

## Comparison of the cumulative energy demand of BEV's and FCEV's in their long-term operation

### ARTICLE INFO

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*The paper presents a method of using the theory of cumulative energy demand to assess this demand in long-term operation of vehicles with a mileage forecast of up to 350,000 km. Based on the results of operational "consumption" of energy and taking into account the energy "costs" of obtaining it, a comparison of the currently popular BEV's (Battery Electric Vehicles) and FCEV's (Fuel Cell Electric Vehicles) was presented. The question arises how much energy must be used to propel vehicles in their natural operation. After calculating using available data, the answer is – by operating FCEV's on average, two times more electricity is needed than by operating BEV's.*

Key words: energy, consumption, BEV's, FCEV's comparison

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### 1. Introduction

Discussions are underway and the first decisions regarding a significant reduction in carbon dioxide emissions have already been made. This also applies to transport. Today's proposals for transportation are either fully electric vehicles (BEV's) or hydrogen hybrid vehicles (FCEV's). Another direction perceived as future-oriented is the use of internal combustion engines powered by e-fuels (mainly ammonia (NH<sub>3</sub>), methane (CH<sub>4</sub>) or methanol (CH<sub>3</sub>OH)). This applies in particular to trucks. These vehicles consume significant amounts of fuel, but their number compared to passenger cars is small, and problems with developing new engines that can run on e-fuels are perceived as niche problems.

The issue of fuel consumption assessment is, of course very extensive and it is impossible to discuss it exhaustively here, however, some literature items on these issues seem to be very interesting.

The general way of treating an internal combustion engine in operation has been presented in [4]. A two-state model of transitions between engine states was developed, a risk function and a renewal (restitution) function were proposed. The possibility of assessing the credibility of the diagnosis for making operational decisions using the statistical decision theory was presented.

It has been found that electronic driver assistance systems help to reduce fuel consumption [7] by appropriately controlling the powertrain, and telling the driver how to steer the vehicle or which route to take. Examples of possibilities to reduce fuel consumption using an electronic controller are given. The support systems of two selected vehicle propulsion systems are described in detail. The article also includes examples of other driver assistance systems that can be used to reduce operational fuel consumption.

The paper [5] presents the results of analyzes of changes in fuel consumption depending on the intensity of everyday use of the vehicle, ambient temperature and cumulative mileage. The database included more than 600,000 kilometers of mileage and fuel purchase records, obtained from the data contained on the website <http://fueleconomy.gov>.

ICEV and HEV vehicles were compared. For ICEV vehicles, the variation within the same make and type was found to be 23% of the total variation, and 77% was between different vehicle brands and types. For hybrids, the figures are 19% and 81%, respectively. On-road fuel economy has been found to increase non-linearly as a function of mileage, with almost all of the increase occurring in the first few thousand miles. The trend for hybrid vehicles is very different from the trend for ICEVs.

Paper [13] presents a model of a fuel cell hybrid electric vehicle (FCHEV), its validation and a comparison of various control strategies for the Toyota Mirai (1st generation). The FCHEV model is created in the MATLAB® Simulink environment. The model was validated using operational data obtained from the open-source Argonne National Laboratory (ANL) database. According to the authors, the ECMS control strategy outperforms other strategies in all driving cycles by 0.4–15.6%.

The aim of the work [14] is to improve the energy efficiency of extended-range electric vehicles (EREV) and reduce the cumulative load on the batteries. The results show that the energy demand in the optimized operating mode under WLTP conditions increases by 4.49%, and the accumulated ampere-hours of the battery is reduced by 11.37%.

Fuel consumption in the WLTP tests was optimized, and the obtained data were verified with the results of controlled operation [2]. A fuel consumption map was created based on a large amount of ICEV data through fast data acquisition with the ISO-15765-4-CAN protocol. Next, a theoretical carbon dioxide (CO<sub>2</sub>) map was generated. The obtained results were compared on the WLTC and the local route. Significant improvements in both consumption and CO<sub>2</sub> emissions were found. It was also found that the use of the hybrid system on local routes with a greater proportion of urban driving conditions resulted in a greater improvement despite a slight decrease in the overall efficiency of the electrical system.

This article [6] implements an artificial neural network (ANN) for fuel consumption modeling to predict total and

instantaneous fuel consumption while traveling based on parameters such as engine load (%), speed (rpm) and vehicle speed (km/h). Data used for modeling were collected at a frequency of 1 Hz using portable monitoring systems (PEMS). The performance of the artificial neural network was assessed using mean absolute error (MAE), and root mean square error (RMSE). The model was further evaluated based on operational data. Artificial neural networks were shown to perform slightly better than other machine learning techniques such as linear regression (LR) and random forest regression (RFR), with high R-square ( $R^2$ ) and lower mean-square error.

The aim of the work [1] was to build a computational model of fuel consumption and CO<sub>2</sub> emissions, taking into account the technical specification, vehicle load and transport distance. The proposed model is evaluated on various examples for different types of vehicles. The model offers an effective tool for making operational decisions for transport systems by calculating fuel consumption and the resulting CO<sub>2</sub> emissions.

Although the presented works seem to be methodologically very interesting, it is difficult to find works covering the issue of long-term fuel consumption (for several years of vehicle operation), especially in relation to new energy carriers, such as for example hydrogen.

The problem of changing energy carriers is of course not new. The author, in the work entitled "Engine eco-fuels" published in 2004 [10], presented a drawing in which he presented the probable development of modern engine fuels.

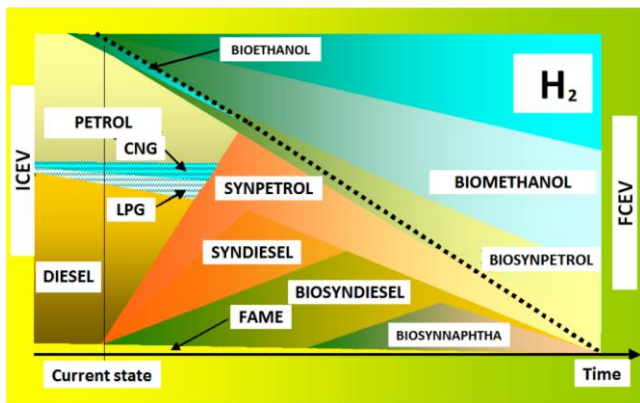


Fig. 1. Probable development of fuels for transport from the perspective of 2004 [10]

As the above (Fig. 1) shows, the main fuels should remain hydrogen (H<sub>2</sub>), bio-methanol (biomethanol) and synthetic gasoline of biological origin (biosynpetrol). It seemed then that internal combustion engines would be replaced by fuel cells, while synthetic bio-gasoline would be the fuel for internal combustion engines operating in hybrid vehicle drives. Fuel cell vehicles were to be of two types; using hydrogen (FCEV) and biomethanol (DMFCEV) as fuel.

A return to electric vehicle drives was not envisaged at that time.

Today, the situation has changed fundamentally – precisely as a result of the introduction of BEV. Although, as you can see, it is difficult to predict the direction of further

development of the automotive industry, but from today's point of view, it seems that in the future, two types of drive will be developed, i.e. electric drive (BEV) and hydrogen fuel cell drive (FCEV). Each of these options has known advantages and disadvantages. In electric vehicles, this is still a low energy density (batteries are still about 10× too heavy, and their charging time is about 30× too long). FCEV vehicles, similar in their assumptions but with an on-board source of converting hydrogen into electricity, are problematic in terms of storing hydrogen on board the vehicle (hydrogen technologies are mastered in large-scale stationary devices, the transition to small-scale and mobile devices is a new technological challenge) – hence the FCEV concept, which has been developed for over 30 years, has not yet conquered the car market.

However, the technological challenge is not limited to vehicle construction. The main problem is the issue of obtaining energy to drive vehicles from renewable resources. Without ensuring the possibility of using energy only from renewable resources, the implementation of new solutions in vehicles is pointless. Therefore, the question arises how much energy must be used to propel vehicles in their natural operation (less precisely defined as everyday) and how the BEV's and FCEV's compare in this aspect. This work is devoted to these issues.

The paper presents the theory of assessing cumulative energy demand and a method of using this theory to assess energy demand in long-term operation of vehicles with a mileage forecast of up to 350,000 km. Based on the results of operational "consumption" of energy and taking into account the energy "costs" of obtaining it, a energetically comparison of operating the currently popular BEV's and FCEV's was presented.

## 2. Use of the theory of cumulative energy/fuel consumption

Analyzed the energy consumption of BEV by the assumptions that  $E_i$  – i-th recharging,  $t_{di}$  – mileage to  $E_i$ , after i-th recharging it is as:

$$EE_i = \frac{100E_i}{t_{di} - t_{di-1}} \quad (1)$$

The term energy economy can be confusing. It is understood similarly to the classic fuel economy, which is based on the concept of fuel consumption. However, energy is not consumed but only changes its form, despite the fact that in the literature, the term energy consumption is used similarly to fuel consumption, so also energy economy seems possible for use.

The average energy economy (EEA) is

$$EEA_k = \frac{1}{k} \sum_{i=1}^k EE_i \quad (2)$$

CEC is given as:

$$CEC(t_{dk}) = \sum_{i=1}^k E_i \quad (3)$$

Using the BEV's database (spritmonitor.de [11], vehicle code 630364) as shown in Fig. 2. In this particular case, in the period from 2014.03.29 to 2017.08.13, the mileage of the car was in the range of 1,619 to 188,472 km, while the number of charges  $k = 103$ .

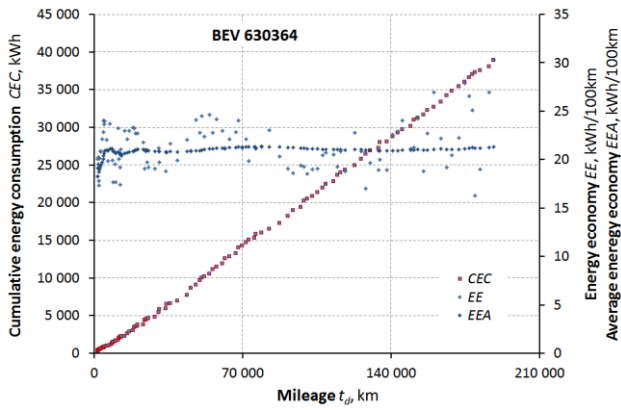


Fig. 2. Energy consumption of analyzed middle class BEV

EE in operation, changes between 16.26 and 30.25 kWh/100 km (about two times). At the same time the EEA changed from 18.25 to 21.31 kWh/100 km. On Fig. 2 is the CEC (in kWh) given, according to [9].

$$CEC(t) = ct^{a+1} \quad (4)$$

wherein: c, a – coefficients.

Most often, mileage “t<sub>d</sub>” is proportional to the operation time “t” also (t → t<sub>d</sub>), therefore

$$CEC(t_d) = ct_d^{a+1} \quad (5)$$

The derivative of the CEC is the intensity of the cumulative energy consumption:

$$ICEC(t_d) = \frac{dCEC(t_d)}{dt_d} = c(a + 1)t_d^a \quad (6)$$

Specific cumulative energy consumption (SCEC) is given as

$$SCEC(t_d) = \frac{CEC(t_d)}{t_d} = ct_d^a \quad (7)$$

The SCEC can be in kWh/km or in Ws/km. Coefficients „c” and „a” are to derived from the data from natural operation of vehicle. One of the good database is for example spritmonitor.de [11]. From this database were 9 BEVs randomly selected. On Fig. 3 are data for BEV 630364 as example presented.

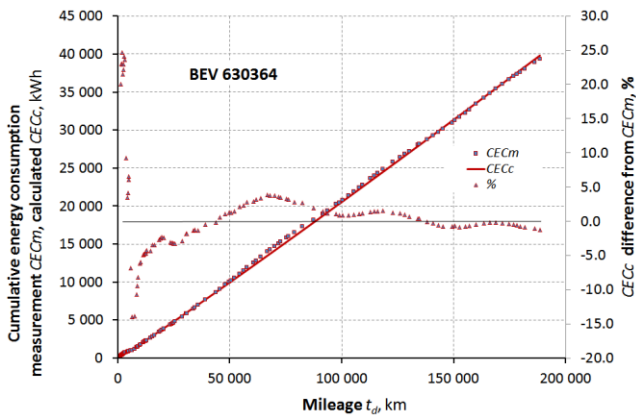


Fig. 3. Measured and model data and its difference for cumulative energy consumption of BEV 630364

The difference DCEC (in %) results from the equation (8)

$$DCEC(t_d) = 100 \frac{CEC_c(t_d) - CEC_m(t_d)}{CEC_c(t_d)} \quad (8)$$

For BEV 630364, the DCEC is on Fig. 3 showing. The adequacy data of the model (4) for all analyzed BEV's are collected in Table 1.

Table 1. Data of the analyzed BEVs

	BEV	R-Square	Rechargings	Coefficient c	Coefficient a
1	<b>658012</b>	0.99983	363	0.373468	-0.061132
2	<b>811970</b>	0.99860	31	0.829841	-0.124191
3	<b>651401</b>	0.99936	493	0.273221	-0.026875
4	<b>829324</b>	0.99989	104	0.193178	0.004073
5	<b>630364</b>	0.99811	103	0.123515	0.044163
6	<b>628759</b>	0.99966	812	0.302101	-0.029461
7	<b>804546</b>	0.99683	82	1.162061	-0.113322
8	<b>607293</b>	0.99863	744	0.205950	0.013584
9	<b>856153</b>	0.99973	38	0.176429	-0.012076

The high values of R-square are not an exception (see e.g. [9]). CEC as a function of mileage seems to be a straight line (Fig. 3), but this is not the case (because a≠0).

By knowledge of „c” and „a” the further characteristics of CEC can be presented. These are the ICEC, SCEC. All these characteristics together form the energy footprint of the vehicle (for BEV 630364 – Fig. 4).

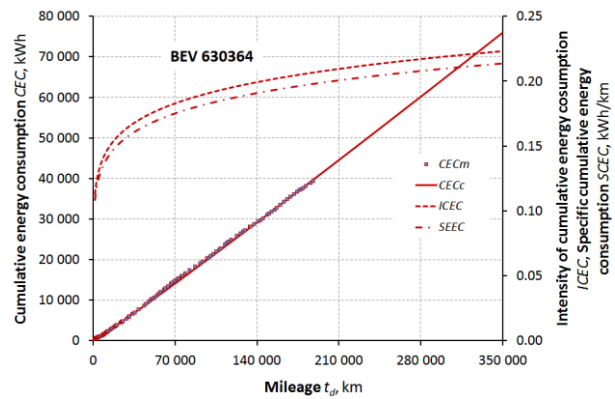


Fig. 4. Energy footprint of BEV 630364

For each of the nine analyzed BEVs the CEC are shown in Table 1 and Fig. 5.

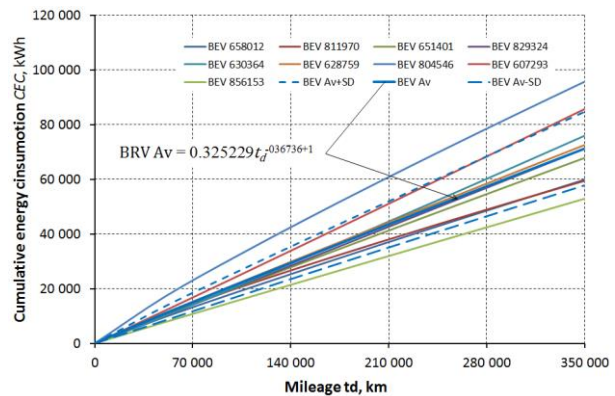


Fig. 5. Cumulative energy consumption of analyzed BEVs

Some CEC (e.g. BEV 804546 or BEV 856153) clearly differ from others. These data reflect the exploitation conditions e.g. BEV 804546 was almost 100% used on highway driving. Since it was decided that the comparison would be between BEV's and FCEV's cars, the cumulative energy consumption theory presented above was used to assess the cumulative energy (fuel) consumption of hydrogen by the FCEV's. An example of processing hydrogen consumption results is shown in Fig. 6. Figure 6 shows fuel economy (FE) calculated according to the same procedure as EE.

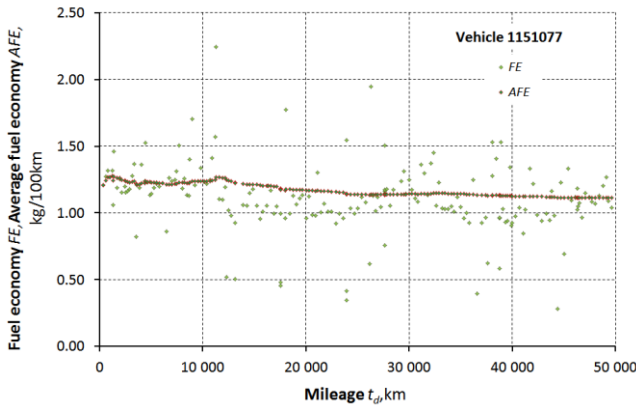


Fig. 6. Fuel economy (FE) and average fuel economy (AFE) for the vehicle 1151077

Fuel consumption footprint of FCEV 1151077 is presented on the Fig. 7.

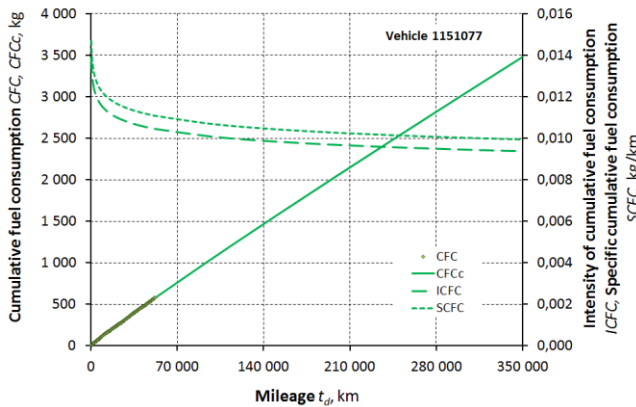


Fig. 7. Fuel consumption footprint of FCEV 1151077

The calculation results for the seven analyzed FCEV's are given in Table 2.

Table 2. The calculation results for footprint of analyzed FCEV's

	FCEV	R-Square	Refuelings	Coefficient c	Coefficient a
1	<b>1151077</b>	0.998687	197	0.020574	-0.056978
2	<b>1254191</b>	0.993665	40	0.016105	-0.044394
3	<b>1316958</b>	0.985653	8	0.005089	0.072905
4	<b>1195603</b>	0.996220	65	0.000080	0.460080
5	<b>1242674</b>	0.999922	5	0.006109	0.015091
6	<b>1349603</b>	0.999762	12	0.007836	-0.008227
7	<b>1394273</b>	0.999547	31	0.011271	-0.006655

Cumulative fuel consumption up to mileage of 350,000 km of analyzed FCEV's are presented here in the Fig. 8.

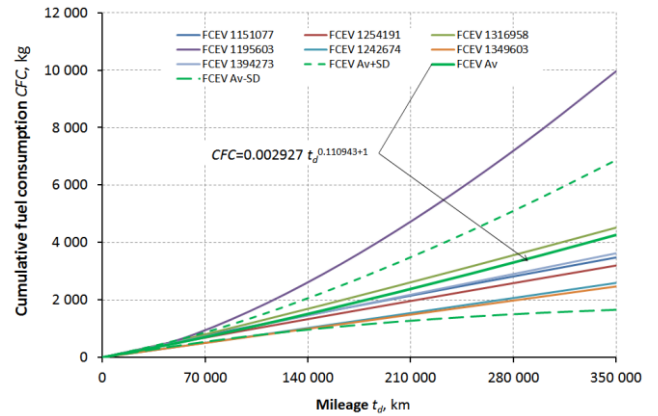


Fig. 8. Cumulative fuel consumption up to mileage of 350,000 km of analyzed FCEV's

As in the case of BEV's, there are significant deviations from the average value in the operation of hydrogen-powered FCEV's. These deviations increase as the mileage of the vehicles increases. Also in this case, these deviations are caused by very different operating conditions of individual cars. As stated earlier, obtaining electricity or fuel requires additional energy inputs related to, for example, transmission losses.

In the case of electricity generation, it is estimated that its supply to vehicle batteries is associated with approximately 20% losses. This means that when estimating the vehicle's demand for electric energy, it is to multiplying the CEC by 1.2.

Obtaining hydrogen involves the need to spend energy on electrolysis of water (if hydrogen is to be obtained from this resource), then purification of hydrogen, its compression (or liquefaction), transport to the gas station, and then pumping it to the tank of the vehicle. It is estimated that these activities require 40 kWh<sub>e</sub> to 70 kWh<sub>e</sub> of electricity for every 1 kg of hydrogen.

In further considerations, it was assumed that in order to obtain 1 kWh of energy in a BEV battery, 1.2 kWh<sub>e</sub> of electricity must be involved, while in order to obtain 1 kg of hydrogen for FCEV, a very favorable variant was adopted that "only" 40 kWh<sub>e</sub> of electricity must be engaged. After the appropriate multiplication of the values of the cumulative electricity and cumulative fuel (hydrogen) consumption in the conditions of vehicle operation, were obtained for average values and standard deviations. The data is shown in Fig. 9.

The obtained results are quite "shocking". The demand for electricity for the operation of hydrogen-powered FCEV's is on average, about twice as high as for BEV's.

In addition, deviations from the average value of FCEV's electricity demand are more than four times higher than for BEV's. Of course, small numbers of vehicles were analyzed. As the number of analyzed vehicles increases, these deviations will, of course decrease. All this assuming the most favorable (currently) indicators. A general improvement in the situation is to be expected in the future.

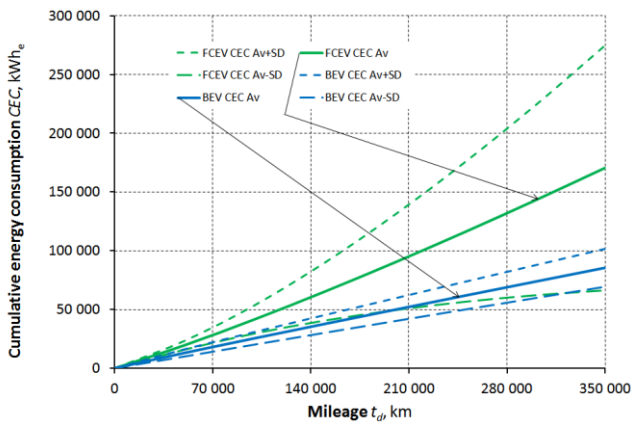


Fig. 9. Summarized cumulative electricity consumption of BEV's and FCEV's for their operation up to 350,000 km

**Summary**

The presented method for assessment of energy demand can be used for assessing of electricity demand for long term operation of vehicles.

The work concern comparison of BEV's and FCEV's. There are no published papers for direct discussion of this problem. The works (e.g. [3, 8, 12]) present part of problem but from the fully other point of view of assessing of energy consumption of vehicles in operation.

For analyzed here BEV's and FCEV's obtained was very good adequacy of the mathematical model of cumulative energy consumption. Correlation coefficients are very high e.g. R-square is higher than 0.99.

Mathematical models of cumulative energy consumption, intensity of this consumption and specific energy consumption, form together the vehicle's "energy footprint". Those footprint can be useful for further analyses.

It is noticed a large dispersion of courses of cumulative energy consumption (although the vehicles of the same type and brand in each group were analyzed). This dispersion increases with the mileage. As a result the discrepancies between the electricity demand in the vehicle group are large and increase with the mileage. In the analyzed case, discrepancies in electricity need are four times higher in case of FCEV's as in BEV's.

The average cumulative electricity consumption of FCEVs is twice BEV's (in analyzed examples with random data).

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**Nomenclature**

a	coefficient	EEA	average energy economy
c	coefficient	CEC(t)	cumulative energy consumption to the time t
e <sub>i</sub>	i-th quantum of energy	CEC(t <sub>d</sub> )	cumulative energy consumption to the mileage t <sub>d</sub>
$\bar{e}(t)$	average size of the quantum of energy	CFC	cumulative fuel consumption
n(t)	energy quantum number	DCEC(t <sub>d</sub> )	difference calculated and measured energy consumption to the t <sub>d</sub>
t	time	FCEV	fuel cell electric vehicle
t <sub>d</sub>	mileage	ICEC(t <sub>d</sub> )	intensity of the cumulative energy consumption
BEV	battery electric vehicle	SCEC(t <sub>d</sub> )	specific cumulative energy consumption
EC	energy consumption		
EE	energy economy		

**Bibliography**

[1] Aksoy A, Küçükoğlu İ, Ene S, Öztürk N. Integrated emission and fuel consumption calculation model for green supply chain management. *Procedia – Social and Behavioral Sciences*. 2014;109:1106-1109. <https://doi.org/10.1016/j.sbspro.2013.12.595>

[2] Balci Ö, Karagöz Y, Gezer O, Kale S, Köten H, Pusat S et al. Numerical and experimental investigation of fuel consumption and CO<sub>2</sub> emission performance for a parallel hybrid vehicle. *Alexandria Eng J*. 2021;60(4):3649-3667. <https://doi.org/10.1016/j.aej.2021.02.025>

[3] Braun A, Rid W. Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real world data on the Erfurt circuit in Germany. *Transp Res Procedia*. 2017;27:468-475. <https://doi.org/10.1016/j.trpro.2017.12.044>

[4] Girtler J. Possibility of estimating the reliability of diesel engines by applying the theory of semi-Markov processes and making operational decisions by considering reliability of diagnosis on technical state of this sort of combustion engines. *Combustion Engines*. 2015;163(4):57-66. <https://doi.org/10.19206/CE-116857>

[5] Greene DL, Liu J, Khattak AJ, Wali B, Hopson JL, Goeltz R. How does on-road fuel economy vary with vehicle cumulative mileage and daily use? *Transport Res D-Tr E*. 2017;55:142-161. <https://doi.org/10.1016/j.trd.2017.06.004>

[6] Katreddi S, Thiruvengadam A. Trip based modeling of fuel consumption in modern heavy-duty vehicles using artificial intelligence. *Energies*. 2021;14(24):8592. <https://doi.org/10.3390/en14248592>

[7] Kropiwnicki J, Kortas P. Potentials for fuel consumption reduction by using electronic driver assistance systems. *Combustion Engines*. 2013;154(3):250-256.

[8] Li W, Stanula P, Egede P, Kara S, Herrmann C. Determining the main factors influencing the energy consumption of electric vehicles in the usage phase. *Procedia CIRP*. 2016; 48:352-357. <https://doi.org/10.1016/j.procir.2016.03.014>

[9] Sitnik LJ. Energy demand assessment for long term operation of vehicles. *SAE Technical Paper 2020-01-2165*. 2020. <https://doi.org/10.4271/2020-01-2165>

[10] Sitnik L. *Engine eco fuels*. Wrocław Publishing House (in Polish). Wrocław 2004.

[11] *Spritmonitor*. <https://www.spritmonitor.de/>

- [12] Travasset-Baro O, Rosas-Casals M, Jover E. Transport energy consumption in mountainous roads. A comparative case study for internal combustion engines and electric vehicles in Andorra. *Transport Res D-Tr E*. 2015;34:16-26. <https://doi.org/10.1016/j.trd.2014.09.006>
- [13] Usmanov U, Ruzimov S, Tonoli A, Mukhitdinov A. Modeling, simulation and control strategy optimization of fuel cell hybrid electric vehicle. *Vehicles*. 2023;5(2):464-481. <https://doi.org/10.3390/vehicles5020026>
- [14] Xu Y, Zhang H, Yang Y, Zhang J, Yang F, Yan D et al. Optimization of energy management strategy for extended range electric vehicles using multi-island genetic algorithm. *J Energy Storage*. 2023;61:106802. <https://doi.org/10.1016/j.est.2023.106802>

Prof. Lech J. Sitnik, DSc., DEng. – Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Poland.  
e-mail: [lech.sitnik@pwr.edu.pl](mailto:lech.sitnik@pwr.edu.pl)

