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Modeling and Analysis Range Extender for Battery Electric Vehicles

Streszczenie. *W publikacji przedstawiono wyniki analiz dotyczących zastosowania spalinowych zespołów prądotwórczych małej mocy wykorzystywanych do zwiększania zasięgu pojazdów z napędem elektrycznym. Spalinowe zespoły prądotwórcze stanowią rozwiązanie podstawowych wad pojazdów elektrycznych, takich jak ich krótki zasięg, wynikający z ograniczonej pojemności akumulatorów i długiego czasu ich ładowania. Stosuje się je głównie do przejazdów na długich dystansach pomiędzy miastami. W pracy omówiono podstawowe konfiguracje układów napędowych stosowanych w pojazdach elektrycznych i hybrydowych, oraz zaprezentowano podstawowe konfiguracje układów napędowych wykorzystujących spalinowe zespoły prądotwórcze do zwiększania zasięgu pojazdów z napędem elektrycznym. Na podstawie testów trakcyjnych zrealizowanych w rzeczywistych warunkach drogowych dla samochodu elektrycznego wspomaganego pracą spalinowych zespołów prądotwórczych (4 kW benzyna, 5,5 kW diesel) zainstalowanych na lekkiej przyczepie, opracowano model matematyczny układu w środowisku Modelica. Opracowany model matematyczny uwzględnia obciążenia dynamiczne działające na zespół pojazdów w ruchu wraz z elektrycznym układem napędowym wspomaganym przez spalinowy zespół prądotwórczy. Przedstawiono wyniki badań symulacyjnych dla wybranych profili trasy i prędkości jazdy. Przeprowadzono badania dla wybranych wartości współczynników stanu naładowania akumulatorów $SOC_{ON\text{-}OFF}$ (ang. State Of Charge), mających kilkuprocentowy wpływ na zmniejszenie zużycia paliwa i emisji szkodliwych gazów do atmosfery przez silniki spalinowe zespołów prądotwórczych.*

Abstract*. The publication presents the results of analysis regarding the use of low-power diesel generating sets used to increase the range of electric vehicles. Diesel generating sets are a solution to basic shortcomings of electric vehicles, such as their short range, resulting from the limited capacity of batteries and their long charging time. They are mainly used for long-distance journeys between cities. The paper discusses the basic configurations of drive systems used in electric and hybrid vehicle and the basic configurations of drive systems using combustion generating sets for increasing the range of vehicles with electric drive are presented. On the basis of traction tests performed in real road conditions for an electric car assisted by two diesel generators (4 kW petrol, 5.5 kW diesel) installed on a light trailer, a mathematical model of the system was developed in the Modelica environment. The mathematical model developed takes into account the dynamic loads acting on the set of vehicles in motion along with the electric drive system supported by the diesel generator set. The results of simulation tests for selected route profiles and driving speed are presented. Research has been carried out on selected values of the state of charge $SOC_{ON\text{-}OFF}$ (State Of Charge) of batteries, which cause a several percent impact on reduction of fuel consumption and the emission of harmful gases to the atmosphere by internal combustion engines.* ***(Modelowanie i analiza zastosowania układu zwiększania zasięgu dla pojazdów elektrycznych).***

Słowa kluczowe: pojazdy elektryczne, układ zwiększania zasięgu, akumulatory litowe, poziom naładowania akumulatora (SOC).
Keywords: electric vehicles (EV, BEV), range extender, lithium batteries (Li-Ion, LiFePO4, LTO), SOC (State Of Charge).

Introduction

Greenhouse gases emitted by internal combustion engines are mainly: carbon dioxide CO_2, carbon monoxide CO, sulfur oxides SO_x, nitrogen oxides NO_x, hydrocarbons, methane and particulates [1]. As one of theories says, greenhouse gases emitted largely by road transport are responsible for intensifying climate change such as global warming and smog in cities [2]. The simplest solution to reduce greenhouse gas emissions is to reduce the fuel consumption of the vehicle. On this basis, the European Union sets strict requirements regarding the reduction of emissions of harmful substances into the environment, forcing automotive companies to use more and more advanced technologies. To achieve this goal, designers and constructors strive to reduce the resistance of vehicle movement by reducing: vehicle weight, aerodynamic resistance and rolling resistance [3]. The most effective solution to reduce the emission of harmful greenhouse gases is to focus the development of the automotive industry on the improvement of vehicles powered by electricity. The primary disadvantages of electric vehicles include their short range, which is caused by limited capacity of the available batteries and the time needed to charge them, which ranges from a few minutes to even several hours.

There are many different technological solutions that aim to increase the range of vehicles while minimizing the emission of harmful greenhouse gases. These solutions include, inter alia, the installation of power lines for the vehicle, installed over the road on which it moves [5] or the construction of a road covered with photovoltaic panels with devices for wireless transmission of energy directly to the vehicle [6, 7]. Another solution to augment an electric propulsion system is to support it with a combustion engine [8–10], micro gas turbine [11–13], fuel cells [14–20], supercapacitors [21], or various types of batteries with the possibility of their charging while driving [22–26].

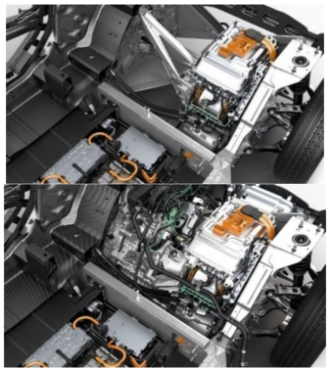

Fig. 1. Comparison of BMW i3 powertrains without REX and with REX [4].

Hybrid vehicles can be divided according to the type of the drive system, i.e. the method of connecting the electric and combustion engine together. There are three main structures: serial, parallel and mixed. In series hybrid propulsion systems the vehicle's wheels are driven by an electric motor, and the internal combustion engine drives the generator that charges the battery pack. This type of drive system requires two electric machines. One of them acts only as a generator, while the other drives the vehicle and can recover energy during braking. The range extender system can be mounted either inside the vehicle structure (Fig. 1) or be attached from the outside (Fig. 2). The installation of the REX (range extender) system inside the vehicle, which was designed for the conventional engine, causes to increase noise [27] and vibration [28] in the cabin while driving. The power of the installed generating set should ensure coverage of the vehicle full energy demand in highway traffic. In the last five years, several simulation results of electric cars equipped with a range extender system installed inside the vehicle have been published [29, 30]. The influence of changes in the SOC [31] and generator power [31–33] on the range of the car was investigated. The research also examined the influence of the engine temperature on its fuel consumption [34]. If the battery state of charge is in the appropriate range, the internal combustion engine is turned off and the vehicle is powered only from the energy contained in the batteries. Only when the amount of stored energy falls below the safe value, the combustion unit will start up.

Fig. 2. EP Tender's REX construction [35].

The greatest advantage of combining two energy sources in one vehicle is more efficient use of both sources. This solution helps significantly reduce greenhouse gas emissions. In addition, drivers of electric and hybrid vehicles can use free parking spaces in city centers, discounts on motor insurance, as well as have the possibility of using bus only lanes.

The disadvantages of all REX systems driven by internal combustion engines are emission of harmful compounds to the atmosphere, necessary maintenance of generators, and additional cost of fuel. After placing the unit on the trailer, there are aspects such as trailer storage and mandatory motor insurance. In addition, performing maneuvers with a trailer for some drivers can be a significant obstacle. The solution to the problem of maneuvering with a trailer can be the use of the concept of the torsional axis of the trailer "BackTracker Steering System" [36] or the solution called "Dock+Go" [37].

Fig. 3. Rinspeed Dock+Go Concept [37].

The perfect electric car is one that, apart from its fashionable appearance, is able to travel about 1000km (620mi) without stopping to charge the batteries. In addition, it should be characterized by highly reliable operation, low operating costs, and most importantly, it does not poison the environment with harmful gases, which it is safe and silent to move around.

In everyday life, a minimum of 80% of European society living in cities, could use electric cars [38], and thus significantly reduce the emission of greenhouse gases and smog in cities. Taking into account the changes in the regulations on the withdrawal of conventional combustion engines [39–42] and the short distance of electric vehicles, engineers and constructors proposed to attach to the vehicle a range extender system that allows to travel a greater distance. Such a solution would allow traveling between cities or outside the city without having to make longer stops to recharge the batteries. Range Extender system, is alternatively called Range Extending Trailer - Generator, Genset Trailer, Long Range [43]. It is usually a trailer with an additional source of electric power installed, such as an additional set of batteries, supercapacitors, a power generator, as well as combinations of various energy sources.

In this article, a simulation analysis of the mathematical model of the drive system of a Fiat Panda EV electric car with a range extender system will be carried out. The simulation will be performed in the Modelica package on the previously registered route profile and the travel speed of the actual section of the route with a length of 271 km between Szczytno and Gdynia. The analysis was subjected to the influence of the SOC_{ON-OFF} coefficient on the battery state of charge and the operation time of generating sets.

Modeling

A. Vehicle model with range extender

The second generation Fiat Panda is a typical "A" segment car ideally suited for urban traffic. The internal combustion engine with a displacement of 1200 ccm has been removed from the car with, and in its place was installed a synchronous motor, powered by an IGBT inverter, which was placed in the central part of the vehicle's front section. Above the electric motor, a container with a packet of lithium-iron phosphate batteries (LiFePO4) is mounted. The other two battery packages were located respectively under the rear passenger seat and in a custom made container located in place of the spare wheel well. In total, 30 LiFePO4 cells were installed, with a capacity of 160 Ah each, which allowed to obtain the total capacity of the battery pack at the level of about 15840 Wh [44].

Fig. 4. View of the Fiat Panda EV engine compartment with electric drive system.

The main element of the drive system is a synchronous motor with a sinusoidal shape of the PMSM electromotive force, with twelve concentrated coils in the stator circuit and an eight-pole rotor. This motor has the following parameters:

- nominal power 50 kW,
- maximum power 85 kW,
- nominal current 260 A,
- maximum current 440 A,
- nominal torque 105 Nm,

• maximum torque of 190 Nm,
• nominal speed 4300 RPM,
• type of cooling: air stream [44].

Presented Fiat Panda EV is equipped with a tow hitch with a special connector that allows electrical energy flow from the range extender.

Fig. 5. Fiat Panda EV with a range extender system.

The REX system is based on power generators, it uses a light trailer with a curb weight of about 120kg with two generators installed in full configuration. It is possible to change the configuration of generators on the trailer, which allows installation of one diesel generator (Gen1) or a one gasoline engine generator (Gen2), or both at the same time.

Fig. 6. Trailer with a Range Extender System.

Fig. 7. A. Gen1-Bergo SD6000, B. Gen2-Aodisen ADS5500.

Table 1. List of generator set data.

	GEN 1	GEN 2
Manufacturer's name	Bergo	Aodisen
Model	SD 6000	ADS5500
Nominal power [kW]	5.5	4
Maksimum power [kW]	6	4.5
Output voltage [V]	230	230
Frequency [Hz]	50	50
Fuel type	Diesel	Gasoline
Fuel tank capacity [ltr]	12.5	25
Combustion at nominal power [l/h]	1	2
Weight [kg]	127	80

B. Drive system model

For research purposes, a mathematical model was developed that describes the drivability of a vehicle set. The set consists of an electric car Fiat Panda EV and a light trailer towed by it, equipped with two power generators (Fig. 8). This model has been implemented in the OpenModelica environment.

The vehicle model contains such subsystems as: electric drive system (motor, converter, and battery pack), gearbox, differential, and drive wheels. In addition, the model includes a block representing the resistance acting on the moving vehicle and the on-board computer block. The developed model assumes the possibility of changing the configuration of installed generating sets, their quantity, power, combustion, and even the amount of fuel in individual tanks. In addition, it is possible to "disconnect" the range extender system (trailer) by changing one variable and loading the route profile and speed profile from a file.

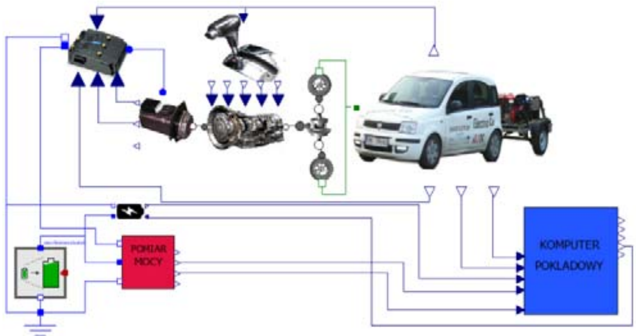

Fig. 8. Fiat Panda EV car model with REX.

If, while driving in a car on a level straight road, the driver of the vehicle moves the gearshift lever to the neutral position, the vehicle will continue to run momentarily, gradually reducing the speed until the vehicle stops. This is due to the presence of resistance to motion, such as rolling resistance caused by unevenness of the surface, resistance in wheel bearings, air resistance, etc. Movement resistance of the vehicle consists of all forces opposing the driving force of the vehicle that the vehicle encounters and overcomes while moving. These include, among others:

- resistance related to the construction of the vehicle:
  - o aerodynamic resistance,
  - o internal resistances of mechanisms.
- resistance related to road conditions:
  - o rolling resistance,
  - o traction force acting on the vehicle [44].

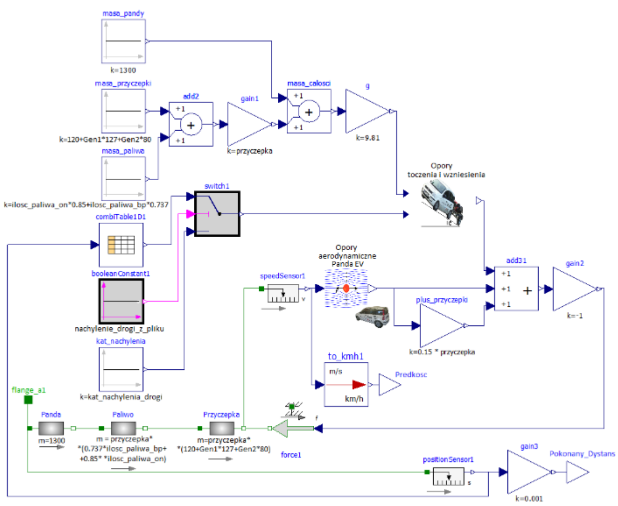

Fig. 9. Schematic model of resistance to motion of the vehicle.

For the modeling of the car Fiat Panda EV with a range extender system, aerodynamic resistance force, rolling resistance forces and traction force acting on the vehicle were used (Fig. 9).

Aerodynamic resistance arises as a result of:

- air pressure on the front surface of the vehicle,
- resistance of air flow through the internal devices of the vehicle,
- resistance of air friction to external surfaces of the body,
- friction resistance of the air flowing under the vehicle chassis.

The block modeling aerodynamic resistance is based on dependence:

(1) $$F_a = \frac{C_x * S * \rho * V^2}{2}\ [kN]$$

where: C_x – vehicle drag coefficient for Fiat Panda 2; $C_x = 0.35$, S – frontal area of the vehicle; S = 0.9*h*w = 2.202 [m^2], h – height of the vehicle; h = 1.54 [m], w – vehicle width; w = 1.589 [m], ρ – ambient air density (temperature +20°, pressure 1013,25 hPa); $\rho = 1.205\ [kg/m^3]$, V – vehicle speed [m/s]

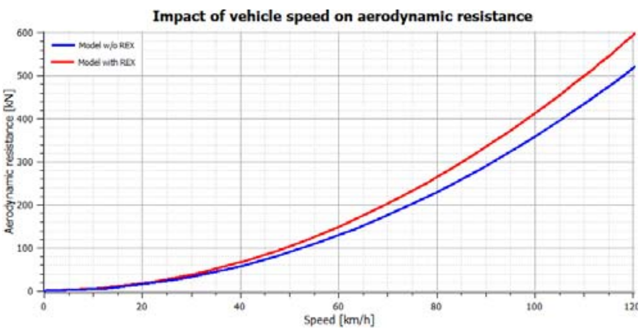

Fig. 10. Impact of vehicle speed on aerodynamic resistance.

In the case of a car pulling a trailer (range extender), the resulting motion resistance, that is the sum of air resistance, rolling resistance and traction force acting on the vehicle, must be additionally taken into account. For calculation of the aerodynamic drag, the Cx coefficient of the whole set is used. The individual aerodynamic resistances of the car and trailer should not be added up, as the trailer moves "in the shadow" of the towing vehicle. Experimental verification shows that the force of aerodynamic resistance of the whole set increases by about 15% in relation to the vehicle itself [45]. When calculating the rolling resistance and elevation, the total weight of the whole set (car and towed trailer) must be taken into account. The weight of the modeled car with driver, passengers and luggage is about 1300 kg, the weight of an empty trailer is 120 kg. The weight of the trailer with power generators and fuel was approx. 360 kg. The mass of gasoline and diesel fuel was determined based on the knowledge of the density of these liquids, the density of which is approximately 0.737 [g/cm^3] for gasoline and 0.85 [g/cm^3] for diesel fuel [44].

The rolling resistance is the sum of the rolling resistance of all wheels at the contact patch of the wheels. The rolling resistance force is directed against the direction of the vehicle's movement. For the car with REX, the rolling resistance force on a level road will be equal to:

(2) $$F_t = f * G\ [kN]$$

where: f – rolling resistance coefficient, for smooth asphalt $f = 0.01$, G – weight of the whole set, The weight of the whole set is the result of gravity, and the direction of its action is always vertical. Its value can be determined from the formula:

(3) $$G = m * g\ [N]$$

where: m – mass of the car and trailer [kg], g – standard gravity, g = 9.81 [m/s^2].

The rolling resistance of the vehicle set moving along the road inclined at the angle α, will be affected only by the weight component perpendicular to the surface, and the dependence describing the rolling resistance takes the form:

(4) $$F_t = f * G * cos\alpha\ [kN]$$

The traction force acting on the set occurring while the vehicle is moving uphill are part of the weight of the tangent assembly for the surface and are described by the dependence:

(5) $$F_w = G * sin\alpha\ [kN]$$

As already mentioned, the total rolling resistance, were determined based on the dependence:

(6) $$F_{tw} = F_t + F_w\ [kN$$

The converter block is supplied with power from the LiFePO4 battery pack. In the modeled vehicle, 30 LiFePO4 cells were used, with a capacity of 160 Ah and a nominal voltage of approx. 3.3 V each, which gives the total capacity of the battery pack at the level of about 15.84 kWh. The simulation does not take into account the influence of temperature changes on the internal resistance of the cells, a constant cell temperature value of 20ºC was adopted.

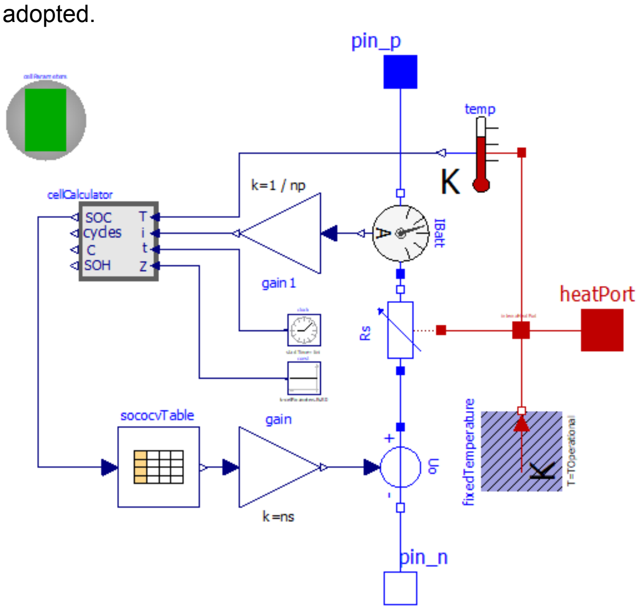

Fig. 11. Model of the battery pack.

The active power measurement was based on the product of the current I_{aku} drawn from the battery pack and the voltage at its terminals U_{aku} (Fig. 12).

(7) $$P = I_{aku} * U_{aku}$$

The on-board computer (Fig. 13) is responsible for calculating all the relevant parameters from the point of view of the analysis of the range extender. The following parameters are determined by the following relationships:

• energy used,
• instant energy demand,
• energy reserve,
• percentage of energy,
• remaining distance.

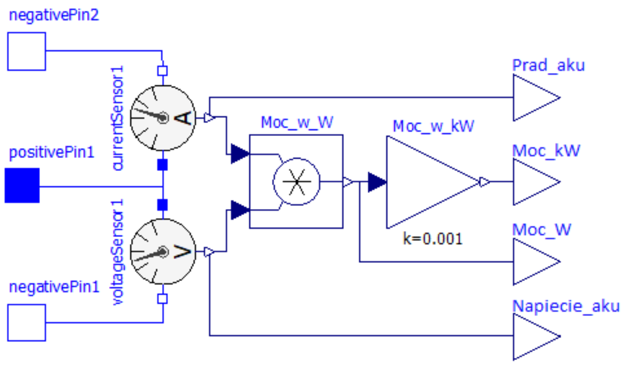

Fig. 12. Power measurement block.

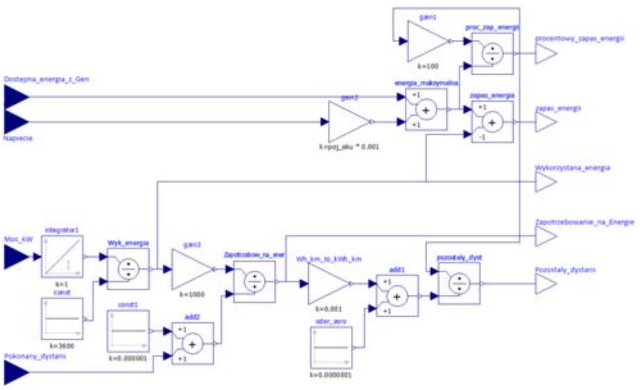

Fig. 13. On-board computer block.

Range extender model (Fig. 14) may include one 5.5 kW diesel or 4 kW gasoline generator, or both. The generator set is switched on and off depending on the level of charge of the battery pack. The REX is activated after the battery charge drops below the threshold set by the operator, while the switch-off takes place after the batteries have been charged to the level of 100%. The first 5.5 kW generator fueled with 12.5 liters of diesel fuel and a second 4 kW generator filled with 25 liters of gasoline can produce about 118.75 kWh of energy.

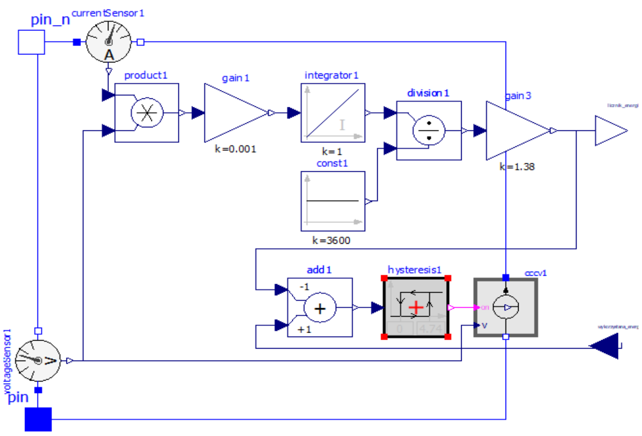

Fig. 14. Block of the range extender system.

Maximum charging current of LiFePO4 cells given by the cell manufacturer is:

(8) $$I_{MAX} = 1 * C\ [A] = 160\ [A]$$

where: C – cell capacity LiFePO4, C = 160 [Ah].

Recommended charging current at which the batteries will be charged to is:

(9) $$I_N = 0.5 * C\ [A] = 0.5 * 160 = 80\ [A]$$

Simulation results

A. Route elevation profile and travel speed profile

The route and travel speed profile used in the Modelica package was registered on the actual section of the 271 km route between Szczytno and Gdynia. Driving with a trailer on Polish roads is associated with a maximum speed limit of 50 km/h in built-up areas and up to 80 km/h outside built-up areas (including express roads and motorways)

To log the speed and road elevation, the free Speedometer GPS application for the phone with the Android operating system was used.

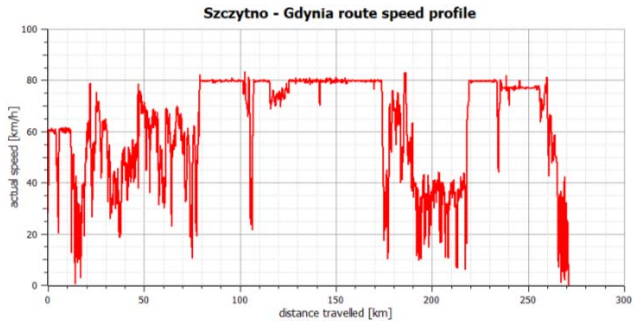

Fig. 15. Speed profile of the modeled route with a length of 271 km between the cities of Szczytno and Gdynia.

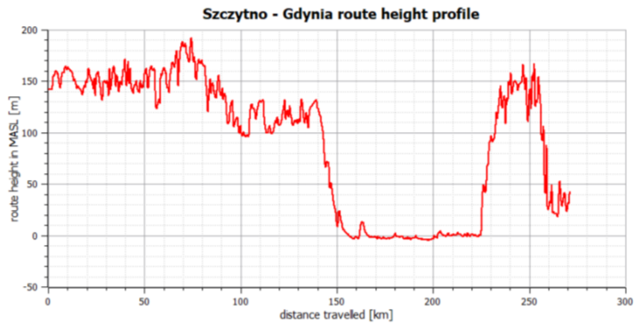

Fig. 16. Elevation profile of the modeled route with a length of 271 km between the cities of Szczytno and Gdynia.

B. Energy consumption

All simulation experiments were carried out for the following conditions:

- a constant air temperature of 20 °C,
- atmospheric pressure 1013,25 hPa,
- smooth asphalt - the rolling resistance coefficient is f = 0.01,
- nominal tire air pressure,
- no wind.

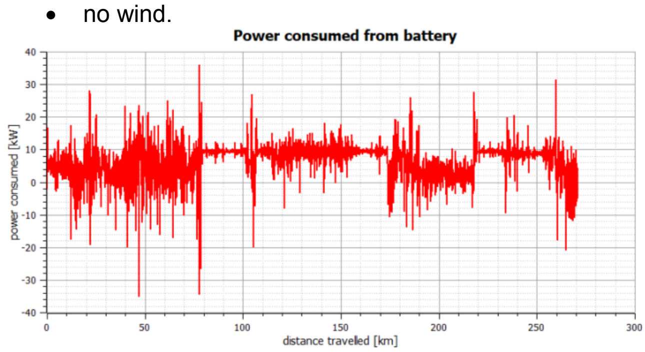

Fig. 17. Power consumed from vehicle battery on a distance of 271 km for two generator sets working in parallel.

On the presented plot of power drawn from battery (Fig. 17), the influence of speed changes on the size and direction of energy transfer is clearly visible. During deceleration, regenerative braking occurs, thanks to which the range of the vehicle increases. With the increase of braking torque, the instantaneous value of the recovered power increases. When driving at a constant speed of 80 km/h, power consumption is fixed at around 10 kW.

The results of the battery charge level tests at which the generators are switched on and off are shown in Figures 18÷21.

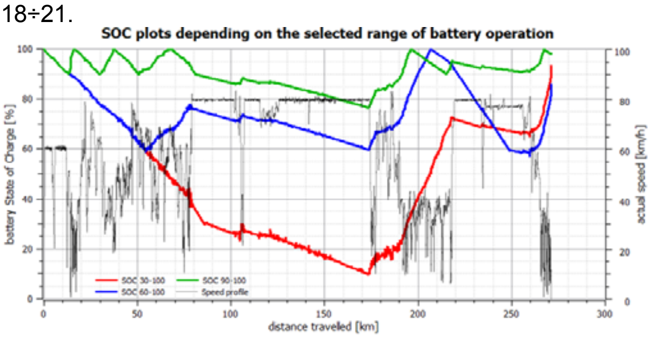

Fig. 18. Comparison of vehicle battery state of charge at a distance of 271km for two generators working in parallel at different levels of activation of the generators set.

The tests were carried out for the following coefficients: $SOC_{30\text{-}100}$, $SOC_{60\text{-}100}$, $SOC_{90\text{-}100}$. Namely, in each case examined, the generator sets were switched off or were to be turned off only after the batteries were fully charged. The obtained test results showed that the value of the adopted $SOC_{ON\text{-}OFF}$ coefficient affects the possible maximum distance without stopping and the amount of fuel consumed (working time of generators). This dependence obviously affects the amount of toxic substances emitted into the environment. The shortest working time of generator sets for the 271 km route was recorded for the $SOC_{60\text{-}100}$ coefficient and it was 58% of the total journey time, while the longest time generators were operating with $SOC_{90\text{-}100}$ coefficient, because they worked as much as 65% of the travel time. Selecting an appropriate value of $SOC_{ON\text{-}OFF}$ coefficient for the route, fuel consumption by the generators can be reduced. At the same time, it should be remembered that in the case of LiFePO4 batteries, the extension of the $SOC_{ON\text{-}OFF}$ operating area or bringing it to a deep discharge of the battery contributes to shortening their service life [44].

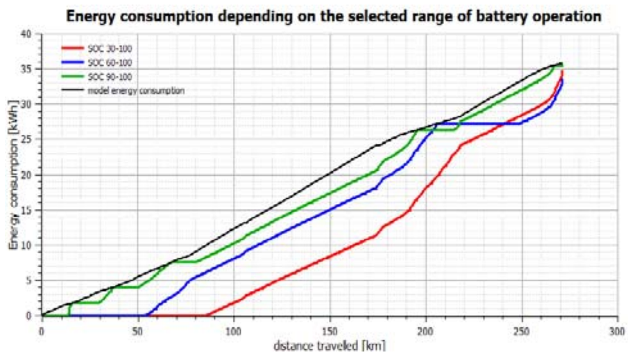

Fig. 19. Comparison of the energy produced by the generator sets with two generators working in parallel, at different levels of activation, to the total energy consumed at a distance of 271 km.

Although the available power from the range extender system is greater than the vehicle's demand for driving at a permissible speed of 80km/h, then the battery charge level is dropping. This is due to the limitation of the battery charging current to the manufacturer's recommended value of 0.5 · C = 80 A. Increasing the charging current above this value would cause an increase in the LiFePO4 cells temperature, and thus in a longer operation could shorten their life time. The solution to this problem may be to increase the number of LiFePO4 cells or to ensure better cooling.

With the $SOC_{90\text{-}100}$ ratio active (green graph) when driving at speeds below 80 km/h results in the units being switched on and off more frequently. On this basis, it can be concluded that the powers of both generating sets are slightly too large, which means that there are periods when aggregates are turned off. Generators should not stop for a long time, because it can cause excessive cooling of their engines and their ineffective operation from the next start, up to the moment of reaching proper operation temperature.

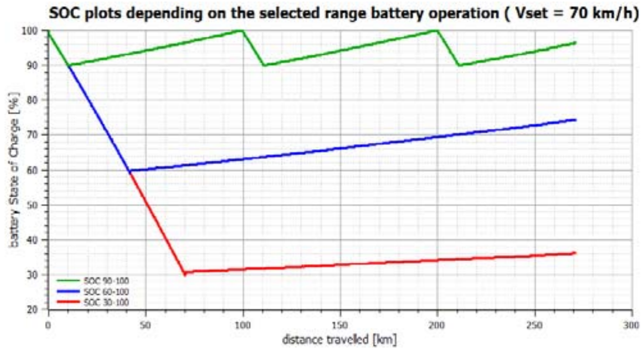

Fig. 20. Comparison of battery state of charge with a 4 kW gasoline and 5.5 kW diesel generators for a speed of 70 km/h, at different levels of switching on the generating sets.

Figure 20 shows the state of charge during the route (271km) with a constant operating speed of 70 km/h for the following factors: $SOC_{30\text{-}100}$, $SOC_{60\text{-}100}$, $SOC_{90\text{-}100}$. At a speed of 70km/h, the traction motor driving the wheels of the car consumes power from the battery pack at the level of 7 kW. This demand is fully satisfied by the range extending system, which makes it a better solution to set a lower SOC_{ON} level. As can be seen, the process of charging for $SOC_{60\text{-}100}$ faster than $SOC_{30\text{-}100}$. This phenomenon is caused by the nonlinear charging characteristics of lithium-iron-phosphate cells. The most economical setting for the speed of 70 km/h is $SOC_{60\text{-}100}$ marked in blue.

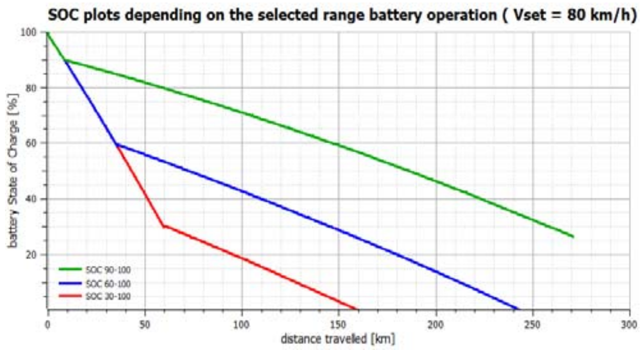

Fig. 21. Comparison of battery state of charge with a 4 kW gasoline and 5.5 kW diesel generators for a speed of 80 km/h, at different levels of switching on the generating sets.

Figure 21 shows the state of charge during the route (271 km) with a constant operating speed of 80 km/h for the following factors: $SOC_{30\text{-}100}$, $SOC_{60\text{-}100}$, $SOC_{90\text{-}100}$. The increase in the speed of the vehicle by 10 km/h caused significantly different changes in the state of charge of the battery pack, which are directly related to the spent fuel and indirectly to the amount of pollutants emitted to the atmosphere. In addition, for the analyzed range extender system for $SOC_{60\text{-}100}$ and $SOC_{30\text{-}100}$ marked in blue and red respectively, the end of route was not reached. Too low the value of the battery charging current caused the batteries to be discharged. Therefore, in a situation where generators do not have enough power to cover the entire energy demand of a vehicle, a better solution is to set a higher SOC_{ON} level.

Installation of the Range Extender system increases the weight of the whole vehicle set, which increases the total resistance of vehicle movement and the energy demand. The range of the vehicle is reduced on the energy accumulated in the batteries.

The energy demand depends on the vehicle speed set and is defined by the force of motion resistance (rolling and aerodynamic). As the speed increases, the energy demand increases and the reachable range decreases. In the figure shown below (Fig. 22 B, C, D), the distance achievable using only the energy contained in the batteries is presented, without taking into account the energy produced by the generators.

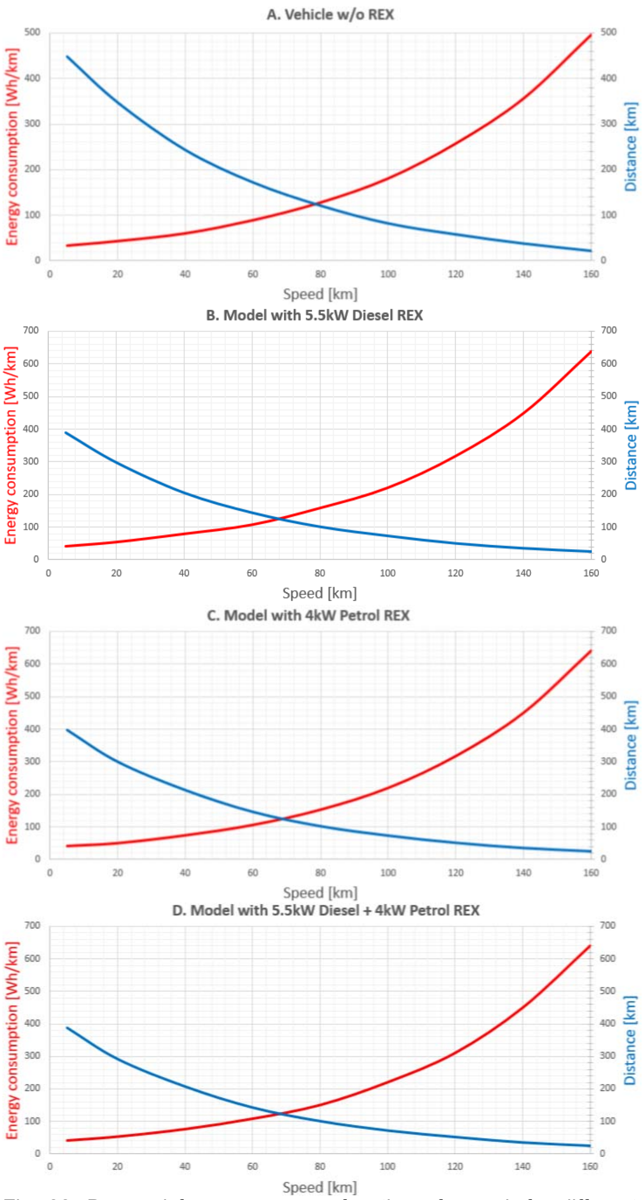

Fig. 22. Demand for energy as a function of speed, for different combinations of the range extender system.

Summary

The drive system of the Fiat Panda EV electric car and the set of an electric vehicle with a light trailer with power generators, whose mathematical model was developed in the Modelica environment, underwent numerous traction tests. During the said tests, all relevant parameters of the electric car and the range extender system were recorded. The object-oriented language used in the Modelica environment allowed to model the object whose basic elements have a different physical nature.

The assessment of the correctness of the operation of the developed propulsion system with the range extender system was possible only after compilation and simulation. The obtained results allowed for comparison with data registered during real tests on the road. The simulation results obtained, faithfully reproduced the modeled object. The differences in driving parameters such as speed, energy demand, power consumption, maximum range or resistance of vehicle movement between the real car and trailer set and its simulated counterpart, have not been exceeded by 5%. Which is a sign of the correctness of the model's performance.

The amount of greenhouses gases emitted during the operation of an electric car with the Range Extender system depends mainly on the assumed SOC_{ON} level for which the generator set is switched on. The value of the SOC_{ON} coefficient should be set based on the assumed distance to travel and the speed profile of the route. A properly selected SOC_{ON} factor has a positive effect on the maximum range of the vehicle without stopping and on the amount of fuel consumed by up to several percent.

The tests have shown the benefits of using the range extending system. The system has positively influenced the overall range of the vehicle, allowing it to increase its range several times, while reducing greenhouse gas emissions.

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