Розглянуто проблему створення екологічно чистих та енергозберігаючих транспортних засобів в бюджетному сегменті на підставі визначення техніко-економічних параметрів. Досягнуто і обґрунтовано підвищення паливної економічності і екологічної чистоти автомобілів за рахунок розробки гібридної силової установки на підставі обраних раціональних техніко-економічних параметрів. Побудовано тривимірні залежності витрати енергії блоку тягових акумуляторних батарей і відносної дальності пробігу від маси і сталої швидкості.

Сформульовано рекомендації щодо вибору енергоємності блоку тягових акумуляторних батарей для гібридних транспортних засобів різної маси і бажаної дальності пробігу в режимі «тільки електрика». Встановлено діапазон пробігу в режимі «тільки електрика» на одному заряді тягових акумуляторних батарей в межах від 20 км до 50 км. Запропоновано вибір гібридного транспортного засобу в залежності від передбачуваного середньодобового пробігу і енергоємності тягових акумуляторних батарей. Це дозволить споживачеві приймати рішення щодо вибору гібридного транспортного засобу, виходячи з індивідуального планованого середньодобового пробігу.

Розроблено концептуальні рішення по створенню гібридних силових установок за економічним принципом їх побудови. Наукові результати підтверджені практично на експериментальному гібридному концепті, який створений на базі ЗАЗ Ланос Пікап. Такий підхід дозволяє підвищити конкурентоспроможність і економічну привабливість гібридних транспортних засобів

Ключові слова: гібридний транспортний засіб, гібридна силова установка, тягова акумуляторна батарея, енергоємність

DETERMINING THE TECHNICAL AND ECONOMIC PARAMETERS FOR DESIGNING HYBRID POWER UNITS FOR THE BUDGET SEGMENT

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1. Introduction

According to statistics, about 1 billion cars were driven in the world at the beginning of the 21st century [1]. The same studies show that at an average mileage of 15 thousand km per year each car burns 2 tons of fuel and about 26–30 tons of air, including 4.5 tons of oxygen, which is 50 times more than the annual needs of a person. At the same time, a car emits into the atmosphere (in kg per year): carbon monoxide – 700, nitrogen dioxide – 40, unburned hydrocarbons – 230, and solid fine particulate matter (PM) – 2–5 [2, 3]. Therefore, it is a relevant issue to introduce electric cars in general, and in Ukraine in particular, in terms of environmental impact. Results from monitoring data [4–6] show that residents in buildings located near major roads or highways at a distance to 10 m suffer from cancer three to four times more often than in buildings located from the road at a distance of 50 m.

At the current stage of science and technology development, the task of designing environmentally friendly and energy-efficient vehicles is solved by the construction of electric vehicles: electric cars or hybrid vehicles. However, attempts to massively introduce electric cars did not yield the desired result. This is mainly due to the limited power reserve for an electric vehicle to travel per a single charge of a traction rechargeable battery (TRB) given its low energy intensity [7, 8]. In the pursuit of improving the environmental component, it is also a relevant task to preserve other characteristics in vehicles (for example, mileage, economy). In this regard, production of hybrid vehicles is a strategically correct direction in the development of automakers. In this case, the most promising are those hybrid vehicles that operate under an electricity-only mode and which can accumulate energy in TRB from stationary energy sources.

2. Literature review and problem statement

Currently, there is no single concept for the construction of hybrid power units, with each manufacturer implementing its own version of hybrid technology [9–12]. Hybrid power units are categorized based on the method

for connecting the engines and an accumulator to the drive: serial, parallel, serial-parallel. General Motors Automobile Corporation (USA) implements a serial hybrid scheme in the hybrid electric car Chevrolet Volt. Honda Motor Co., Ltd. (Japan) is developing the hybrid vehicles Honda Insight, Honda Civic Hybrid, Honda CR-Z based on the parallel scheme. Toyota Motor Corporation (Japan) produces hybrid vehicles of the series Toyota Prius, Lexus RX400h, Lexus GS450h and others based on the serial-parallel technology [13, 14]. However, these and other hybrid vehicles are not widely used because of the high cost. Savings from lower fuel consumption do not nearly exceed the cost of a hybrid power unit. In this case, the analysis of studies [15, 16] has revealed a series of unresolved problems and drawbacks. These are, specifically:

– significant complexity and the mass of a hybrid power unit, which leads, on the one hand, to an increase in cost, on the other hand, to an increase in the weight of a car (Volt, Prius, CR-Z);

– the lack of fuel efficiency given the inefficient conversion of fuel energy into electrical energy (Volt);

– the low efficiency of TRB use because TRB acts as an energy buffer (Prius, CR-Z);

– the lack of eco-friendliness due to that the "electricity only" mode operates automatically (Prius) or there is no such mode at all (CR-Z).

Study [17] proposes a method to improve the operation of a refitted bus power unit, constructed using hybrid technology. In the study, its author focuses only on improving economic and environmental indicators. The author does not draw a parallel between the specified and energy parameters.

Paper [18] substantiated a pattern in the operation of electric energy storage systems in tractor-trailers and machine-tractor assemblies, which make it possible to improve production efficiency, reduce energy costs, and enhance environmental safety. In this case, the paper ignores the efficiency indicator, which is not less important for the consumer than the environmental and energy aspects.

Work [19] focuses on the design and construction of hybrid power units based on economic feasibility, which is the most promising in the creation of hybrid vehicles in the budget segment. However, this approach ignores the energy component, which leads to a decrease in dynamics.

Study [20] proved the optimal ratio of energy consumption to engine efficiency. In this case, the authors define the main drawback of their design – the inability to drive under an electricity-only mode over the entire speed range of the car.

The researchers engaged in the construction of a hybrid power unit based on an environmental principle suggested, in order to achieve the appropriate balance of engines, the use of high-power electric motors [21]. In this case, the economic component, which is significant for the budget sector, was completely ignored.

In this regard, the improvement of hybrid vehicles, in the context of their introduction to the budget segment, is a strategically correct direction in the development of automakers. The absence of a unified integrated approach, which would take into consideration the environmental, energy, and economic components in the development of hybrid power units, indicates the need for appropriate research to define the technical-economic parameters.

3. The aim and objectives of the study

The aim of this study is to define the technical-economic parameters in order to design hybrid power units for the budget segment.

To accomplish the aim, the following tasks have been set:

– to formulate a generalized criterion for the choice of hybrid power units, taking into consideration the energy, environmental, and economic components;

– to build three-dimensional energy and mileage dependences on mass and steady speed in order to select the energy intensity of a TRB unit for hybrid vehicles under an electricity-only mode;

– to devise conceptual solutions for hybrid power unit construction in the budget segment.

4. Building a generalized criterion for the choice of hybrid power units

4. 1. Principle of economic feasibility in building hybrid power units

The principle of economic feasibility relates to building a hybrid vehicle for the budget segment. This means that the cost of an electric drive would be less than 30 % of the cost of the base vehicle. Traction electric motors implement the maximum torque when starting at a low speed of rotation, which is why they, in contrast to ICE, show high energy efficiency, which is demonstrated at a constant speed of about 8.5 m/s (Fig. 1).
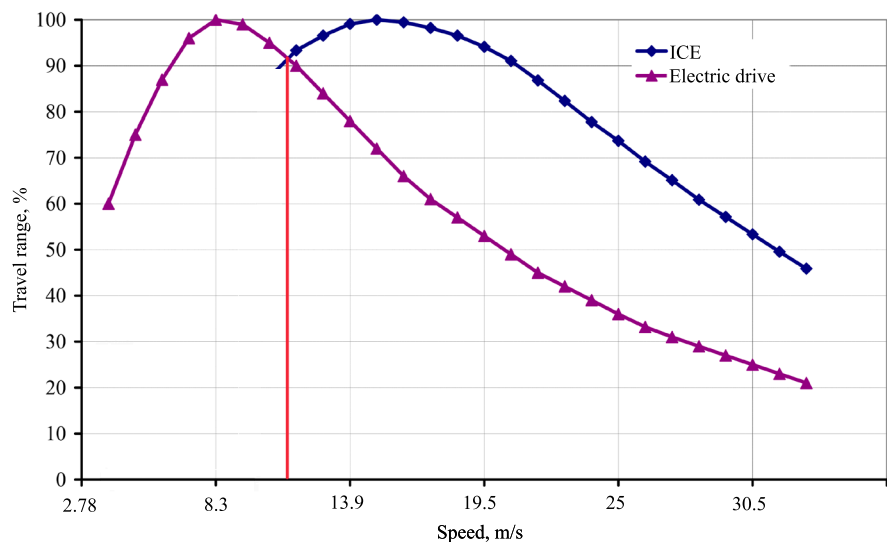

Fig. 1. Illustration of the principle of economic feasibility for building hybrid power units

The dependence of relative travel range on the motion speed of a car equipped with ICE was derived from the typical fuel characteristic of the car steady speed, %:

$$D = \frac{Q_{min}}{Q_n} \cdot 100\,\%, \qquad (1)$$

where Q_{min} is the minimum fuel consumption, l/100 km; Q_n is the current fuel consumption, l/100 km.

It follows from Fig. 1 that the "electricity only" mode is executed to a speed of about 12 m/s. It is advisable to connect the ICE for further acceleration. In this case, the ratio of electric engine power to the power of the ICE can range from 1/3 to 1/2. Thus, one can use an inexpensive traction electric motor.

The principle of economic feasibility in building hybrid power units makes the most of the economic possibilities of a traction electric motor and the ICE. The main drawback of a given principle when building a hybrid power unit is the inability to travel under an electricity-only mode over the entire speed range [22].

The principle of economic feasibility underlies a hybrid concept built on the basis of the car ZAZ Lanos Pickup at the Department of Automotive Electronics of the Kharkiv National Automobile and Road University (KhNADU).

4. 2. Energy principle for building hybrid power units

The energy principle of building hybrid power units considers the movement of a hybrid vehicle in terms of the optimal energy consumption (gasoline and electricity) taking into consideration efficiency of the electric motor and the ICE. We calculate the ICE effective energy, released at gasoline combustion, according to the following formula, kWh:

$$Q_e = \eta \cdot \frac{H_u \cdot V \cdot \rho}{1000}, \qquad (2)$$

where $\eta = 0.3$ is the ICE efficiency; $H_u = 44.0$ MJ/kg= $=12.22$ kWh/kg is the lower heat of the gasoline AI 95 com-

bustion; V is the volume of gasoline used, l; $\rho = 750$ kg/m^3 is the specific density of gasoline AI 95.

The dependence of the ICE energy consumption (Fig. 2) is built based on the typical fuel characteristic for a car motion, taking into consideration the recalculation using formula (2). The dependence of energy consumption by an electric car was derived considering efficiency of the electric motor $\eta_{EM} = 90\,\%$.

According to the energy principle for building hybrid power units, it is advisable to use a traction electric drive at speeds of up to 22 m/s and, at further acceleration, it is expedient to connect the ICE. In this case, the ratio of electric engine power to the ICE power can range from 1/2 to 1/1.

The cars that are built based on the energy principle include Toyota Prius (Japan), modifications 2 and 3, whose maximum speed under an electricity-only mode reaches 17 m/s.

Compared to the principle of economic feasibility, the disadvantage of this approach is the higher price and the impossibility of driving under an "electricity only" mode across the entire speed range [23].

4. 3. Environmental principle for building hybrid power units

When building a hybrid power plant based on the environmental principle, the movement of a vehicle over the entire range of speeds is executed exclusively by an electric drive. The system ICE-a generator unit is connected only when power in the TRB unit is exhausted, in order to charge it (Fig. 3).

In order to implement the environmental principle in building hybrid power units, high-power electric motors must be used, which are not inferior to ICE in terms of power. A typical example of a car built on the environmental principle is the hybrid electric car Chevrolet Volt (USA).

The disadvantage of such a principle of building a hybrid power unit is that the ICE is used only to generate electrical energy in order to charge TRB, which is not economically feasible. In addition, the weight of a vehicle increases significantly due to the mass of the ICE, generator plant, fuel tank, etc. [14, 23].
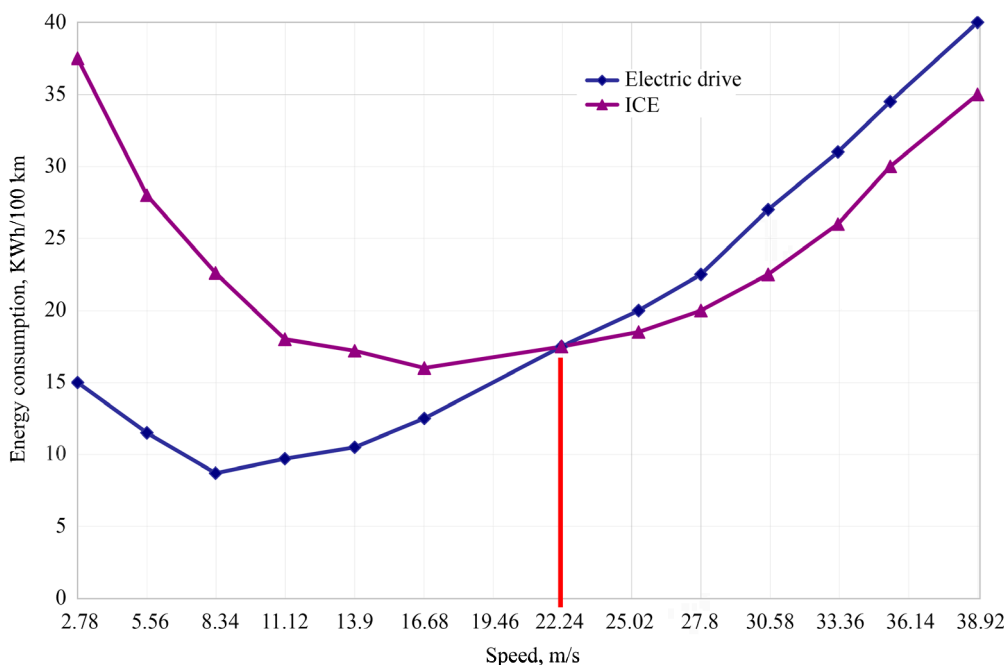

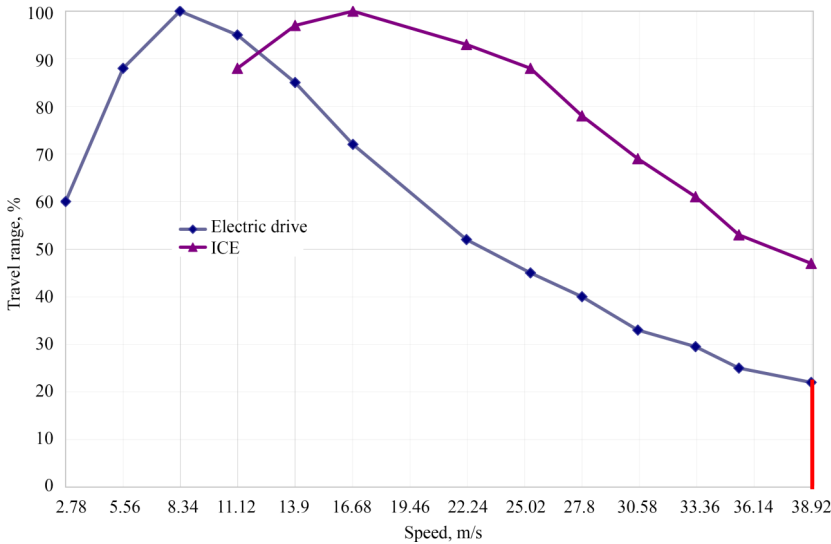Fig. 2. Illustration of the energy principle for building hybrid power units

Fig. 3. Illustration of the environmental principle for building hybrid power units

4. 4. Comparing the principles of building hybrid power plants

The operation of hybrid power units based on different principles can be represented using the movement of hybrid vehicles along the European travel cycle as an example (Fig. 4).
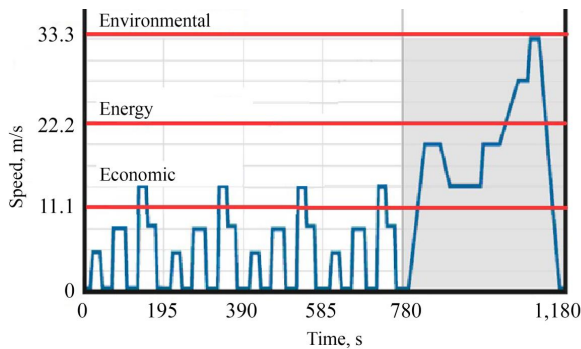

Fig. 4. Example of ICE connection

When the appropriate speed is reached, the ICE is connected to implement the economic or energy principle of building hybrid power units.

4. 5. Designing hybrid power units, based on the economic principle, on the basis of the concept ZAZ Lanos Pickup

Hybrid vehicles are not widely used given their much higher price than similar cars equipped with ICE. The solution to this problem is to design a hybrid power unit for the budget segment. That would increase the competitiveness and economic attractiveness of hybrid vehicles. At the same time, all the positive properties of hybrid vehicles are preserved, namely, moving under an electricity-only mode, charging a TRB from the stationary electric network.

To confirm this concept, we modernized the car ZAZ Lanos Pickup at the Department of Automotive Electronics of KhNADU to make it a hybrid vehicle. In this case, the vehicle itself and its operating power unit remain almost unchanged. It is only supplemented with a traction electric motor of the valve type, a TRB, a voltage converter, a control system, a TRB unit

charge system, etc. This improves the reliability of the hybrid power unit.

The hybrid concept ZAZ Lanos Pickup uses 20 sequentially connected rechargeable batteries TS-LFP90AHA as a TRB, with a total energy intensity of 5.76 kWh and a valve electric motor capacity of 15 kW.

The quasi-static and transitional operation modes of the valve electric motor are described by a system of equations, which is recorded in the orthogonal coordinate axes (d, q):

$$\begin{cases} u_d = R_s i_d + L_d \dfrac{di_d}{dt} - \omega L_q i_q; \\[2mm] u_q = R_s i_q + L_q \dfrac{di_q}{dt} + \omega L_d i_d + \omega \Psi_m; \\[2mm] M = \dfrac{3}{2} p\left[i_q \Psi_m + i_d i_q (L_d - L_q) \right]; \\[2mm] J \dfrac{d\omega}{dt} = M - M_l, \end{cases} \quad (3)$$

where u_d, u_q are the projections of stator voltage vectors on the axes (d, q); R_S is the active resistance of the stator winding; i_d, i_q u_d, u_q are the projections of stator current vectors on the axes (d, q); ω is the angular frequency of rotor rotation; p is the number of pairs of poles; L_q, L_d are the longitudinal and transverse inductance of the stator; Ψ_m are the flux linkage of the stator winding with a rotor winding; J is the cumulative moment of inertia; M is the electromagnetic moment of an electric motor; M_l is the moment of load on the electric motor shaft.

The equation of current transition from a three-phase to the orthogonal coordinate system takes the following form:

$$\begin{cases} i_d = \dfrac{3}{2}\left[\begin{array}{l} i_A \cdot \cos\gamma + i_B \cdot \cos\left(\gamma + \dfrac{2\pi}{3}\right) + \\[2mm] + i_C \cdot \cos\left(\gamma + \dfrac{2\pi}{3}\right) \end{array} \right]; \\[6mm] i_d = \dfrac{3}{2}\left[\begin{array}{l} i_A \cdot \sin\gamma + i_B \cdot \sin\left(\gamma + \dfrac{2\pi}{3}\right) + \\[2mm] + i_C \cdot \sin\left(\gamma + \dfrac{2\pi}{3}\right) \end{array} \right], \end{cases} \quad (4)$$

where i_A, i_B, i_C are the currents in the corresponding stator windings, $i_A + i_B + i_C = 0$; γ is the angle between the magnetic axis of phase A and the longitudinal axis of the rotor d.

The inductances of stator windings are the periodic functions of the angle between a magnetic axis of the phase and the longitudinal axis d with a period equal to π:

$$L_A = l_0 + l_2 \cdot \cos 2\gamma_A + l_4 \cdot \cos 4\gamma_A + ...;$$

$$L_B = l_0 + l_2 \cdot \cos 2\gamma_B + l_4 \cdot \cos 4\gamma_B + ...;$$

$$L_C = l_0 + l_2 \cdot \cos 2\gamma_C + l_4 \cdot \cos 4\gamma_C ..., \quad (5)$$

where l_0 is the average inductivity of a phase winding; l_2, l_4 is the amplitude of change in inductance due to the action of harmonics 2 and 4.

By neglecting the fields of higher harmonics and moments, it would suffice to take into consideration no more than two components:

$$L_A = l_0 + l_2 \cdot \cos 2\gamma_A = l_0 + l_2 \cdot \cos 2\gamma;$$

$$L_B = l_0 + l_2 \cdot \cos 2\gamma_B =$$
$$= l_0 + l_2 \cdot \cos\left(2\gamma + \frac{2\pi}{3}\right);$$

$$L_C = l_0 + l_2 \cdot \cos 2\gamma_C =$$
$$= l_0 + l_2 \cdot \cos\left(2\gamma - \frac{2\pi}{3}\right). \tag{6}$$

Mutual inductances are the paired periodic functions of the angle between the d axis and the line drawn between the magnetic axes of phases:

$$M_{AB} = m_0 + l_2 \cdot \cos\left(2\gamma - \frac{2\pi}{3}\right);$$

$$M_{AC} = m_0 + l_2 \cdot \cos\left(2\gamma + \frac{2\pi}{3}\right);$$

$$M_{BC} = m_0 + l_2 \cdot \cos 2\gamma, \tag{7}$$

where m_0 is the constant component of mutual inductance.

In the system of equations (3) inductances along the longitudinal and transverse axes are determined from the following formulae:

$$L_d = l_0 - m_0 + \frac{2}{3}l_2, \tag{8}$$

$$L_q = l_0 - m_0 - \frac{2}{3}l_2. \tag{9}$$

Valve electric motors, in contrast to ICEs, implement a maximum torque when starting and at a low rotation speed, therefore even the relatively low power of an electric motor makes it possible to attain the required dynamic characteristics of the car at the onset of motion.

5. Building 3D dependences of energy consumption and travel distance on the mass and steady speed of hybrid vehicles

A universal mathematical model of a hybrid vehicle was used to build the three-dimensional dependences; it was implemented in the licensed MATLAB Simulink environment [22]. The adequacy of the modeling results was confirmed by practical experiments involving the hybrid concept ZAZ Lanos Pickup and Toyota Prius. The results of our study are summarized in Fig. 5.

The best economical efficiency is demonstrated by the vehicle under an electricity-only mode at speeds of up to 17 m/s. The minimum energy consumption by TRB is observed at a steady speed of about 8 m/s.
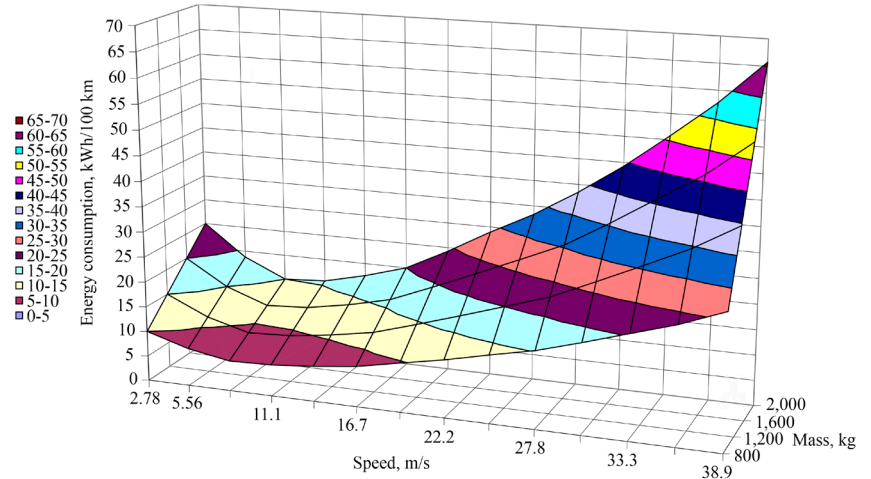

Fig. 5. 3D dependence of energy consumption by a traction rechargeable battery unit on mass and steady speed

Let us determine the vehicle's relative travel range S under an electricity-only mode, %:

$$S = \frac{E_{TRB\min} \cdot 100\,\%}{E_{TRB}}, \tag{10}$$

where $E_{TRB\min}$ is the minimum energy consumption by TRB for vehicles of the same mass, kWh/100 km; E_{TRB} is the current energy consumption by TRB, kWh/100 km.

The 3D dependence of the vehicle's relative travel range under an electricity-only mode on mass and steady speed is represented in the form of a three-dimensional dependence (Fig. 6).

We determine the specific energy consumption E_{sp} by rechargeable batteries recalculated for 1 kg of mass and for 1 km of vehicle mileage, W·h/km·kg:

$$E_{sp} = \frac{E_{TRB} \cdot 1000}{m \cdot S}, \tag{11}$$

where m is the vehicle weight, kg; S=100 km is the mileage of a vehicle, km.

The three-dimensional dependences of travel range on TRB power intensity (depending on the number of rechargeable batteries, the type of TS-LFP90AHA) are shown in Fig. 7, 8 for vehicles weighing 800 kg and 1,600 kg, respectively.
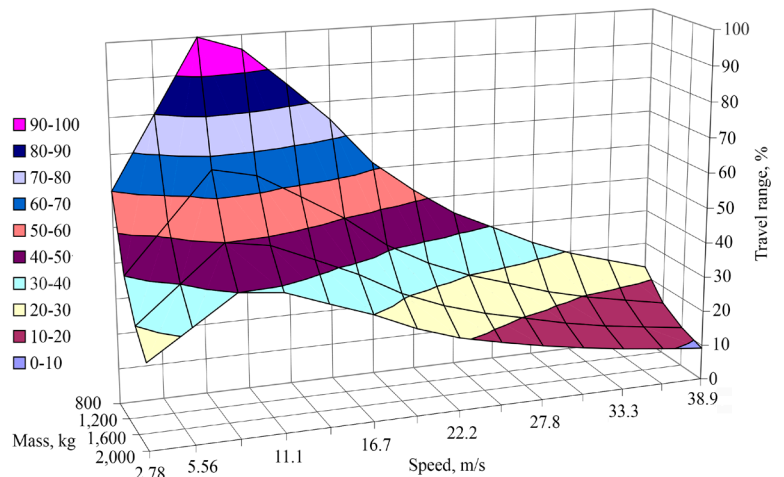

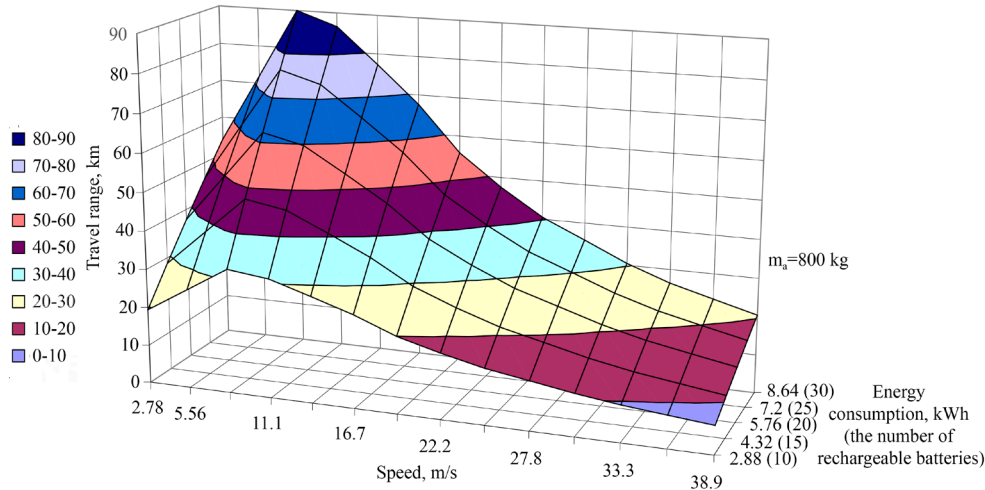Fig. 6. 3D dependence of the vehicle's relative travel range under an electricity-only mode on mass and speed

Fig. 7. Three-dimensional dependences of travel range on TRB power capacity for vehicles with a mass of 800 kg

The dependence of travel range on the mass of a vehicle and steady motion speed, when using 20 rechargeable batteries, the type of TS-LFP90AHA, is shown in Fig. 9.
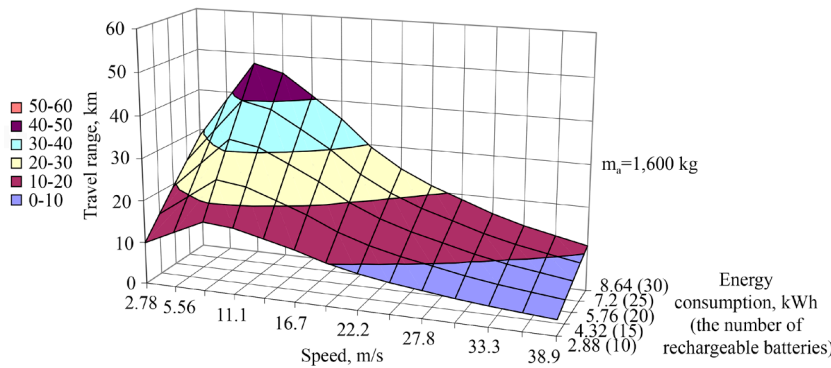

Fig. 8. Three-dimensional dependences of travel range on TRB power capacity for vehicles with a mass of 1,600 kg
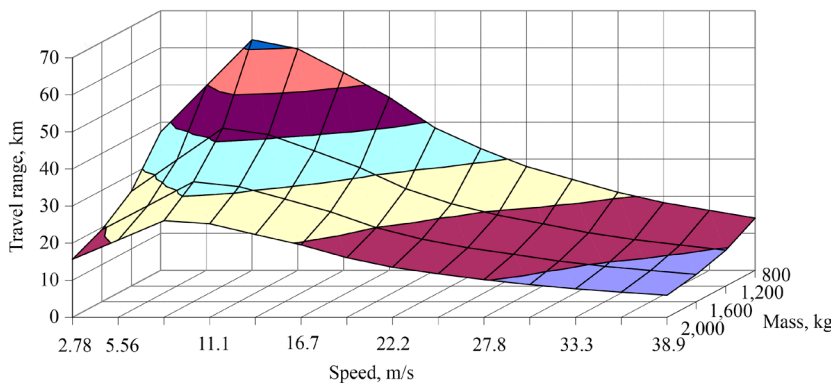

Fig. 9. Dependence of travel range on mass and steady speed when using 20 rechargeable batteries, the type of TS-LFP90AHA

6. Development of conceptual solutions to design hybrid power units for the budget segment

The principle of economic feasibility in the development of hybrid power units makes it possible to design vehicles for the budget segment. In this case, one can use low-cost traction electric motors of low power (up to 30 kW). In-creasing the RTB energy intensity leads, on the one hand, to an increase in the travel range under an electricity-only mode, on the other hand, to an increase in the price of a hybrid power unit. Increasing the mass of a vehicle from 800 kg to 2,000 kg reduces its travel range by almost 2.5 times under an electricity-only mode with an identical energy reserve in TRB.

The results of our study show that a maximum travel range of 90 km can be obtained for a vehicle weighing 800 kg at the steady speed of 8 m/s with the energy intensity of traction rechargeable batteries of 8.64 kWh, which corresponds to the energy intensity of 30 rechargeable batteries such as TS-LFP90AHA. Under similar conditions, a vehicle weighing 1,200 kg would travel 62 km, weighing 1,600 kg – 47 km, weighing 2,000 kg – 38 km.

The travel range is significantly affected by a steady speed. Increasing the speed of a vehicle under an electricity-only mode from 8 m/s to 22 m/s reduces the travel range by two times while increasing the speed from 8 m/s to 33 m/s shortens the travel range by three times. Reducing the speed of a vehicle under an electricity-only mode from 8 m/s to 2.5 m/s reduces the travel range by 1.7 times.

The results of this study could prove useful in selecting the energy intensity of a TRB unit to justify the travel range under an electricity-only mode for hybrid vehicles.

The projected proposals are to design a hybrid multifunctional vehicle. In this case, the car itself, due to an energy-intensive battery, functions as an energy station, which could power autonomous objects. That would improve work and rest conditions in places where there is no stationary source of energy.

7. Conclusions

1. We have formulated a generalized criterion for the choice of hybrid power units, which, in contrast to known

ones, takes into consideration not only the energy and environmental indicators but economic feasibility as well. This approach has made it possible to design hybrid vehicles for the budget segment. In this case, the entire TRB energy intensity is used for movement, not just as an energy buffer in the Prius and CR-Z. The TRB is charged from an external electrical grid, not from the system ICE-a generator plant executed in the Prius and CR-Z, and partly in the Volt.

2. Three-dimensional dependences of energy consumption and travel range on mass and steady speed have been built, based on which we devised recommendations on the choice of energy intensity for a TRB unit for hybrid vehicles of different mass and the desired travel range under an electricity-only mode. It has been determined that the most efficient is the speed in the range from 7 m/s to 9 m/s. We have

improved the hybrid concept ZAZ Lanos Pickup weighing 1,240 kg (with a driver and an electric drive). When using 20 rechargeable batteries, the type of TS-LFP90AHA, it has a maximum travel range of 42 km at a steady speed of 8 m/s and consumes 9.4 kWh/100 km.

3. Conceptual solutions for constructing hybrid power units for the budget segment have been devised. The hybrid concept, built on the basis of ZAZ Lanos Pickup, has an affordable price, and it is not inferior to foreign analogs in terms of operational characteristics. The travel range under an electricity-only mode per a single TRB charge can vary from 20 km to 50 km. A consumer might choose the range when ordering a hybrid vehicle, depending on the estimated average daily mileage and the cost of traction rechargeable batteries.

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