurs in load-free state at a speed of 1000 rpm. In this context, a gradual loading of the internal combustion engine was conducted by an increase in torque in steps of 5 Nm at a fixed speed up to the respective maximum torque. Consecutively, the rotational speed was increased each time by 200 rpm. Thereby, the same torque variation at this fixed speed was conducted. In respect of the coarse measurement of the internal combustion engine, a maximum speed of 2800 rpm and a load of the engine with a torque of 45 Nm were attained. Based on the collected data of the conducted measurement, the characteristic engine map in terms of fuel consumption was subsequently developed. Thus, inferences on the operating performance could be drawn.

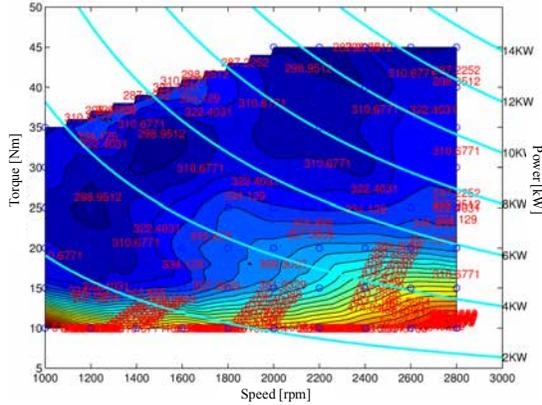


Figure 2: Engine characteristic Map.

In consideration of potential target areas for design and set-up of a steady-state range extender operation, the evaluation of the developed characteristic engine map as regards consumption showed that in particular two operating areas of the combustion engine should be pursued in order to ensure efficient energy conversion. Within these operating areas the mechanical power output is achieved at the least amount of fuel used. The dark blue areas in Figure 2 illustrate these optimal operating points. In respect of a high performance of the combustion engine, potential steady-state operations at a speed range from 1400 to 1600 rpm with a load of 30 to 35 Nm (offering about 5 kW) as well as from 2100 to 2300 rpm with a load of 40 to 42.5 Nm (offering about 10 kW) were detected by an additional engine test bench (detailed in Figure 3). The following fine survey of the combustion engine provides a specification of the measurements to confirm these potential areas and to further investigate the effects. Hence, similar to the coarse measurement of the combustion engine a specific measuring point scheme was created.

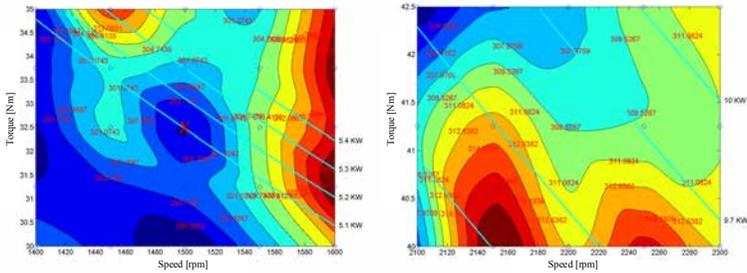


Figure 3: Specified Engine Maps.

As a result of the realised measurements shown in Figure 3, a steady-state operation at a speed of 1500 rpm is deduced for an efficient representation of a partial load of 5 kW (red cross on the left). Considering an efficient transformation of fuel used in mechanical energy output, implementing a full-load operation of 10 kW necessitates a speed range from 2200 to 2300 rpm (Figure 3, right).

### 3.3 Universal Use of Range Extenders

Apart from the utilisation of range extenders in the field of electric mobility, these systems can be used as stand-by generators. With respect to this alternative usage, the survey of the range extender technology gains additional currency. Accordingly, efficient and environmentally compatible combustion engines come in the focus of prospectively scientific research. Against this background, the decentralisation in terms of energy generation is enhanced. In this context, battery electric vehicles act as flexible energy storages balancing the discontinuous feed-in of renewable energy (wind, solar, biogas, etc.).

## 4 CONCLUSION

In summary, an exemplary solution by means of existing technology and partially modified combustion generator technology represents an initial solution to illustrate the functioning of the merging of two power trains. Hereby, the researchers combined modern and alternative power trains from the traditional internal combustion engine with highly innovative generators and control systems. Against the background of the resulting prototype, statements on evolution and development of new components can be made. Furthermore, the usefulness of relevant components is derived. Editha represents a testing platform that additionally offers an available space (the former engine) for a potential integration of a range extender as unique characteristic.

Characterising the driving cycles and conditions for the determination of appropriate operating points, it can already be noted that fundamental solutions for the combination of combustion technologies for extended range are possible. From a scientific point of view, particularly in the integration of miniaturised combustion technology into the existing vehicle design the question of a use-optimised basic design arises. In addition, the weight problem exists as well as the interplay of power train and energy source with respect to control technology. Thus, the range extender is systematically interpreted as universal benefit for the potential user. The overall scientific benefit thus obtains from the systematisation of combinatorics of different energy sources for generating electric mobility and the related alternative uses.

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## REFERENCES

- Fischer, R. 2009. Die Elektrifizierung des Antriebs – vom Turbohybrid zum Range Extender. In *30th International Vienna Motor Symposium*. May 7<sup>th</sup>/8<sup>th</sup>, 2009, Vienna.
- Helmers, E. and Marx, P. 2012. Electric cars: technical characteristics and environmental impacts. In *Environmental Sciences Europe*. Vol. 24, No. 14.
- Larminie, J. and Lowry, J. 2003. *Electric vehicle technology explained*. Chichester: John Wiley & Sons.
- Münkel, Ü., Schmalzl, H.-P., Wenger, U., Kohler, B. 2011. Die Zukunft des Verbrennungsmotors im elektrifizierten Fahrzeugantrieb. In *6. MTZ-Fachtagung - Der Antrieb von Morgen*. January 25<sup>th</sup>/26<sup>th</sup>, 2011, Wolfsburg.
- Kampker, A., Burggräf, P., Gartzten, T., Swist, M., Bäumers, Y., and Petersohn, G. 2012. Herausforderungen bei der Montage von E-Fahrzeugen. In *wt – Werkstattstechnik*. Vol. 102, No. 9, pp. 122-127.
- Tschöke, H. 2012. *Wankelmotor – Der bessere Range Extender?* February 13<sup>th</sup>, 2012, Wolfsburg.
- van Basshuysen, R. and Schäfer, F. 2012. *Handbuch Verbrennungsmotor*. Wiesbaden: Vieweg+Teubner.
- Wagenhaus, G., Heinicke, M., Kuhlmann, and K., Schünemann, M. 2012. Energy efficiency and sustainability in the car-based mobility - the case of the electric vehicle Editha. In *Advanced manufacturing technology XXVI*. Vol. 2. - Birmingham: Aston Business School, pp. 687-692.