

Research Paper

## The Effects of Use of the Range Extender in a Small Commercial Electric Vehicle

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### Abstract

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Research on the effects of the use of the range extender developed for a small commercial electric vehicle was presented in this paper. The range extender has a maximum output power of 2.65 kW. The developed auxiliary power unit consists of a three-phase generator propelled by an industrial low-power spark-ignition engine. The exhaust system was improved using a more efficient muffler. The implemented motorcycle muffler has a three-way catalyst (TWC) integrated inside. The use of the more advanced exhaust system aimed at reducing noise and exhaust emissions of the range extender. The efficient operation of the three-way catalytic converter requires a stoichiometric air-fuel ratio. To enable desired air-fuel ratio a fuel system was modified. In the first stage of research, the effects of improvements of the exhaust system on the range extender noise emissions were quantified. The next step covered the research of the fuel conversion efficiency, the exhaust gas composition, and the efficiency of conversion of the three-way catalyst. A significant decrease of noise and toxic gas emissions and an increase in the fuel conversion efficiency were revealed. The mentioned research was conducted in stationary conditions. After that, in the final part research of the running vehicle with the range extender on was made. The beneficial outcome of these tests enabled the development of a set of rules of the control of the range extender.

**Keywords:** Electric vehicle; Range extender; Fuel conversion efficiency; Spark ignition engine; TWC conversion efficiency; Noise reduction

### Abstrak

Penelitian tentang efek penggunaan range extender yang dikembangkan untuk kendaraan listrik komersial kecil disajikan dalam makalah ini. Range extender memiliki daya keluaran maksimum 2,65 kW. Unit daya tambahan yang dikembangkan terdiri dari generator tiga fase yang digerakkan oleh mesin bensin satu silinder daya rendah. Sistem pembuangan ditingkatkan menggunakan knalpot yang lebih efisien. Knalpot sepeda motor yang diimplementasikan adalah three-way catalyst (TWC) yang terintegrasi di dalamnya. Penggunaan sistem pembuangan yang lebih canggih bertujuan untuk mengurangi kebisingan dan emisi gas buang dari range extender. Pengoperasian yang efisien dari TWC memerlukan rasio udara-bahan bakar stoikiometri. Untuk mengaktifkan rasio udara-bahan bakar yang diinginkan, sistem bahan bakar dimodifikasi. Pada tahap pertama penelitian, efek perbaikan sistem pembuangan pada emisi dan kebisingan range extender dihitung. Tahap selanjutnya meliputi penelitian efisiensi konversi bahan bakar, komposisi gas buang, dan efisiensi TWC. Penurunan yang signifikan dari kebisingan dan emisi gas beracun dan peningkatan efisiensi konversi bahan bakar terungkap. Penelitian tersebut dilakukan dalam kondisi stasioner. Setelah itu, pada bagian akhir dilakukan penelitian kendaraan yang sedang berjalan dengan range extender. Hasil yang menguntungkan dari pengujian ini memungkinkan pengembangan satu set aturan kontrol range extender.

**Kata-kata kunci:** Kendaraan listrik; Perluasan jangkauan; Efisiensi keseluruhan; Mesin pengapian busi; Efisiensi konversi TWC; Pengurangan kebisingan



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## 1. Introduction

### 1.1. Background

Since the invention of the first motor vehicle until now, a continuous increase in the number of vehicles on the roads almost everywhere in the world is observed. This process is basically a result of lowering the price of cars produced on a mass scale, but also from the dynamic enrichment of societies in many countries considered so far poorly developed. The best examples of such countries are China and only to a slightly lesser extent India [1]. The development of motorization, however, puts many new and increasingly difficult challenges for those involved in this process. The continuous widespread use of hydrocarbon fuels for motor vehicles is associated with significant emissions of carbon dioxide and toxic gases into the atmosphere. What is more, fuels for vehicles now come mainly from crude oil refining, the resources of which will be depleted over the next few dozens of years. The length of the period in which humanity will use all the available oil reserves remains, admittedly, the subject of dispute among many scientists, but it is unquestionably certain that such a moment will come sooner or later [2].

A current concept to reduce the automotive emissions of carbon dioxide and toxic components of exhaust and replace fossil fuels used to drive vehicles with another energy source seems to be the popularization of vehicles powered by electric machines [3]. In addition to completely eliminating CO<sub>2</sub> emissions at the place of use of an electric vehicle, the use of electric drive has one more important advantage over the drive from the combustion engine. It is the reversible operation of the electric machine, which gives the possibility of recovering energy into the battery, which during the braking would be dissipated to heat in the elements of the vehicle's braking system [4]. Unfortunately, there are also several major obstacles to the development of electric vehicles. The most serious of them is still many times lower ability to accumulate energy in batteries in relation to the same mass or volume of fuel stored in the vehicle's tank. This results in a very significant limitation of the electric vehicle range compared to modern cars using an internal combustion engine [5]. Another serious challenge for the development of the electric vehicles sector is still a high price of batteries with a high specific

energy (Wh/kg), and it is obvious that such batteries must be used in vehicles in order to achieve a reasonable range [6].

A beneficial solution for a transitional period seems to be the combined use of an internal combustion engine and an electric machine in a vehicle with a hybrid drive system. Vehicles of this type are characterized by a clearly reduced fuel consumption and emission of toxic components of exhaust gases [7], [8], and on the other hand their range is the same or even larger than in the case of a comparable car driven solely by an internal combustion engine. It is just a matter of the size of the fuel tank. In cars with full hybrid drive system it is also possible to cover a distance of usually several kilometers with zero CO<sub>2</sub> emission. A slightly different concept of reducing the inconvenience resulting from low coverage on a single battery charge is the use of an on-board electric generator in an all-electric vehicle. Such a generator usually has a power significantly lower than the maximum power of the vehicle's propulsion motor, but it enables a significant increase of the vehicle's range without charging it from an external energy source. From its basic function, this device is usually referred to as the "range extender". The most well-known electric car produced in series, in which the optional range extender equipment is available is the BMW i3 model [9].

A similar concept for the development of electromobility guided the student project of a range extender designed for an electric light commercial vehicle with electric drive equipped with 48V electrical system. The device has been designed and made at the Faculty of Mechanical Engineering of the Cracow University of Technology by students associated in the Scientific Club of Combustion engines founded at the Institute of Automobiles and Internal Combustion Engines. This article describes the phases of further development of the project, which aims to familiarize students of mechanical engineering with the issues of the use of electric and hybrid drive in automotive vehicles. Preliminary information and a general description of the project can be found in the article [10].

### 1.2. The Existing Range Extenders

Many companies producing components for the automotive industry or research and

development institutions offer range extenders (RE) for motor vehicles with an electric drive [11], [12]. They are devices with a power usually not exceeding 50 kW. To achieve high efficiency, they are built based on a combustion engine with a small number of cylinders (often two) directly coupled with a brushless electric machine with excitation from permanent magnets. In order to reduce vibrations of the assembly, the engine is often equipped with a balancing shaft, sometimes a V-arrangement of cylinders is used, or even a rotary piston engine - Wankel type [13].

Nowadays, auxiliary power units are also manufactured for electric light vehicles with a relatively low system nominal voltage of 36 to 72V. Such devices are offered by at least several producers from Asian countries, mainly from China. They are most often built on the basis of a single-cylinder, air-cooled, spark-ignition engine with a displacement up to 300 cm<sup>3</sup>, but in a smaller number also range-extenders with liquid-cooled engines are available. The electric machine is usually mounted directly on the output shaft of the engine. In addition to the engine displacement, external dimensions of the assembly, its own weight and sometimes maximum power, manufacturers do not provide more detailed data on these devices. In many cases, it is not fully clear whether the power stated refers to the power of the internal combustion engine, or is the output power of the generator. According to the manufacturers' declaration, the offered range-extenders are equipped with automatic start of the charging unit and maintaining the desired operating parameters. **Figure 1** shows a general view of several exemplary range extenders offered on Asian markets for light electric vehicles.

A major difficulty in the analysis of the current state of knowledge in the field of on-board charging devices available for light electric vehicles is the fact that the mentioned range extenders are not offered on the European market, hence no more detailed technical information is available for these devices.

## 2. Materials and Method

### 2.1. 48V Range Extender Developed at the Cracow University of Technology Electric vehicle

The range extender being subject of this article has been developed for the electric light commercial vehicle Melex 945DS. It is a vehicle used for a transport of light loads inside factories or as a golf cart. Passenger versions are also produced, commonly used to transport tourists in historical centers of many Polish cities. The tested vehicle is in the possession of the Institute of Automobiles and Internal Combustion Engines of the Cracow University of Technology (CUT). The vehicle is used for didactic purposes, mainly for laboratory classes, but also for the implementation of student final projects in the field of electric drive in vehicles. The general view of the vehicle is shown in **Figure 2**.

The nominal voltage of the vehicle's electrical system is 48V. The vehicle's drive provides a separately-excited DC motor with an electronic controller. The factory electric energy storage system was built based on lead-acid batteries, however, as part of previous research and development [14] batteries were replaced with nickel metal hydride (NiMH) batteries adapted from the Toyota Prius NHW11 full-hybrid vehicle. **Figure 3** shows a general view of the currently used NiMH battery pack.



**Figure 1.** Low-voltage range extenders for light electric vehicles offered in Asian markets; a) 1 kW range extender with an air-cooled 2-stroke engine, b) 3 kW range extender with an air-cooled 4-stroke engine, c) 4.2 kW range extender with a water-cooled 4-stroke engine.



**Figure 2.** Electric light commercial vehicle Melex 945DS.



**Figure 3.** NiMH battery pack developed for the tested vehicle.

Thanks to the use of NiMH batteries, a significant reduction in the weight of the energy storage system (40 kg vs. 240 kg) has been achieved, which in the perspective allows to

increase the vehicle's payload. Deficiencies in the form of limited vehicle range can be compensated, if needed, by using the developed range extender. Due to the fact that the single NiMH battery module has a nominal voltage of 7.2V and 6.5Ah capacity, a serial connection of 7 sets of 5 modules connected in parallel is used in the developed pack. This gave the nominal voltage of the new 50.4V package, which is a value very similar to the previously mentioned 48V Melex electrical system voltage. Parallel connection of five modules results in a nominal pack capacity of 32.5 Ah. The basic technical specifications of the vehicle with the currently used energy storage system based on NiMH batteries and with the attached range extender is presented in [Table 1](#).

The total weight indicated in table 1 includes both the NiMH battery pack as well as the range extender developed in the current version. The range in all-electric driving mode is given for the driver + passenger load.

#### Description of the range extender design

The concept of design of the range extender has been based on the use of easily accessible, inexpensive materials and equipment as well as basic techniques for machining and joining materials, without resorting to casting technology

**Table 1.** Technical specifications of the tested vehicle with a NiMH battery pack and range extender

Parameter	Value/Description
Length x width	2660 x 1230
Wheelbase	1660 mm
Curb weight	460 kg
Vehicle capacity	2 people + 150 kg load
Battery type	NiMH modules(7.2V 6.5Ah)
Module connection in the pack	7 in series of 5 in parallel
Nominal voltage	50.4 V
Battery pack capacity	32.5 Ah
Motor type	DC, separately excited
Motor symbol	DV3-4006AA
Parameter	Value/Description
Motor controller	Curtis 1244
Rated armature current	100 A
Rated output power	3.9 kW at 4,300 rpm
Rated torque	8.2 Nm
Max. Motor efficiency	75 %
Total gear ratio	16
Tyre size	145/80 B10
Maximum speed	>30 km/h
All-electric range	approx. 10 km

or advanced machining. The on-board power unit developed at CUT was created as a combination of a single-cylinder spark-ignition internal combustion engine and a three-phase AC generator from a heavy-duty vehicle. The linking of these two devices is provided by a ribbed belt multiplier transmission. The devices were mounted on a frame made of steel profiles fastened to the body of an electric vehicle through rubber-metal elements damping vibrations. On the frame of the assembly there is also space for control and measuring devices of the range extender. The used internal combustion engine is equipped with a carbureted fuel system cooperating with a centrifugal governor. The useful range of rotational speed maintained by the governor is from 2,500 to approx. 3,700 rpm. The ignition system is of the electronic type. The ignition advance angle is fixed at 25°CA BTDC.

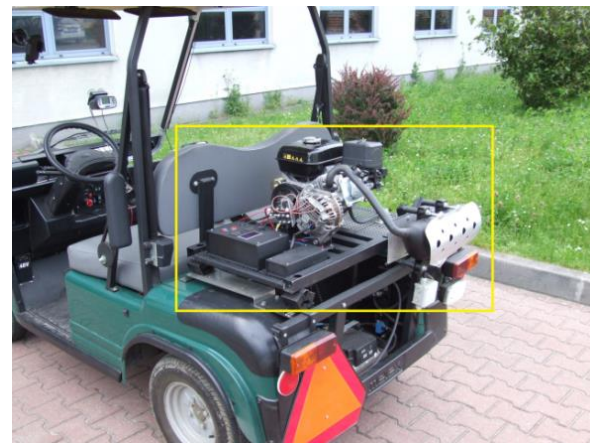
The output voltage of the used generator is regulated by changing the excitation current. Adopting the operation of the drive engine with constant speed, it allows the use of a relatively simple regulator of the output parameters of the generator. Due to the fact that the voltage of the end of charging of NiMH batteries used in the test vehicle exceeds 60V, the factory rectifier bridge integrated in the generator housing has been replaced with an external one with an increased allowed operating voltage.

In addition to the recoil starter, the range extender engine is equipped with an electric starter. This allows the auxiliary power unit to be activated while the vehicle is moving. At the moment, the start-up of the range-extender

depends on the decision of the driver of the vehicle. After testing the unit and the vehicle under various conditions, a controller will be made to enable the automatic start of the charging system according to current needs. [Table 2](#) presents the technical specification of the range extender used in this study.

The rotational speed at the maximum and rated output power of the range extender is given for the internal combustion engine. These figures were obtained after the introduction of modifications to the engine's power supply system allowing it to be supplied with a stoichiometric mixture. This system will be described later in the article.

The general view of the range extender in the current state of development is presented in [Figure 4](#). For better orientation, the developed range extender assembly was marked with a yellow rectangle.



**Figure 4.** General view of the developed range extender attached to the vehicle body

**Table 2.** Technical specifications of the range extender developed at CUT [10].

Parameter	Value/Description
Length x width x height	495x850x375 mm
Net weight	40 kg
Engine model	WEIMA 168FA
Engine type	four-stroke, spark ignition, single cylinder
Engine cooling method	forced air cooling
Engine displacement	163 cm <sup>3</sup>
Engine maximum power	3.8 kW at 3,600 rpm
Engine maximum torque	10 Nm at 2,500 rpm
Generator model	Mitsubishi A004TA0592
Generator type	3-phase AC, star winding connection
Rectifier type	3-phase full-bridge (6 diodes)
Transmission type	ribbed belt (gear ratio 0.55)
Range extender peak power	2.65 kW at 3,420 rpm (45A at 59V)
Range extender rated power	~2.20 kW at 3,420 rpm (42A at 53.5V)

## 2.2. Improvements of the 48V Range Extender Developed at Cut

### Motivation

As mentioned before, the engine used in the range extender was equipped with a carbureted fuel system. It provides easy start-up and stable operation of the engine under variable load, but under all operating conditions the engine is powered by a rich mixture. This does not have a positive effect on exhaust emissions and engine efficiency. Similarly, the exhaust muffler used in the factory design has small dimensions and, although it does not increase the external dimensions of the engine, but its noise suppression efficiency is relatively low.

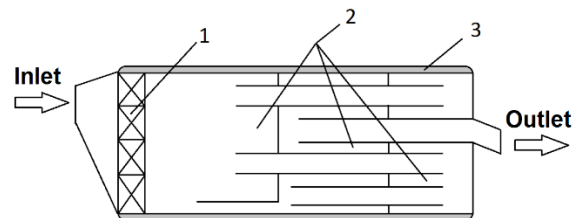
Due to the above-mentioned inconveniences in the further development work in the fuel system of the range extender, a modification was introduced involving the dilution of the air-fuel mixture formed by the carburetor into the stoichiometric composition using additional air supplied downstream from the throttle, and the original compact muffler was replaced by a muffler with an integrated three-way catalytic reactor adapted from a motorcycle engine with a similar displacement. These activities were aimed essentially at reducing noise and exhaust emissions and improving the overall efficiency of the range-extender.

### Muffler with an integrated three-way catalyst

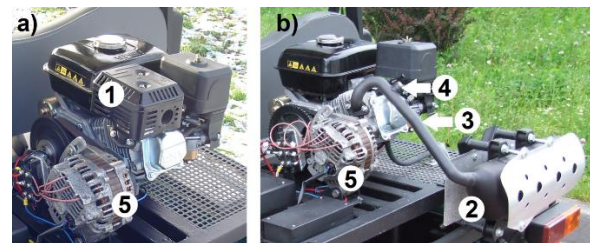
As part of the range extender modification work, the factory Weima engine muffler was replaced by a muffler coming from the Yamaha Majesty S XC125R motorcycle. This motorcycle is equipped with a 125 cm<sup>3</sup> displacement engine, which has a maximum power of 8.8 kW at 7,500 rpm. The muffler has three main chambers and a three-way catalytic reactor. **Figure 5** shows a schematic cross-section of the muffler made on the basis of pictures from an endoscopic camera. A three-way catalytic reactor with a metal support is embedded in the inlet part of the muffler.

The tube connecting the engine exhaust port with the muffler is made of steel pipes with an outside diameter of 26 mm and a wall thickness of 2 mm. Pipes made of a structural steel S235 were used. The pipes were connected by TIG welding in an argon shield. Exhaust ports for sampling exhaust gas and an oxygen sensor nut for the air-

fuel ratio correction system are located on the outlet pipe. The flange fastening the exhaust pipe to the cylinder head has been closely matched to the contour of the cylinder head outlet port in order to minimize the flow losses. **Figure 6** presents views of the range extender with the original muffler and the muffler adapted from the motorcycle.



**Figure 5.** A scheme of the muffler with an integrated three-way catalytic reactor; 1 - three-way catalytic reactor, 2 - chambers, and 3 - heat shield



**Figure 6.** Exhaust system of the developed range extender; a) old with the factory muffler, b) new with the muffler with an integrated catalytic converter; 1-factory muffler, 2-muffler adapted from a motorcycle engine, 3-exhaust pipe, 4-oxygen sensor nut, and 5-generator

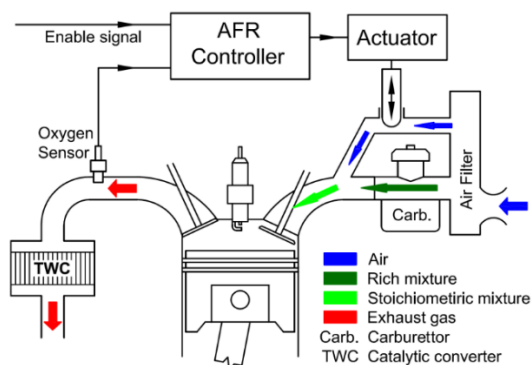
The new muffler is equipped with thermal shields and attached to the support frame of the range extender in such a way that no flexible fittings are required on the exhaust pipe connecting the cylinder head exhaust port with the muffler.

### Air-fuel ratio control system

The horizontal carburetor of the engine used in the range extender is of the float type. This carburetor is equipped with a typical butterfly throttle, the main system and an additional idle fuel nozzle. Enrichment of the mixture during the time of starting and initial warming up of the engine is accomplished by means of an additional, manually controlled throttle that obscures the inlet to the carburetor throat. Such a fuel system

has so far been widely used in industrial low power engines with spark ignition. It ensures correct and stable operation of the engine in the entire load and speed range, however, as already mentioned, the composition of the mixture coming to the engine is relatively rich. During the preliminary research, it turned out that relative air-fuel ratio (rel. AFR or  $\lambda$ ) when the engine is running under load is permanently lower than 0.9, and often also reaches values closer to 0.8. This causes high emission of carbon monoxide and unburnt hydrocarbons to the atmosphere. In addition, this causes a reduction in the efficiency of the engine and, as a result, the entire generator set.

In connection with the above, a decision was made to introduce a modification of the engine fuel system consisting in a controlled dilution of the rich mixture formed in the carburetor using the air fed downstream from the carburetor. The scheme of the developed system is shown in [Figure 7](#).



**Figure 7.** Scheme of the modified fuel system of the developed range extender

The closed-loop air-fuel ratio control system uses the oxygen sensor signal in the exhaust gas. Its task is to maintain the stoichiometric composition of the mixture (rel. AFR = 1.0) by adjusting the cross-section of the carburetor bypass. This is a prerequisite for the effective operation of the three-way catalytic converter (TWC) integrated in the muffler adapted to the range extender from a motorcycle engine. The principle of correction of the composition of the mixture is that the larger the cross-section of the port, the more air gets through the by-pass valve and the more diluted is the mixture prepared by the carburetor. Adjustment of the bypass channel cross section takes place by means of an actuator in the form of a stepper motor with a screw-nut

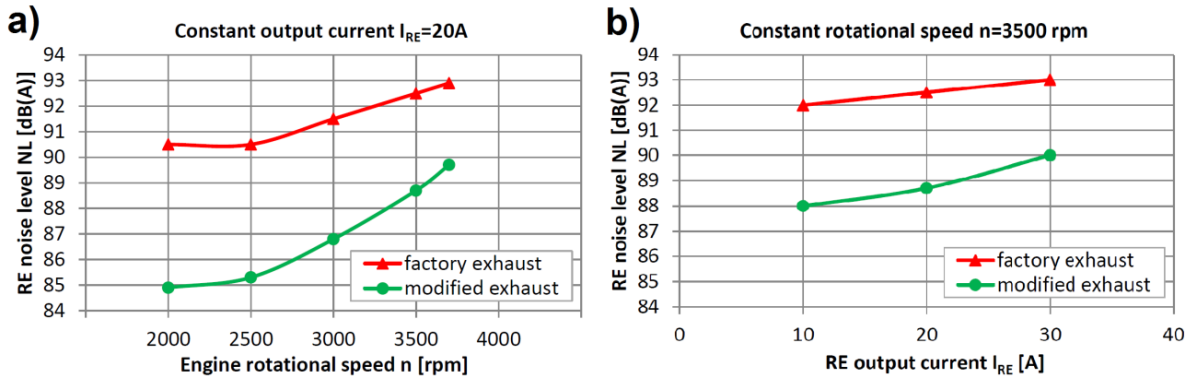
type transmission. Rotation of the stepper motor rotor displaces the stem covering the channel. On the engine start-up phase and its initial warm-up, the carburetor bypass valve remains completely closed, which allows the engine to be powered with a mixture of a suitably rich composition. The enable signal to start regulation of the air-fuel ratio is generated by the generator's control system. A detailed description and analysis of the functioning of the range extender air-fuel ratio correction system developed at the Cracow University of Technology is the subject of a separate article.

### 3. Result and Discussion

#### 3.1. Noise Emissions Reduction

After introducing the described modifications to the range extender, tests have been carried out to determine their effect on the operation of the charging unit. First, the noise level of range extender was tested. Noise tests were carried out in accordance with the Polish standard PN-S-04051:1992 based on the international regulation ISO 9645:1990. It provides that the ambient noise level should be measured before and during the measurement. The ambient noise level should be at least 10 dB(A) less than the noise generated by the vehicle. The measurement should be carried out under favorable ambient conditions, wind speed should not exceed 5 m/s. The measurement should be made in an open area, free from obstacles reflecting acoustic waves. The surface on which the measurement is made should be flat and horizontal. The measuring microphone should be positioned at the outlet pipe outlet height, pointing towards the tip and 0.5 m away from it. The maximum microphone sensitivity axis should be parallel to the surface of the measurement area and form a 45° angle with the vertical plane passing through the exhaust direction axis.

Noise measurement was carried out with a MeasureMe MT90 sound level meter in dB(A). The ambient noise level at the test site was 50 dB(A). A series of 8 measurements was carried out at different operating points of the power unit, and hence the engine load and rotational speed. The measurement results for the factory exhaust system and the modified exhaust system are shown in [Figure 8](#). In part a) a comparative graph for a generator output current of 20A and variable



**Figure 8.** Noise level of the range extender with a factory- and modified exhaust system; a) in a function of engine rotational speed at a constant load, b) in a function of RE load at constant engine rotational speed

speed is shown, while in part b) a dependence for a constant engine speed of 3,500 rpm and variable generator load is shown. The modified exhaust system caused a significant reduction in the level of sound intensity emitted by the range extender, in each case by at least 3-4 dB(A). It means that for the human ear the noise emitted by the range extender is at least twice as small.

The results of the research are also confirmed by the subjective feelings of the authors of this study. The difference in the intensity of the sound emitted by the exhaust system is so significant that after the modification the operation of the internal engine mechanisms, i.e. the crankshaft and timing system, started to be heard.

### 3.2. Overall Efficiency and Exhaust Emissions Improvements of the Range Extender

In order to determine the effects of modifications of the exhaust system and fuel system on the overall efficiency of the range extender  $\eta_{RE}$ , measurements of fuel consumption at several points of the engine's map were carried out simultaneously registering the energy supplied by the power unit to the battery. The general efficiency of the range extender is determined by Eq.(1):

$$\eta_{RE}=100 \cdot \frac{E_{RE}}{m_f \cdot LHV} \quad (1)$$

where:

$\eta_{RE}$  - overall efficiency of the range extender, %  
 $E_{RE}$  - energy delivered by the range extender, kJ  
 $m_f$  - mass of a gasoline consumed in the test, kg  
 $LHV$  - lower heating value of the gasoline, kJ/kg

The gasoline  $LHV$  value of 43,000 kJ/kg was used for calculations [13]. Measurement of the fuel

consumption was realized by placing the fuel tank on the Shinko Denshi Vibra AJ-12KCE electronic balance and determining the mass of fuel consumed under the determined engine operating conditions during the registration of energy supplied to the storage system.

The amount of energy supplied to vehicle batteries is determined using following Eq.(2):

$$E_{RE} = \int_{t_0}^{t_1} V_{bat} \cdot I_{RE} dt \quad (2)$$

where:

$V_{bat}$  - battery voltage, V

$I_{RE}$  - current delivered by the range extender, A

$t$  - time, s

0/1- start/end of the measurement

The value of the battery charging current was measured using an ACS758 current sensor with a sensitivity of 0.04 V/A. To measure the battery voltage a resistive voltage divider with 1:6 ratio was used. During the measurements, the battery temperature based on the voltage signal from the thermistor sensor and the engine speed based on the pulse signal from the Hall sensor were also recorded. Analog signals of battery voltage, RE output current, battery temperature and frequency signal of speed were being recorded in the Racelogic PerformanceBox, which is basically intended for testing traction parameters of vehicles using GPS 10Hz technique, but after retrofitting with a data acquisition module also works well as a logger of measurement data, both in dynamic and stationary measurements.

First of all, tests of the overall efficiency of the power unit were carried out before the modification of the exhaust system and the fuel



system were introduced. To obtain a sufficiently high accuracy of measurements, the time of recording of operating parameters was defined as the time of mass consumption of approximately 60-70 g of fuel. Four points were selected from the range extender operational map (output current - engine rotational speed) of 15 A - 2,500 rpm, 25 A - 2,500 rpm, 28 A - 3,500 rpm, and 37 A - 3,500 rpm.

Testing the overall efficiency of the charging unit after using a new exhaust system and fuel system with the correction of the air-fuel ratio was carried out for two points from the range extender operational map of 25 A - 2,500 rpm and 37 A - 3,500 rpm.

Together with tests to determine the effect of the use of the new exhaust system and the mixture correction system on the overall efficiency of the charging unit, the engine exhaust composition tests were also carried out. In the case of the factory exhaust system, measurements of the exhaust gas composition leaving the engine were carried out, while after the application of a new muffler, the exhaust gas composition measurements were carried out both upstream and downstream from the catalytic converter. In addition to assessing the composition of the exhaust gases leaving the engine, it allowed to determine the conversion efficiency of the three-way catalyst.

Arcon Oliver K4500 analyzer was used to measure of volumetric concentration of CO<sub>2</sub>, CO, O<sub>2</sub>, NO<sub>x</sub> and total HC in exhaust. The used analyzer is of class 0 and employs NDIR (Non-Dispersive Infrared) method to indicate carbon dioxide, carbon monoxide and hydrocarbons concentrations. Oxygen and nitric oxides concentrations are measured using electrochemical cells. The modified Brettchnieder formula is applied in analyzer to calculate relative air-fuel ratio basing on the measured exhaust components concentrations.

Figure 9 presents the results of the overall efficiency of the unmodified range extender operating in the four above-mentioned points of the operational map and in two points for the power unit after the modification of the exhaust and fuel systems.

The tests carried out showed that while working with a relatively low load (points 15A-2,500 rpm and 28A-3,500 rpm), the range extender achieved overall efficiency below 15%. For this

reason the modified unit was not examined at these points.

A comparison of the overall efficiency of the range extender obtained at 2,500 rpm and 25A load indicated that after the introduction of AFR correction to the stoichiometric point and the new muffler, a relative efficiency gain of 4.8% was obtained, and at 37A - 3,500 rpm the relative efficiency increase was above 11%. Achieving the overall efficiency of 17.9% means that the specific fuel consumption at this point was equal to approximately 468 g/kWhe, what may be considered as a beneficial result for such a simple design of genset and a small SI engine. The reasons for the efficiency increase should be seen mainly in the application of the air-fuel ratio correction system. The use of a new exhaust system played a smaller role here.

Figure 10 to Figure 13 show the results of the exhaust composition tests for four analyzed operational points of the range extender. In the case of points 15A - 2,500 rpm and 28A - 3,500 rpm, the results of measurements of the composition of exhaust gases collected from the port connecting the engine cylinder head with the factory muffler Weima are presented. For points 25A - 2,500 rpm and 37A - 3,500 rpm, comparisons of the exhaust compositions of the engine running without AFR correction with the factory muffler and after the application of a new muffler with a catalytic converter and with the working AFR correction system are presented. In the case of the modified range extender, the composition of the exhaust gas was measured both upstream (upstr.) and downstream (dwnstr.) from the catalytic converter.

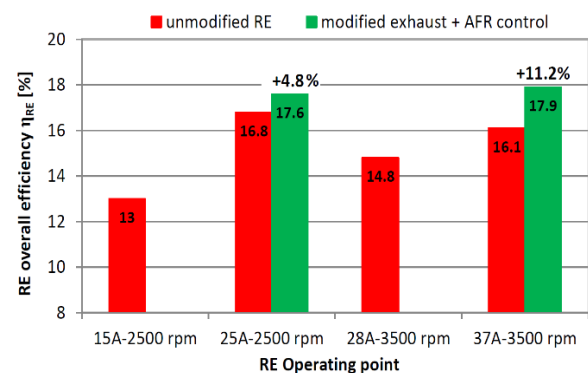


Figure 9. Overall efficiency of the range extender before- (red bars) and after (green bars) introducing modification of exhaust system and air-fuel ratio correction system.

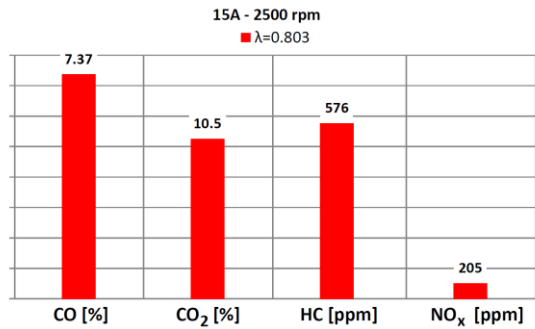


Figure 10. Exhaust gas composition recorded for the unmodified range extender in the operating point 15A - 2,500 rpm

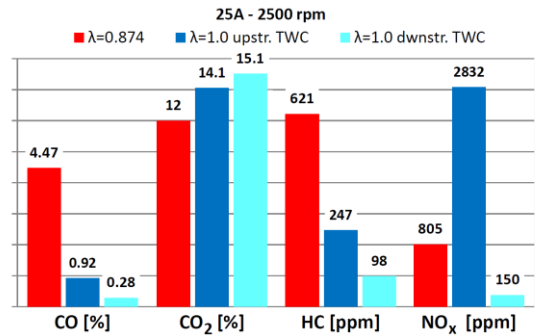


Figure 11. Exhaust gas compositions recorded for the unmodified ( $\lambda=0.874$ ) and modified ( $\lambda=1.0$ ) range extender in the operating point 25A - 2,500 rpm

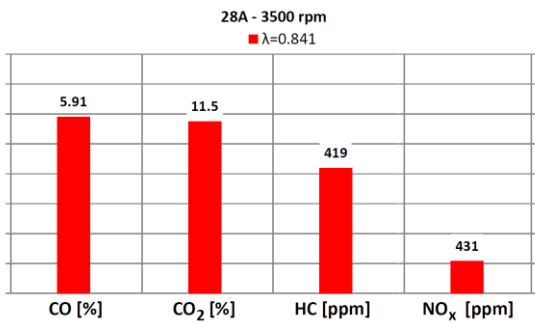


Figure 12. Exhaust gas composition recorded for the unmodified range extender in the operating point 28A - 3,500 rpm

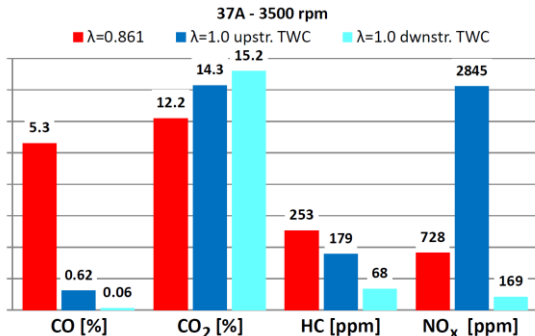


Figure 13. Exhaust gas compositions recorded for the unmodified ( $\lambda=0.861$ ) and modified ( $\lambda=1.0$ ) range extender in the operating point 37A - 3,500 rpm

In each of the four operational points it was revealed that the engine of the unmodified range extender was running on the rich mixture, in the case of 15A - 2,500 rpm relative air-fuel ratio  $\lambda$  reached a value very close to 0.8, which resulted in a very high concentration of CO in the exhaust. Due to the supply of a rich mixture, also the concentrations of unburned hydrocarbons in the exhaust gases were high. After applying the modification of the fuel system allowing engine operation on the stoichiometric mixture, the volumetric concentrations of CO and HC decreased significantly, while the concentration of nitrogen oxides in raw exhaust gases increased significantly, which was expected. However, as

can be seen, the catalytic converter performed very well with NO<sub>x</sub> concentration reduction, so that their volumetric concentrations downstream from the catalytic reactor were significantly lower than in the raw exhaust of the range extender before modifying the fuel and exhaust system.

As in the case of the modified range extender, the composition of the exhaust gases was measured both upstream and downstream from the catalytic converter, it was possible to determine the efficiency of the aftertreatment system. Figure 14 presents the results of conversion efficiency of harmful exhaust components by a catalytic converter integrated in a muffler adapted from a motorcycle.

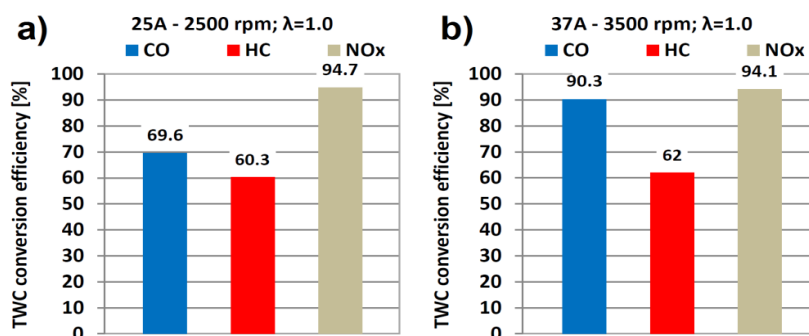


Figure 14. Three-way catalyst conversion efficiencies in the operating points: a) 25A - 2500 rpm and b) 37A - 3500 rpm

The most beneficial efficiency of decreasing the emissions of toxic exhaust components was achieved by the catalytic converter in the case of nitrogen oxides - approx. 94%. In the case of carbon monoxide for point 25A - 2,500 rpm, the efficiency of TWC conversion obtained the value of about 70%, in the second of the measurement points it was already over 90%. Slightly lower values were obtained in the case of efficiency of neutralization of unburnt hydrocarbons, however, in both cases efficiency exceeded 60%. In general, the analysis of conversion efficiency of a catalytic converter indicates that the device works very effectively.

### 3.3. Mode of a Maximal Utilizing of All-Electric Range

After successful tests in stationary conditions, the range extender tests during normal vehicle driving were performed. The first of two dynamic tests of the vehicle, which are the subject of this study, consisted in verification of the possibility of driving a vehicle with a fully discharged battery and with the working power unit. This test was aimed at determining the maximum all-electric range of the Melex vehicle, assuming that arrival

to the destination will be done at a limited speed and with the range extender working. The tests were carried out with the vehicle loaded with two people (driver and passenger). The vehicle's, range extender and batteries operating parameters recorded during this test are presented in Figure 15.

After travelling distance of 11.9 km, the batteries of the vehicle reached full discharge (State of Charge, SOC = 0%). In the graph showing the battery voltage as a function of time, this fact is reflected in the form of a temporary voltage drop below 40V. Further driving in all-electric mode was not possible in this situation, because it would lead to irreversible damage of the battery. After the battery was completely discharged, the range extender was started. As can be seen in the lower part of the Fig. 15, the engine of the range extender was operated at 2,750 rpm, while its output power was set at 1.3 kW, which resulted from the output current of 27A. The use of such range-extender settings has enabled the vehicle to continue to travel to its destination after just 19 seconds from the time the battery charge was started. The only limitation was a slight reduction in the speed of the vehicle when returning.

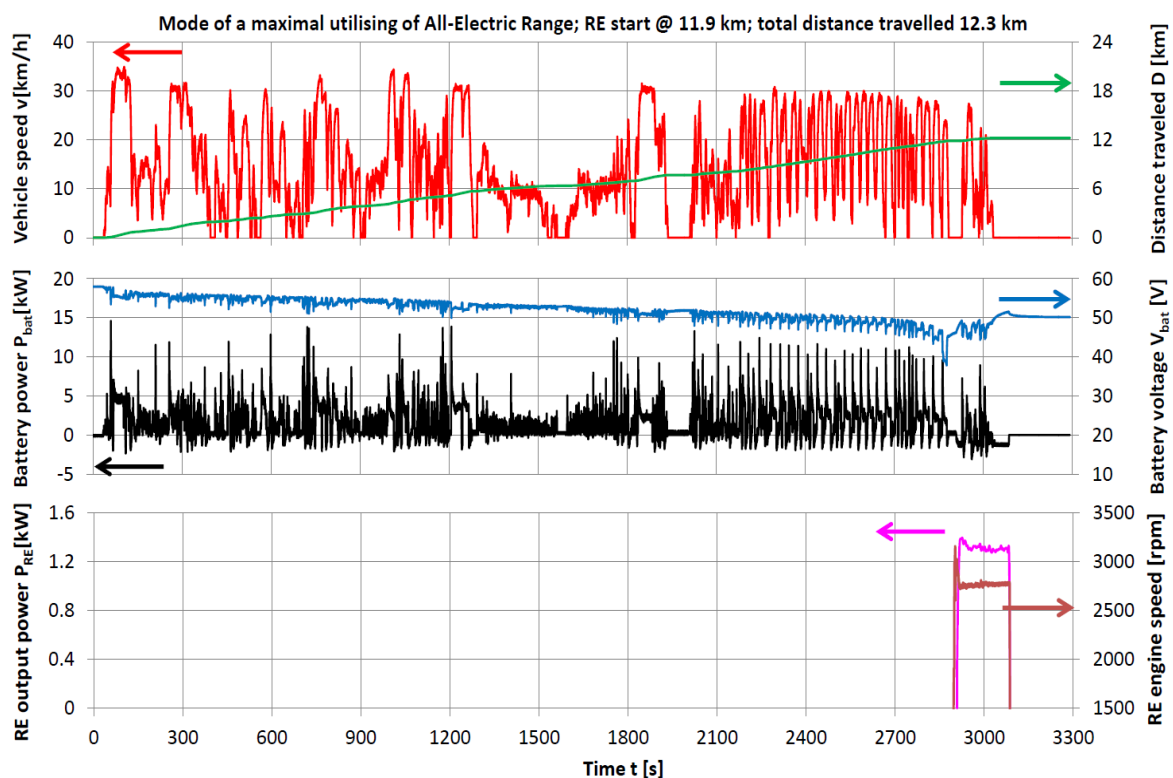


Figure 15. Vehicle, range extender and battery operational parameters during test of the mode of maximal utilizing of all-electric range

### 3.4. Extended Range Mode

The last attempt was made to verify to what extent the use of the developed range extender makes it possible to extend the range of the electric vehicle. Before testing, the vehicle batteries were charged to 100% SOC. The tests were carried out with the vehicle loaded with two people (driver and passenger). The first five kilometers the vehicle passed in pure electric mode, which meant the use of about 45% of the electricity stored in batteries. The generator has been started at this moment. It was adopted that the engine will work at the rotational speed of approximately 2,500 rpm and a generator load of 23A, i.e. at the point where the range extender after modifications achieved high efficiency above 17.5% in stationary tests and low noise emission below 86 dB(A). Figure 16 presents the graphs of driving speed and distance covered by the vehicle, power and voltage of the battery as well as output power and engine speed of the range extender registered in the extended range test.

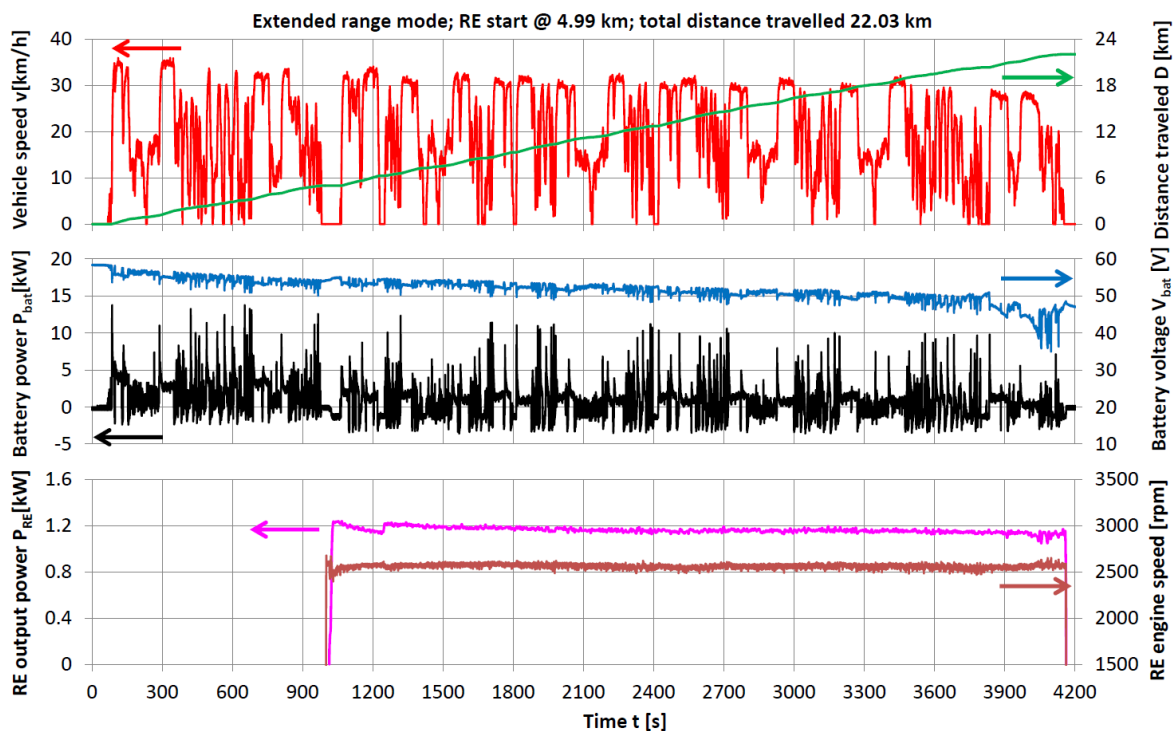
Driving with a running generator continuously supplying 1.2 kW of electric power enabled the vehicle to travel a total distance of 22 km, until the battery voltage under load dropped below 42V, which is the limit value of discharge for the NiMH package used [15]. Obtaining a

distance of 22 km means more than doubling the range of the vehicle compared to the all-electric mode.

While testing the range extender's operation in the extended range mode, the mass of the tank with fuel before and after test was determined. This made it possible to determine the fuel consumption of the power unit, and in combination with the results of electrical parameters, also the overall efficiency of the range extender in real traffic conditions. Table 3 presents the results of measurements and calculations of fuel consumption, energy supplied and overall efficiency of the range extender operating in the extended range mode. The value of overall efficiency of the range extender obtained in this test coincides with the value obtained during one of the stationary tests.

**Table 3.** Working parameters of the range extender in the extended range mode

Parameter	Value
RE operation time	3148.7 s
Distance travelled with RE operating	17.04 km
Energy delivered by RE	1.01 kWh
Mass of the consumed fuel	481.4 g
RE overall efficiency	17.6 %



**Figure 16.** Vehicle, range extender and battery operational parameters during test of the extended range mode

#### 4. Conclusion

The introduced improvements of the range extender significantly influenced on lowering of the environmental burden. The noise and exhaust emissions were remarkably reduced. The applied muffler with the integrated aftertreatment allowed the increase in the fuel conversion efficiency of the range extender. That causes reducing of CO<sub>2</sub> emissions and lowers costs of energy for the vehicle. The research of the efficiency of the range extender revealed the points where it operates the most favorable. That enabled development of the beneficial algorithm for the control of the range extender. Among others the current state of the battery and the driver's wishes could be taken into account there. Essentially, it is preferable that the charging unit provides the needed power at the lowest engine speed, i.e. operating at a high relative load for the engine and generator. As it is known, both devices obtain the highest efficiency in this case [16]. The belt transmission efficiency also obtains high values for a high relative load. The tests confirmed that the parameters of the ribbed belt transmission were chosen correctly. It is not necessary to use a more complicated transmission of another type, e.g. with a toothed belt [17], which was considered at the initial stage of the development of the design. Despite the use of the simple generator and the belt transmission, a satisfactory results of the overall efficiency of the range extender developed in the CUT has been achieved. During stationary tests, it was also determined that the three-way catalytic converter integrated in the new muffler achieved very good neutralization efficiency of toxic exhaust components. It is important to precisely maintain the stoichiometric composition of the mixture, which is the task of the correction system of the mixture composition. The test results confirmed that the developed air-fuel ratio correction system correctly performs the assigned task.

The tests of the running vehicle with range extender on confirmed the results of stationary tests of the range extender, as well as its appropriate action. The use of range extender supplying electric energy to the vehicle when the battery being discharged allowed the full use of the vehicle's electric range. The user did not have to worry to not to arrive to chosen location. The second dynamic test when the auxiliary power

unit operated continuously starting at 50% of the state of the charge of the battery revealed that the vehicle range could be increased at least twice using the developed range extender. If the higher output power of the unit would be set, even a greater range gain could be obtained, but the conservative working parameters of the range extender was chosen to allow comfortable driving. When the unit is working with higher speed and output power, the system generates more noise and vibrations. Optimization of the vibration reduction system will be the subject of one of the next studies.

The development of the range extender is going to be continued. The plans foresee implementation of a fuel injection system and an integrated electronic engine management system. Together with the engine design modifications those should enable to further improve in the range extender efficiency and to reduce exhaust toxicity also in non-stationary operation (i.e. during engine start-up, warming up, changes of rotational speed and load, as well as during its switching off). Finally the use of alternative fuels for the range extender is considered. Application of various gaseous fuels, bioethanol blended with gasoline - E85, or gasoline with high bio-components content, could help to decrease CO<sub>2</sub> emissions. That is caused by the more beneficial hydrogen/carbon ratio for these fuels comparing to petrol [18]–[20].

In summary, it should be stated that the developed range extender design is worth pursuing further research and improvement. The auxiliary power unit is a good facility to deepen knowledge, develop interests and skills acquired by students in the field of mechanical engineering, in particular hybrid and electric drive systems. Certainly, this is not possible to implement it to a similar extent during classical laboratory classes conducted in larger groups and limited time frames.

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#### Author's Declaration

##### Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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## Availability of data and materials

All data are available from the authors.

## Competing interests

The authors declare no competing interest.

## Additional information

No additional information from the authors.

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