REDUCTION OF CO_2 EMISSION AS A RESULT OF THE USE OF 48-VOLT ELECTRICAL INSTALLATIONS IN PASSENGER CARS

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Abstract:

The introduction of a new standard of 48-volt electrical systems in cars comes at an additional cost to the vehicle. Acceptance of these costs is justified because it becomes a way to achieve lower CO_2 emissions and lower fuel consumption. An important factor in favor of adopting 48-volt systems is the reduction in CO_2 due to the use of a highly efficient 48-volt motor-generator unit coupled to a DC/DC converter. A methodology for testing new solutions to quantify CO_2 savings and reductions therefore becomes crucial. This methodology must be capable of demonstrating the CO_2 benefits primarily of the innovative technology proven in real-world driving conditions and with a large amount of realistic statistical data. The introduction of new eco-innovations must take into account the linkage and impact on other environmentally oriented eco-innovative solutions. When implementing new technical solutions, a necessary aspect is the interaction with other innovations installed in vehicles with new electrical installation standards. Therefore, for the expected synergy of solutions to occur, two or more innovative technologies must be installed. Then the combined savings from one of them will affect the performance of the other technologies, and vice versa. The new technology of a high-efficiency 48-volt motor-generator unit cooperating with a 48V/12V DC/DC converter fits very well in creating interactions with other implemented solutions aimed at reducing CO_2 emissions. The article discusses the problems of the introduced new technology of a high-efficiency 48-volt motor-generator unit cooperating with a 48V/12V DC/DC converter. The publication analyzes the impact of increasing the voltage rating of current passenger car installations to 48V. Based on the methodology for determining the reduction of CO_2 emissions of a vehicle with a 48V/12V DC/DC voltage converter installed, the mass of fuel per unit of engine operation time was determined. The amount of fuel saved was determined, and CO_2 emission reductions were calculated for the three adopted passenger vehicles tested.

Keywords: passenger vehicles, 48-volt motor-generator, 48V/12V DC/DC converter, CO_2 reduction, fuel consumption reduction

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1. Introduction

Nowadays, vehicles equipped with combustion engines use many modern electronic, mechatronic and executive systems with the use of engines and actuators. It happens due to considerable growth of consumption of power and current of starting systems, air-conditioning systems, power steering systems and engine operation control systems. It leads to increasing losses in the systems of motor vehicles. Standard supply systems are 12V electric circuits, which are powered by lead-acid batteries charged by an alternator. Due to much higher consumption of current, 12V systems must be have larger diameters, causing additional considerable weight of vehicles. In modern vehicles, cabling can be even a few kilometres long This additional weight can be reduced by growth of voltage of electrical installations of motor vehicles, which will cause reduction of voltage drops and power losses. An additional profit of such change will be considerable reduction of diameters of the wires of the systems their weight, which will result in reduction of a vehicle mass. Growth of rated voltage makes it easier to meet normative requirements concerning permissible voltage drops in specific circuits of the systems (PN-85/S-76001, 1985). Increasing voltage causes reduction of power losses and voltage drops and makes cabling lighter. With current state of technology of vehicles and power consumed by them, 12V car systems have reached their limit. Therefore, there are more and more attempts to implement 48V supply voltage to electric circuits of the vehicles of higher power demand (Kumawat et al., 2017). The first trials and implementations of this voltage take place in parallel with still operated 12V system. 48V system is added to 12V system, which is powered by lithium ion batteries. 12V system is used to manage operation of an engine, lights, seat adjustment, mirrors and audio - navigating system. Whereas, 48V system is dedicated to power high voltage receivers, that is, electric power steering, starter and air-conditioning system. In addition, 48V system is intended for application of new techniques of storing electric energy and provision of much more current in comparison with 12V system. Dual voltage system enables to use much larger amount of electric energy, reducing power losses. It gives the opportunity to develop many technical solutions, making motor vehicles more efficient and also more comfortable. It is also

another way and chance to reduce emission of carbon dioxide. In light of the ongoing struggle to meet stringent exhaust gas standards, we can expect such a solution to become widespread - first in the most expensive models, and later in more popular ones.

The matter of the future of 48-volt automotive electrical systems is already a foregone conclusion. The use of 48 volts also avoids costly requirements for unsafe vehicle installation voltages. It becomes unnecessary, among other things, the use of expensive special cables and their expensive safe connections, as well as stricter service requirements related to safety of use. As a result, 48V has become a de facto standard for an increasing number of manufacturers who have already introduced such installations for commercially available vehicles.

The publication presents the new 48-volt rated voltage standard for automotive installations being introduced in passenger vehicles. The impact of increasing the installation's voltage rating from 12V and 24V to 48V was analyzed. On the basis of the methodology for reducing CO_2 emissions of a vehicle with a 48V/12V DC/DC converter installed, as well as the adopted calculation relationships, the mass of fuel per unit of engine operation time, its savings and the calculated reduction in CO_2 emissions were determined for three tested passenger vehicles.

2. Literature review

Trials with determining new voltage ratings for automotive electrical systems were initiated by the world's largest automobile companies. As a result of these trials, 36V (42V operating voltage) was adopted as the nominal voltage for automotive installations, instead of the previous 12V (Jankowski, 2007). The choice of this voltage value was a compromise between the need for its radical increase and electric shock safety considerations. A more extensive analysis of these issues is presented in the works (Jankowski, 2007; Jankowski, 2009).

The result of ongoing research was also the appearance of the first hybrid passenger cars (Bilo J. et al., 2016). The authors of the works note the use of electrical installations that exceeded the safety voltages of 60V DC (Jankowski, 2012; Jankowski, 2014). During the evolution of hybrid and electric vehicles, an additional voltage level was defined in order to use high-power loads associated with power steering and electric pumps, compressors and electric heaters

(Kuypers, 2014; LV 148). It has been proven that powertrain electrification will play an important role in reducing fuel consumption and emissions over the next few decades (Do, 2014). Current trends toward the introduction of 48V rated systems have been indicated on the basis of ongoing research work and initial applications at individual automobile corporations (Jankowski, 2017). The higher efficiency has made it possible to introduce solutions that were previously unavailable due to the limitations of the lower voltage. This involved limiting the wiring length of modern vehicles due to power take-offs and voltage drops (Horn, 2020; Jankowski, 2007).

The development of modern vehicle electrical system standards requires the introduction of modern bidirectional DC-to-DC converters. Instead of a conventional boost converter, DC-DC converters with parallel combinations of IGBTs and MOSFETs (Das, 2014) with zero-voltage switching (ZVS) with high voltage gain and ripple-free input current are used (Shang, et al., 2017; Do, 2014).

With the introduction of modern inverters into vehicles, it was necessary to analyze the battery requirements of their solutions and the technical challenges of designing a 48-volt battery pack, with particular attention to cell selection and thermal management of the entire pack (Hall, et al., 2020). Emerging conclusions from the analyses suggest that high-power Lithium-Iron-Phosphate (LFP) batteries can meet the needs of advanced 48-volt architectures, providing consumers with new features and excellent fuel economy (Abdellahi, et al., 2017).

3. 12V and 48V system in the installations of motor vehicles

Nowadays, majority of motor vehicles are equipped with 12V electrical installation. It usually consists of three circuits: energy provision circuit, motor circuit and current load power circuit. It must be added that in the cars equipped with a spark ignition engine, there is also an ignition system, and in the cars equipped with diesel engines, there is a starting system instead. The main elements of energy provision circuit include an alternator and battery, which accumulates generated electric energy. Alternator meets energy demand of current loads in a car and battery charging. Starting system in a car includes battery, starter and switch. We can clearly see that the wires in these circuits have larger diameter than the others due to considerable values of currents flowing

through them. Another circuit is a circuit of the receivers:

– directly powered receivers, for example, external lighting, hazard warning lights, alarm system, radiator fan or central lock,
– receivers switched on using an ignition switch, for example, ignition system, indicators, additional external lights or fuel pumps.

Despite many improvements, 12V systems have reached their limits due to high power demand of the vehicles. Currently applied alternators and capacities of the batteries are not sufficient enough to meet the demand of modern motor vehicles. New solution and also support for 12V circuits are 48V electric circuits (Smith et al., 2020; Zhao, 2017; Leach, 2016). Higher efficiency makes it possible to implement solutions that have not been available so far due to limitation of lower voltage. New concepts are aiming at application of electrical installation of the vehicles as two-system ones. The circuits of 48V system are slowly becoming a standard in many producers who have noticed advantages of this feeding system.

48/12V systems are separated, that is, traditional 12V circuits using lead-acid battery and 48V circuits powered by lithium ion battery. Both circuits have separate charging systems, and DC/DC converter combines 12V circuits with 48V circuits (Das, 2014; Olin et al., 2019). Lithium ion battery cooperates with an alternator of optimized, increased efficiency, making driving system almost a hybrid one. The advantage of such solution is an option of energy recovery. Advanced alternator can recover even 10 kW of electric power during recuperation. In this way, emission of carbon dioxide per kilometre can be reduced by even ten grams, which is an equivalent of an amount of 0,4 litre of fuel per 100 kilometres (Lodi et al., 2022). The interest in vehicles equipped with 48V system is obvious because it allows to meet the requirement applicable since 2021 for newly registered passenger vehicles of emitting less than 95g of CO_2 per kilometre (DC/DC converters, 2019).

Management and control of flow of electric power in both directions between circuits of different voltages is becoming a challenge to 48/12V system. The use of bidirectional converter enables to reduce and increase voltage during power transmission between circuits. The disadvantage of such solution is complicated structure of an electrical system, increased

costs of installation and additional components and necessity of finding a place in a vehicle. Figure1. presents a bidirectional supply system for energy flow in 48/12V system.

48/12V systems are subject to the requirements of compliance with LV 148 standard, which defines resistance to short-lived over voltages lasting 40 ms. The elements and devices used in the system must have strength 70 V in the input, and after adding safety margin, this requirement is increased to 100V (Horn, 2020; Kuypers, 2014; LV 148). It will enable to avoid additional and expensive insulating systems (DC/DC converters, 2019).

Despite long-term operation of 12V system and first experiences with this system, the vehicles working electrically that only use voltage of 48 V are already being developed. The systems of these vehicles use bare and bidirectional converters, which process power of a few kilowatts and power electric devices working using voltage of 12V, as well as subassemblies working on higher voltage (Horn, 2020). 12/48V system is powered by one 48V battery with the use of many bidirectional converters. Figure 2 presents power diagram of 48/12V electrical installation with the use of 48V battery and high-performance converters.
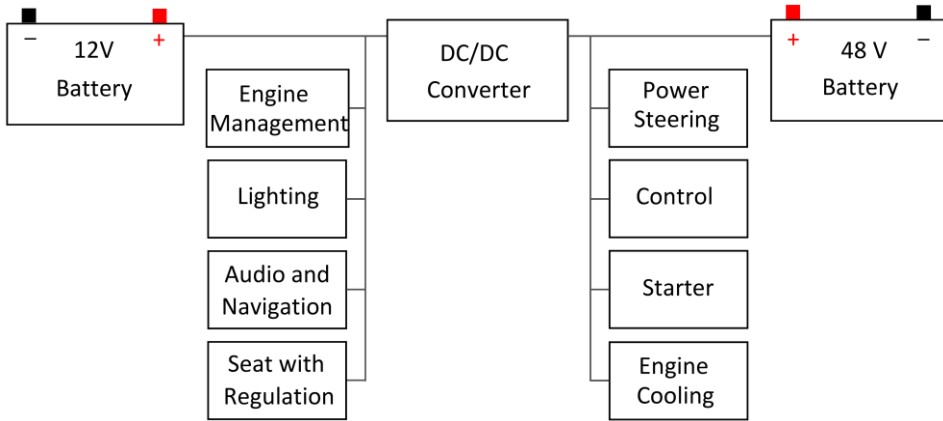

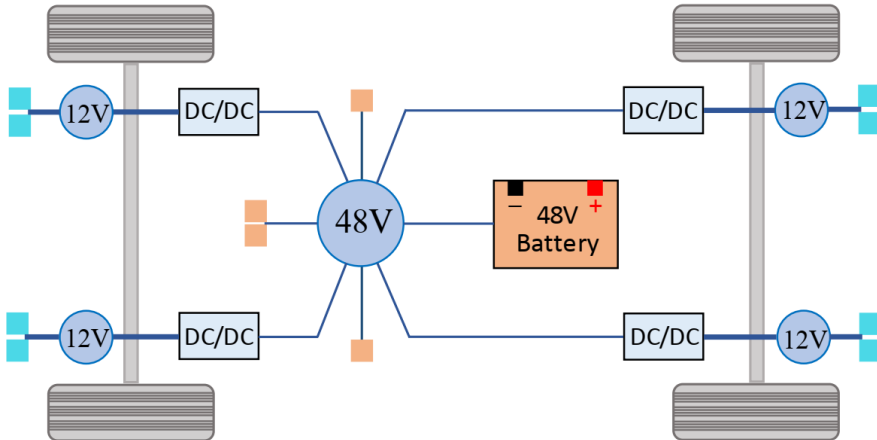Fig. 1. Bidirectional supply system in 48/12 V two-system installation

Fig. 2. 48/12V electrical installation with the use of DC/DC bidirectional converters

The first experiences in application of a new system showed more effective heat abstraction and reduction of working temperature of the converters and reduction of distances of 12V circuits, which leads to reduction of mass of a vehicle (Spessa et al., 2018).

4. Certification of CO_2 savings

Supporting implementation of new innovative technologies aiming at reduction of CO_2 emission in the vehicles, European Commission, by an Executive Decision (DCID EU, 2020) no. 1167/2020, confirmed that 48V technology of engine-generator unit combined with 48V/12V DC/DC converter is an innovative technology. The producers, while implementing new technology of reducing emission of CO_2 in new passenger vehicles, must meet criteria certifying reduction of CO_2 by at least 0,5 g CO_2/km. It is compliant with the provisions of regulation (CIR EU, 2011) no. 725/2011 in the event of passenger vehicles or executive regulation (CIR EU, 2014) no. 427/2014 in the event of light commercial vehicles. To prove reduction of CO_2 emission, it is necessary to conduct on the products of new technology a test procedure defined in regulation (CR EU, 2017) no. 692/2008 and fulfil the following conditions (DCID EU, 2020):

− technology is installed in passenger vehicles (M1) or in light commercial vehicles (N1) equipped with conventional combustion engines or in hybrid electric vehicles not charged externally, in which values of uncorrected measurement of fuel consumption and CO2 emission can be used in accordance with regulation (CR EU, 2017) 2017/1151,

− resultant efficiency of technology of 48V motor generator and efficiency of 48V/12V DC/DC converter is at least:
  − 73,8% for vehicles powered by petrol, different than turbocharged ones;
  − 73,4% for turbocharged vehicles powered by petrol;
  − 74,2% for vehicles powered by diesel fuel.

Reduction of CO_2 emission of a vehicle as a result of application of 48V technology of engine-generator unit combined with 48V/12V DC/DC converter will be determined with the use of computational methodology below.

5. Methodology of reduction of CO_2 emission of a vehicle equipped with 48V/12V DC/DC converter

Reduction of CO2 emission of high-performance 48V motor generator combined with 48V/12V DC/DC converter used in the vehicles of M1 or N1 category should be determined separately for 48V motor generator and separately for 48V/12V DC/DC converter.

5.1. Determination of efficiency of 48V motor generator

Efficiency of 48V motor generator is determined in accordance with ISO 8854:2012, which includes methods of tests and general requirements concerning determination of data of electrical characteristics of alternators of road vehicles. In accordance with the provisions of this standard, a producer, based on presented measurements, must confirm that frequency ranges of 48V motor generator are the same as values listed in table 1or equivalent (ADCID, 2020). Measuring stand and scope of measurements in accordance with ISO 8854:2012 were presented in the following publication (Łukasik et al., 2021).

Table 1. Frequency range during test of a 48V motor generator

Operating point i	Holding time [s]	Rotational frequency n_i [min^{-1}]	Frequency operating points h_i
1	1 200	1 800	0,25
2	1 200	3 000	0,40
3	600	6 000	0,25
4	300	10 000	0,10

Efficiency of 48V motor generator is determined on the basis of measurements made for operating points mentioned in table 1. Current intensity of 48V unit in each of these points must at least half of rated value of current. Measuring methodology also defines voltage during measurement and52 V must be maintained for every operating point i. For such measuring methodology, efficiency η_{MGi}, 48V unit is expressed in [%] and for every operating point, i is calculated using the following formula (1):

$$\eta_{EI_i} = \frac{60 \cdot U_i \cdot I_i}{2\pi \cdot M_i \cdot n_i} \cdot 100 \tag{1}$$

where:
U_i – measurement voltage 52 [V],

I_i – measurement output current [A],

M_i – torque [Nm],

n_i – rotational frequency [min^{-1}].

Every operating point of tested unit has efficiency measured five times and each of these measurements is determined. Every measuring series j requires to determine average efficiency $\overline{\eta_{MG_i}}$ for every i – of this operating point. Finally, efficiency of 48V motor generator is calculated using a formula (2).

$$\eta_{MG} = \sum_{i=1}^{j} h_i \cdot \overline{\eta_{MG_i}} \qquad (2)$$

where:

$\overline{\eta_{MG_i}}$ – average efficiency of 48V motor generator for i-of this operating point [%],

h_i – frequency i- of this operating point defined in table 1.

5.2. Determination of efficiency of 48V/12V DC/DC converter

The producers, in order to determine efficiency of high-performance 48V/12V DC/DC converter, must determine its efficiency, fulfilling the following conditions during measurements:

− persistent input voltage measurement - 52 V,

− persistent output voltage measurement - 14,3 V,

− output current determined from ratio of rated power of a converter to output voltage 14,3 V.

Rated power of tested converter is an output power, which has to be certified by the product supplier in accordance with the requirements defined in ISO 8854:2012. Efficiency of a converter $\eta_{DC/DC}$ is determined based on current and voltage measurements, and it is calculated using a formula (3), showing result in [%].

$$\eta_{DC/DC} = \frac{U_{12V} \cdot I_{12V}}{U_{48V} \cdot I_{48V}} \qquad (3)$$

where:

U_{48V} – fixed input voltage - 52 [V],

I_{48V} – current measured in the input of a converter [A],

U_{12V} – fixed output voltage - 14,3 [V],

I_{12V} – current measured in the output of a converter equal to its rated power divided by output voltage [A]. A necessary condition is to take measurements five times, and after each of them, calculating converter efficiency. Based on the average from the calcula-

tions, requested efficiency of 48V/12V DC/DC converter can be obtained. Obtaining from a formula (2) and (3) efficiency of 48V motor generator and 48V/12V DC/DC converter, resultant efficiency η_{TOT} can be determined using the following formula (4).

$$\eta_{TOT} = \eta_{MG} \cdot \overline{\eta_{DC/DC}} \qquad (4)$$

where:

η_{MG} – efficiency of 48V motor generator [%],

$\overline{\eta_{DC/DC}}$ – average efficiency of 48V/12V DC/DC converter [%].

5.3. Determination of reduction of CO2 emission

The value of reduction of CO_2 emission obtained as a result of application of 48V motor generator combined with 48V/12V DC/DC converter is calculated after determination of mechanical power saving ΔP_m resulting from application of innovative combination of both technical solutions. This saving is obtained based on calculation of difference between mechanical power saving with application under conditions of real use of a vehicle with the use of innovative combination of 48V unit – converter, and mechanical power saving under conditions expected in obtaining homologation of a vehicle with applied combination of 48V unit – converter. The calculations are done using a formula (5).

$$\Delta P_m = \Delta P_{mRW} - \Delta P_{mTA} \qquad (5)$$

where:

ΔP_{mRW} – mechanical power saving of 48V motor generator with 48V/12V DC/DC converter used under real conditions [W],

ΔP_{mTA} – mechanical power saving of 48V motor generator with 48V/12V DC/DC converter used under conditions of homologation [W].

ΔP_{mRW} saving is calculated using a formula (6), whereas ΔP_{mTA} using a formula (7).

$$\Delta P_{mRW} = \frac{P_{RW}}{\eta_B} - \frac{P_{RW}}{\eta_{TOT}} \qquad (6)$$

$$\Delta P_{mTA} = \frac{P_{TA}}{\eta_B} - \frac{P_{TA}}{\eta_{TOT}} \qquad (7)$$

where:

η_{TOT} – resultant efficiency of 48V motor generator combined with 48V/12V DC/DC converter [%],

P_{RW} – mechanical power required during use under real conditions - 750 [W],

P_{TA} – mechanical power required during homologation - 350 [W],

η_B – assumed efficiency of an alternator 67 [%].

Knowing the value of mechanical power saving from a formula (8), reduction of CO_2 emission is determined.

$$C_{CO_2} = \Delta P_m \cdot \frac{V_{Pe} \cdot CF}{v} \qquad (8)$$

where:

ΔP_m – mechanical power saving [W],

v – average driving speed in accordance with WLTP, that is, 46,6 [km/h],

V_{Pe} – consumption of power mentioned in table 2 [l/kWh],

CF – conversion ratio of fuel into CO_2 mentioned in table 3[gCO₂/l].

New standards concerning the values of fuel consumption have been defined in the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), which defines not only fuel consumption, but also emission of CO_2 (ECE/TRANS, 2014). New research method defining consumption of fuel by the vehicles was described in the procedure. Based on real data collected around the world, this method allows to simulate realistic driving of car, even under laboratory conditions. In this way, not only different situations and speeds in road traffic, but also various variants of accessories and mass classes of a vehicle are taken into account. WLTP was implemented for all new models of passenger vehicles as of September 1, 2017 (CR EU, 2017).

Table 2 presents consumption of power from every litre of fuel, and table 3 presents conversion of consumed fuel into amount of CO_2.

Obtained reduction of CO_2 emission is connected with some degree of accuracy of measurement of physical quantities. Measuring precision is limited by imperfection of devices used during measurement, precision of sense organs of an observer and in some cases models applied in an analysis of measuring data. Mentioned factors have impact on the most accurate measurement, which is affected by measuring uncertainty and it is an approximation of real value. Taking into account that obtained values of reduction of CO_2 emission are affected by meas-

uring uncertainty, its quantitative value must be determined. Therefore, percentage standard deviation must be calculated:

− efficiency of $S_{\eta MG}$ 48V motor generator in every operating point of a unit,

− efficiency of $S_{\overline{\eta_{DC/DC}}}$ 48 V/12V DC/DC converter.

Table 2. Effective power consumption of the vehicle

Type of engine	Effective power consumption of the vehicle (V_{Pe}) [l/kWh]
Petrol	0,264
Petrol turbo	0,280
Diesel	0,220

Table 3. Fuel conversion factor

Type of fuel	Conversion factor (1/100km)-(g CO₂/km) (WK) [gCO₂/l]
Petrol	2 330
Diesel	2 640

To calculate standard deviation of efficiency $S_{\eta MG}$, we must first calculate standard deviation of efficiency for 48V motor generator in every operating point $S_{\overline{\eta_{MG_i}}}$ using a formula (9).

$$S_{\overline{\eta MG_i}} = \sqrt{\frac{\sum_{j=1}^{m}\left(\eta_{MG_{i_j}} - \overline{\eta_{MG_i}}\right)^2}{m(m-1)}} \qquad (9)$$

where:

m – the number of the measurements in j measuring series made in every operating point i for efficiency of 48V motor generator,

$\eta_{MG_{i_j}}$ – efficiency of 48V motor generator calculated for measurement of one j series of measurements in an operating point i [%],

$\overline{\eta_{MG_i}}$ – average efficiency of 48V motor generator calculated for an operating point i [%].

Then, standard deviation of efficiency $S_{\eta_{MG}}$ is calculated using a formula (10).

$$S_{\eta_{MG}} = \sqrt{\sum_{i=1}^{j}\left(h_i \cdot s_{\overline{\eta_{MG_i}}}\right)^2} \qquad (10)$$

where:

$s_{\overline{\eta_{MG_i}}}$ – standard deviation of efficiency of 48V motor generator [%],

h_i – frequency i- of this operating point defined in table 1.

Percentage standard deviation of efficiency of $s_{\overline{\eta_{DC/DC}}}$ 48 V/12V DC/DC converter is calculated from a formula (11).

$$S_{\overline{\eta_{DC/DC}}} = \sqrt{\frac{\sum_{j=1}^{L}\left(\eta_{DC/DC_i} - \overline{\eta_{DC/DC}}\right)^2}{L(L-1)}} \tag{11}$$

where:

L – the number of measurements l made for 48V/12V DC/DC converter,

$\eta_{DC/DC}$ – calculated efficiency of 48V/12V DC/DC converter for single l measurement [%],

$\overline{\eta_{DC/DC}}$ – average efficiency of 48V/12V DC/DC converter [%].

Final calculation is determination of uncertainty of value of reduction of CO_2 emission obtained as a result of application of 48V motor generator combined with 48V/12V DC/DC converter. The following formula shall be used for this purpose (12), whereas, calculated uncertainty may not exceed 30% of obtained value of reduction of CO_2 emission.

$$S_{C_{CO_2}} = \frac{(P_{RW} - P_{TA})}{\eta_{TOT}} \cdot \frac{V_{Pe} \cdot CF}{v} \cdot \sqrt{\left(\frac{s_{\eta_{MG}}}{\eta_{MG}}\right)^2 + \left(\frac{s_{\overline{\eta_{DC/DC}}}}{\overline{\eta_{DC/DC}}}\right)^2} \tag{12}$$

where:

P_{RW} – mechanical power required during use under real conditions - 750 [W],

P_{TA} – mechanical power required during homologation - 350 [W],

η_{TOT} – resultant efficiency of 48V motor generator combined with 48V/12V DC/DC converter [%],

V_{Pe} – consumption of power listed in table 2 [l/kWh],

CF – conversion ratio of fuel into CO_2 mentioned in table 3 [gCO2/l],

v – average driving speed in accordance with WLTP, which is 46,6 [km/h],

$s_{\eta_{MG}}$ – standard deviation of efficiency of 48V motor generator [%],

η_{MG} – efficiency of 48V motor generator [%],

$s_{\overline{\eta_{DC/DC}}}$ – standard deviation of efficiency of 48V/12V DC/DC converter [%],

$\overline{\eta_{DC/DC}}$ – efficiency of 48V/12V DC/DC converter [%].

A necessary condition of the calculations is approximation to maximum two decimal places of obtained value and uncertainty of reduction of CO_2 emission. Whereas, total value of rounded off value of reduction of emission was lower than 0,25g CO_2/km. The value of rounding off is very important for a vehicle equipped with discussed ecoinnovation because it is necessary to meet a minimum degree of reduction of emission, which is at least 1gCO2/km (CIR EU, 2011). Obtaining a minimum degree of reduction is checked using a formula (13).

$$\left(C_{CO_2} - s_{C_{CO_2}} - \Delta CO_{2_m}\right) \geq MT \tag{13}$$

where:

MT – minimum reduction 0,5 [g CO_2/km],

C_{CO_2} – value of reduction of emission [g CO_2/km],

$s_{C_{CO_2}}$ – uncertainty of summary value of reduction of CO_2 emission [g CO_2/km],

ΔCO_{2_m} – CO_2 correction for obtained difference of Δm [kg] between 48V motor generator combined with 48V/12V DC/DC converter and 7 [kg] reference alternator, calculated in table 4 [g CO_2/km].

Table 4. CO_2 correction

Type of fuel	CO_2 correction ΔCO_{2_m} [gCO2/km]
Petrol	0,0277 Δm
Diesel	0,0383 Δm

For computational purposes, the producers of a motor vehicle must give mass of 48V motor generator combined with 48V/12V DC/DC converter certified by the producer of mounted devices.

The final stage of determination of reduction of CO_2 emission is certification of the values of CO_2 savings as a result of application of ecoinnovation, presented in details in (CIR EU, 2014). The value of reduction of CO_2 emission that requires certification can be calculated from a formula (14).

$$CS_{CO_2} = \left(C_{CO_2} - s_{C_{CO_2}}\right) \tag{14}$$

where:

C_{CO_2} – value of reduction of emission [g CO_2/km],

$s_{C_{CO_2}}$ – uncertainty of summary value of reduction of CO_2 emission [g CO_2/km].

6. Tests confirming reduction of CO_2 emission of a vehicle equipped with 48V/12V DC/DC system

Increasing voltage from 12 V to 48V allows to increase efficiency of constructional solutions of motor vehicles. 48V supply system enables to use large amount of electric energy, which leads to increased efficiency and comfort of use of the vehicles. Therefore, 48V has already become a standard in numerous producers who implemented such systems in the vehicles available on the market. By using 48V electrical installation, apart from advantages mentioned above, fuel consumption is lower and meeting the standards of exhaust emission are met. The producers have come to this conclusion through tests and test drives according to the standards of values of fuel consumption, which are defined in WLTP. Tests conducted on the vehicles showed lower burning and proper functioning of 48V motor generator combined with 48V/12V DC/DC converter and functional components powered in two directions. Making tests on fuel consumption in accordance with WLTP corresponds to the values of consumption under conditions of everyday use and takes into account a driving profile more similar to the real one. Test procedure allows more precise forecast of real fuel consumption in a given car thanks to more realistic test parameters. Testing the vehicles enable to determine the amount of fuel saved as a result of application of 48V motor generator combined with 48V/12V DC/DC converter. The vehicles equipped with two-system installations were selected for an analysis and based on conducted tests, amount of saved fuel and reduction of carbon dioxide were determined, which would be emitted to atmosphere. Passenger vehicle having an ideal burning, which during burning of 1 kg of petrol causes emission of 3,1 kg of CO_2 was used for the calculations. It means that as a result of burning of 0,322 kg of petrol, 1kg of CO_2. is generated Therefore, in a tested idling vehicle, emission of CO_2 is 0,76 g/s. In accordance with a formula (15), mass of fuel per time unit of an engine operation can be calculated (Łukasik et al., 2021):

$$0,76 \frac{g}{s} CO_2 \cdot 0,332 \frac{gPetrol}{gCO_2} = 0,245 \frac{g}{s} Petrol \quad (15)$$

Assuming density of petrol ρ = 0,745 g/cm3, intensity of fuel consumption is determined using a formula (16) (Łukasik et al., 2021):

$$0,76 \frac{g}{s} CO_2 \cdot \frac{0,332 \frac{gPetrol}{gCO_2}}{0,745 \frac{g}{cm^3}} = 0,33 \frac{cm^3}{s} Petrol \quad (16)$$

The values of fuel economy under conditions of normal traffic and calculated reduction of CO_2 emission for three tested passenger vehicles of leading brands were presented in table 5.
Reduction of fuel for a vehicle equipped with 48V/12V DC/DC system was shown on Figure 3. Reduction of CO_2 emission for a vehicle equipped with 48V/12V DC/DC system was presented on Figure 4.

Table 5. Reduction of fuel use and CO_2 emissions for the vehicle with the installation 48V/12V DC/DC

Tested vehicle	Petrol consumption [l/100km]	Petrol savings [l/100km]	Saving CO_2 [kg/100km]
Vehicle I	9,4	0,71	1,64
Vehicle II	8,4	0,43	1,35
Vehicle III	7,2	0,57	1,32

According to data from ODYSSEE-MURE, average annual mileage of the vehicles in the European Union in 2019 was 11 313 (km/year), whereas in Poland, 8 607 (km/year). The highest mileages reached vehicles in Austria, 13 699 (km/year), and in Germany, 13 602 (km/year) (Odyssee-mure, 2022). For tested cars, obtained fuel economy and reduction of emission for average value of the EU and Poland was presented in table 6.
Annual petrol savings were presented on Figure 5. Annual reduction of CO_2 emission is presented on Figure 6.

Table 6. Annual reduction of fuel consumption and CO_2 emission for a vehicle equipped with 48V/12V DC/DC system

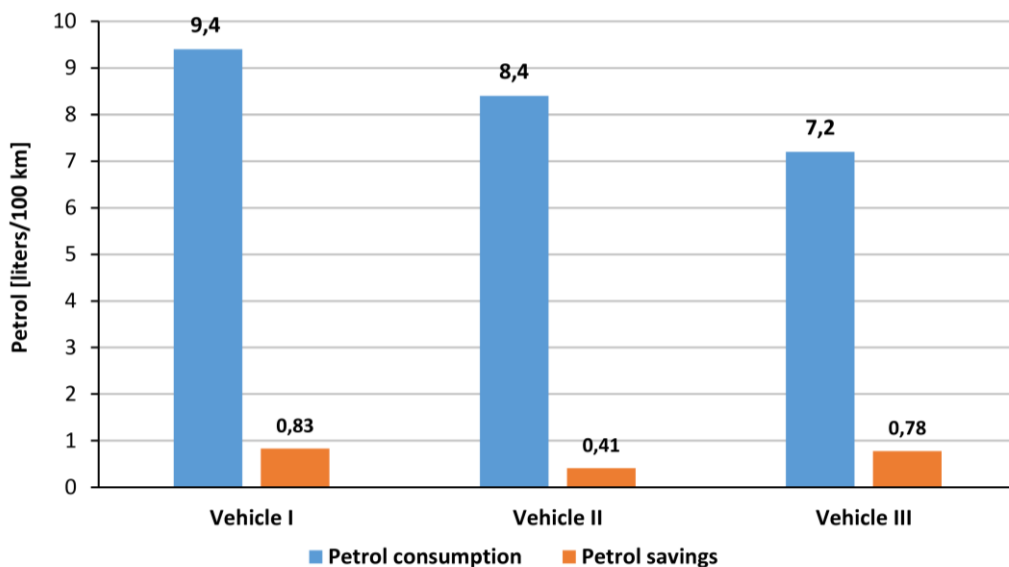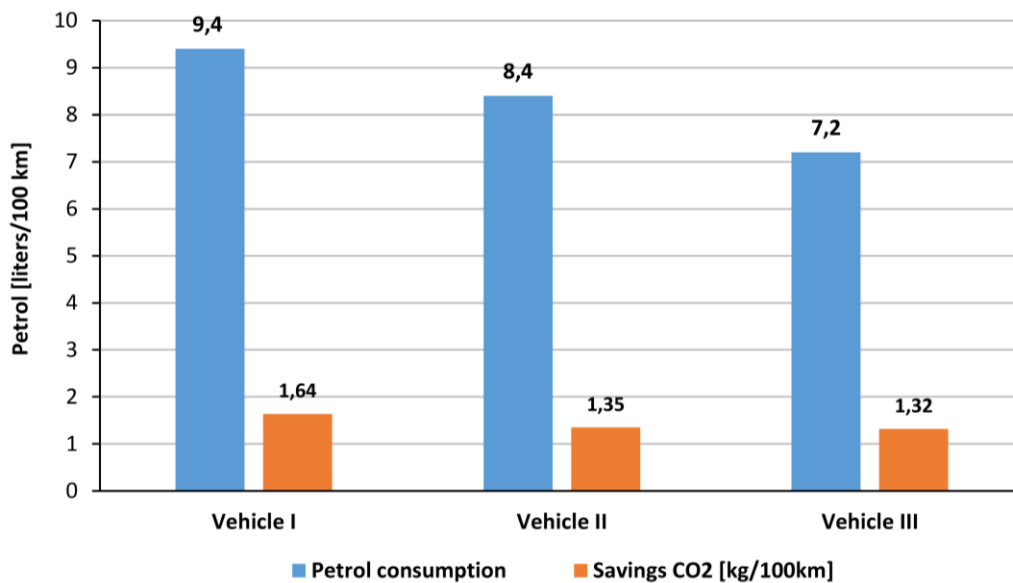| Tested vehicle	Petrol savings [l/year]		Saving CO_2 [kg/year]	
	EU	Poland	EU	Poland
Vehicle I	80,32	61,11	185,83	141,38
Vehicle II	48,64	37,01	112,53	85,62
Vehicle III	64,48	49,06	149,18	113,52

Fig. 3. Reduction of fuel for a vehicle equipped with 48V/12V DC/DC system

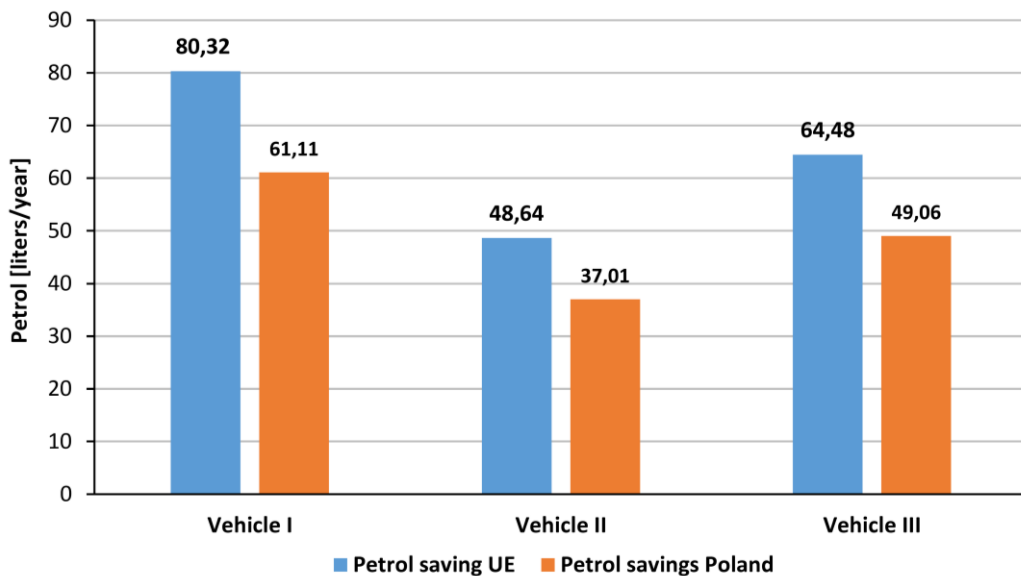Fig. 4. Reduction of CO_2 emission of a vehicle equipped with 48V/12V DC/DC system

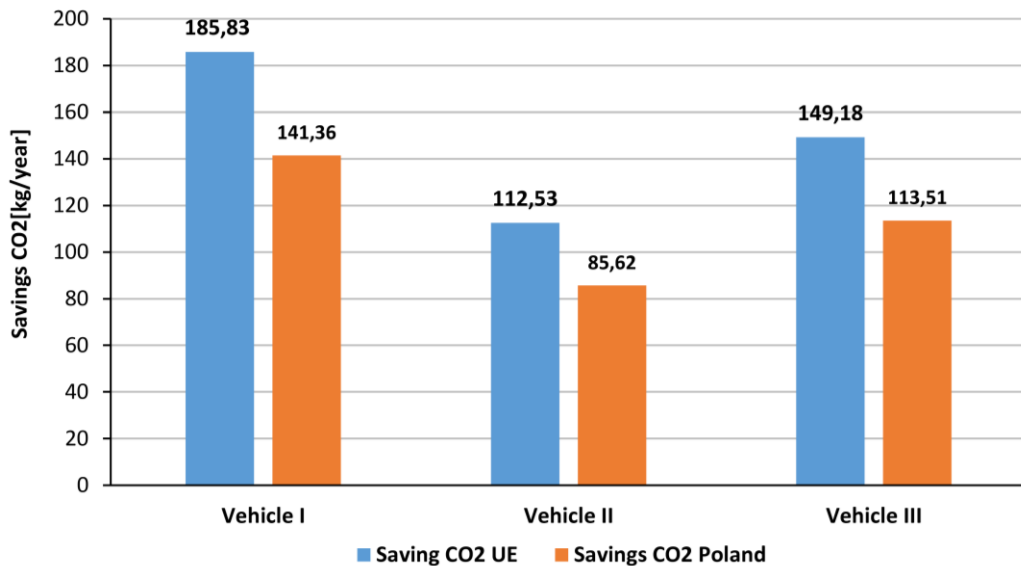Fig. 5. Fuel reduction of a vehicle equipped with 48V/12V DC/DC system in the European Union and Poland

Fig. 6. Reduction of CO_2 emission with 48V/12V DC/DC system in the European Union and Poland

7. Discussion and conclusions

Application of 48V motor generator combined with 48V/12V DC/DC converter is a cost-effective solution meeting regulations on exhaust emission and will fully meet growth of demand for energy energy-consuming electric components of motor vehicles in the future. It is expected that the use of 48V technology will increase even more and more and more rigorous regulations are being implemented within the scope of CO_2 emission, and the use of combustion engines will be constantly decreasing. In the European Union, general number of passenger vehicles in 2020 was 246 355 770, 51,7% (127 365 933) of them are petrol vehicles, whereas in Poland, there was 25 113 862 passenger vehicles, including 48,8% of petrol vehicles (12 255 564). If we assume average annual mileage from 2019 and an assume that the vehicles are equipped with 48V/12V DC/DC systems, fuel economy and reduction of CO_2 emission would largely affect protection of environment. Fuel economy showed in this article is promising for tested vehicles and they are a large source of reduction of CO_2 emission.

The values of saved fuel under conditions of normal use of a vehicle with a 48 V/12V DC/DC installation in city traffic for the three tested vehicles ranged from 0.57 to 0.71 (l/100km), resulting in CO_2 emission savings of 1.32 to 1.64 (kg/100km). Assuming the average annual mileage of vehicles according to ODYSSEE-MURE data in the European Union - 11,313 (km/year) and in Poland - 8,607 (km/year) for one of the tested vehicles, the savings in fuel consumed can reach up to 80 liters-EU and 60 liters-Poland. CO_2 emission reduction 186 (kg/year)-EU and 141(kg/year)-Poland. Considering the number of vehicles in use and their expected growth in the coming years, the use of a 48-volt motor-generator unit coupled with a 48V/12V DC/DC converter will be a serious alternative to other solutions for reducing CO_2 emissions.

Another aspect mentioned in this article is reduction of consumed power by the vehicles equipped with 48V system. Growth of rated voltage in electrical installations of the motor vehicles leads to reduction of voltage drops and power losses. Large reduction of diameter of the wires results in lower weight and lower costs of production. It is particularly important in the event of constant increasing of amount and power of electric and electronic devices and replacement of mechanical and hydraulic devices with electric and mechatronic devices. Inevitable development of the motor vehicles equipped with electric and hybrid drives is aiming at forcing changes of rated voltage of the systems, which will, for financial reasons, require higher voltage, not only in the whole system, but also in selected points and circuits.

But not only the transition to a higher voltage will fully meet the growing demand for energy-intensive electrical components of cars in the future. Other innovations are also needed to support the growing demand for power while maintaining a green vehicle development course. The following should be mentioned here: Advanced stop-start (including passive engine-off coasting), Active engine-off coasting , Brake recuperation, Boost assistance (or torque assistance), E-creeping and torque vectoring. To these innovations, we must add 48-volt hybridization, which offers several other functionalities, among which the possibility of reducing emissions should be emphasized.

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