UDC 629.331 DOI: 10.30977/AT.2219-8342.2023.53.0.05

ENERGY ASPECTS OF AUTOMOBILE TRANSPORT DEVELOPMENT

Borodenko Y.[1], Hnatov A[1], Arhun S[1], Sokhin P.[1]

[1]Kharkiv National Automobile and Highway University, Ukraine

Abstract. Problem. *Improving automobile transport means increasing fuel economy and environmental indicators. Fuel, in a broad sense, means energy used to activate the car's power plant. Potential energy is dispersed in the earth's interior, on its surface, in the atmospheric air, and even in space. Moreover, some of them exist in different substances. On the one hand, the efficiency of an energy product use is assessed by its energy intensity; on the other hand, it is evaluated by the costs of its production (transportation) and the quality of its transformation into a consumer type of energy. Special attention is paid to renewable and unlimited kinds of energy sources.* ***Goal.*** *The purpose of the study is a qualitative analysis of the road transport development direction from the standpoint of the alternative energy sources use, taking into account the factors that comprehensively determine the economic and environmental indicators at the stages of production and processing of fossil raw materials, production of power plants and conversion, transformation, and transportation of energy in the field of transport technologies.* ***Methodology.*** *The first direction consists of the adaptation (conversion) of the design of thermal internal combustion engines for alternative liquid or gaseous fuel types. The advantage of this approach is minimal costs for engine conversion and fuel production. The second approach involves using hybrid power plants, consisting of a main and auxiliary engine, an energy source or accumulator, an energy converter, and a braking recuperation system. The third direction is the use of non-traditional energy sources.* ***Results.*** *The directions of the development of power plants for motor vehicles related to the increase in the energy density of hydrocarbon fuels, the use of hybrid power plants, and the use of alternative energy sources have been determined. A qualitative assessment of the considered approaches is given.* ***Originality.*** *A comprehensive approach to evaluating the effectiveness of using alternative types of energy in road transport is considered in terms of energy, economic, and environmental indicators.* ***Practical value.*** *The obtained results can be regarded as recommendations when drawing up plans for the evolution of industries of fossil extraction and transformation of other energy resources, the development of motor vehicles, and transport infrastructure technologies, taking into account the natural and industrial potential of the country.*

Key words: *energy source, fuel energy density, alternative drives, hybrid power plant, traction battery, fuel cells, solar cells, cryogenic installations, road transport.*

Introduction

Improving automobile transport's main tasks are increasing fuel economy and environmental indicators. Fuel, in a broad sense, means energy used to activate the car's power plant.

Potential energy is dispersed in the earth's bowels, on its surface, in the atmospheric air, and even in space. Moreover, some of them exist in different substances. For example, hydrogen in various chemical compounds is found underground (hydrocarbons), on the ground (biomass), and in the atmosphere (air).

On the one hand, the efficiency of an energy product's use is assessed by its energy intensity; on the other hand, it is evaluated by the costs of its production (transportation) and the quality of its transformation into a consumer type of energy. Special attention is paid to renewable and unlimited kinds of energy sources. At the same time, it should be understood that any product obtained as a result of the process of phase transition of matter will ultimately have a lower energy density than the product obtained as a result of a process based on chemical reactions. In turn, the products obtained as a result of chemical reactions have a lower energy density than substances undergoing nuclear transformations.

Analysis of publications

Leading car manufacturers conduct research and develop various variants of concept cars. At the same time, it is possible to distinguish three directions of development of power plants operating on alternative energy [1] (Fig. 1).

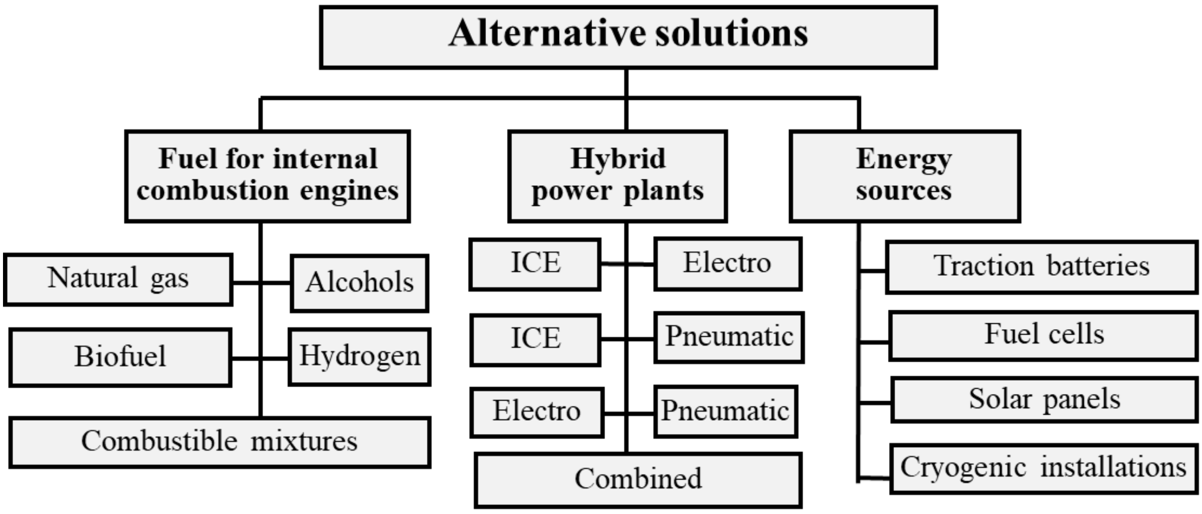


Fig. 1. Development directions of car power plants

The first direction consists of the adaptation (conversion) of the design of thermal internal combustion engines for alternative liquid or gaseous fuel types. The advantage of this approach is minimal costs for engine conversion and fuel production. The efficiency of using alternative fuel, in this case, is evaluated according to several items characterized by quantitative indicators:

- environmental safety (specific content of harmful substances);
- production costs (stocks, extraction, processing, preparation);
- energy intensity of fuel (calorific value);
- quality of use (engine coefficient of performance);
- costs for engine conversion and additional equipment;
- expenses on infrastructure facilities.

The second approach implies using alternative engines operating from non-traditional energy sources. Examples of such concepts are the latest developments of vehicles with electrochemical galvanic, pneumatic, solar, nitrogen, hydrogen, and even nuclear energy sources [2-4]. The disadvantage of this approach can be considered a significant cost for developing the power plant and energy source. At the same time, the indicators of specific energy and production cost of most alternative energy are significantly inferior to traditional gasoline and diesel fuel (0.085 liters of fuel in terms of calorific value is equivalent to the consumption of electrical energy in 1 kWh).

A compromise option is a combination of these approaches to build hybrid cars. Attributes of hybrid power plants (HPP) are main and auxiliary engines, energy source (accumulator), energy converters, and braking recuperation system. The control of the HPP with the nominal indicators of the power units is carried out by the electronic power distribution system [5].

We note that using an internal combustion engine and an electric motor (EM) in the structure of the HPP cannot be considered the only sensible option. Suppose specific requirements for the vehicle and operating conditions are met. In that case, it may be entirely appropriate, for example, to use a pneumatic drive in which the pneumatic unit is the primary or auxiliary engine.

In the third direction, the dominant role belongs to electrochemical energy sources, in which electrical energy is used as a product of direct or buffer conversion into the energy of vehicle movement with the help of an electric motor. In the first case, when developing an electric vehicle, several specific issues arise related to providing the necessary capacity of the traction accumulator battery (TAB) (weight, dimensions, voltage level) and the electric drive power (electric motor, transmission); location of TAB for car operation (center of mass); using the energy recuperation system for cooling electrical units; supporting the operational characteristics of the power plant (acceptability, TAB charge time).

The main restraining factor in developing vehicles with autonomous electric traction is the low energy capacity of traction batteries. So, for example, the best lithium-ion batteries have a specific energy of up to 0.4 MJ/kg, while for gasoline, this indicator is about 40 MJ/kg. Even with a three-fold difference in coefficient of performance and the ability to recuperate braking energy, approximately a ton of batteries are needed to replace a 40-liter gas tank.

Thus, the disadvantages of using an electric drive include the TAB's high cost and limited service life, the need for long-term charging, and the limited resources for the autonomous movement of the vehicle. At the same time, the operating costs of maintaining an electric car are lower than those of an automobile with an internal combustion engine. [1-8].

Purpose and Tasks

The purpose of the study is a qualitative analysis of the directions of road transport development from the standpoint of the alternative energy sources use, taking into account the factors that comprehensively determine the economic and environmental indicators at the stages of production and processing of fossil raw materials, production of power plants and conversion, transformation, and transportation of energy in the field of transport technologies.

To achieve the goal, the following tasks must be solved:

- determine the direction of motor vehicle power plant development;
- explore ways to improve the characteristics of fuel alternative types;
- analyze ways of hybridization of the power plant;
- investigate the use of alternative energy sources for vehicles.

Improving the characteristics of alternative types of fuel

For cars with heat engines, natural hydrocarbon gas, contained in special cylinders in a liquefied or compressed state (cylinder fuel volume), ranks third after gasoline and diesel fuel. Gas sources in the bowels of the earth are various geological locations. There are traditional (gas deposits, associated oil gas) and non-traditional (coal, bituminous, shale) sources of natural gas. The extraction method and the volume of natural gas deposits largely determine its raw material price [6-8].

The main part of the gas is methane CH4, which is from 70% to 98%. The gas composition may include heavier hydrocarbons (homologs of methane): ethane C2H6, propane C3H8, butane C4H10, and pentane C5H12.

Compressed (under a pressure of 20 MPa) methane and liquefied (under a pressure of 1.5 MPa) propane (propane-butane mixture) are used to refuel the car (after processing raw materials).

General advantages of gas fuel:

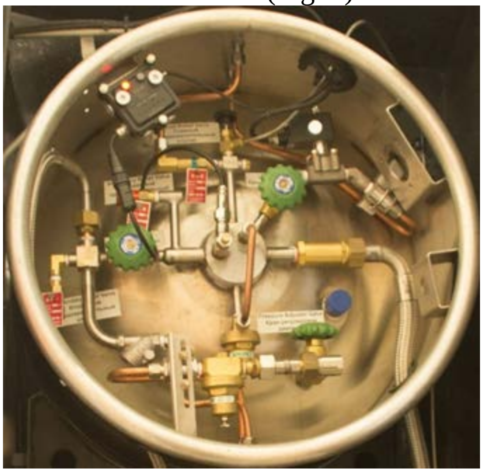
- lower price for gasoline;
- ecological safety;
- increase in mileage on the same volume of cylinder fuel;
- less wear and tear of convertible engine parts.

General disadvantages of gas fuel:

- relative shortage of infrastructure facilities;
- reduced power and increased wear of non-convertible engine parts.

Different densities and pressures of cylinder methane and propane largely explain the advantages and disadvantages of their use as automobile fuel. Gas cylinder equipment for propane is 70% cheaper than for methane, and the refueling cost is higher. At the same time, the weight of propane cylinders is several times lighter than that of compressed methane, and the content of liquefied propane in an equal volume of the cylinder provides three times more mileage than methane. The power loss of an internal combustion engine compared to gasoline for propane is 5%, and for methane, it is 20%. The environmental indicators of propane are worse than that of methane. Methane is less explosive, and the equipment for preparing and refueling methane is more straightforward than propane, but the network of methane refueling stations is less developed.

It should be noted that there is a tendency to use liquefied methane in road transport. This technology, on the one hand, allows you to increase the energy density of the fuel. On the other hand, it requires significant energy consumption since liquefied methane is obtained by cooling the gas to minus 160 ºC. At the same time, its storage involves using special cryogenic (thermostated) containers at gas stations and cylinders on board the car (Fig. 2).



a

b

Fig. 2. Cryogenic tanks for liquefied methane:
a – bus MAZ 203945 (end face);
b – truck tractor IVECO Stralis

A two-stage pressure reduction is carried out to supply fuel to the internal combustion engine cylinders - in the evaporator and the reducer. The use of liquid methane as an ecological motor fuel is justified under the conditions of its operational use on fixed distances. For example, a tank with a capacity of 320 liters (120 kg of methane) provides a power reserve for the bus, about 400 km, and a truck tractor with a 700 liters tank can cover more than 700 km of the route.

High calorific indicators characterize the alcohol types of fuels (methanol, ethanol, butanol) and their mixtures.

Ethanol (ethyl, grain alcohol) is produced by fermentation and distillation of grain products. Ethanol, like other types of alcohol, can be mixed with gasoline to obtain fuel with a higher octane number and lower content of harmful substances in emissions compared to pure gasoline. If the percentage of ethanol in a mixture with gasoline is at least 85%, then such a mixture is considered an alternative fuel type. Mixtures with low concentrations of ethanol are considered gasoline fuel with the addition of an additive.

Bioethanol is ethyl alcohol obtained in processing vegetable raw materials (biofuel). In a mixture with gasoline or diesel fuel, it can be used in most cars with convertible and non-convertible internal combustion engines. From an ecological point of view, bioethanol makes sense since the carbon dioxide emitted during combustion in the engine is compensated for by the gases absorbed during its production. The disadvantage is increased consumption.

Methanol (wood, methyl alcohol) can be used as an alternative fuel type in vehicles with a convertible internal combustion engine (a mixture of methanol - 85% and gasoline - 15%). Currently, methanol has limited use in transport. However, in the future, it can be used as a source of hydrogen for the operation of fuel cells.

Ammonia (hydrogen alcohol – a compound of hydrogen and nitrogen) has a low energy density (two times lower than gasoline), but its production is cheaper than other alcohols. It is used as a fuel for piston engines, as well as in fuel cells. Ammonia does not contain carbon and has zero harmful carbon dioxide emissions. Restrictions in application are related to the safety of storage and transportation. Mixed fuel is used in transport, which consists of 70% ammonia and only 30% gasoline.

Biodiesel fuel (fats) is a fuel obtained based on vegetable oils (rapeseed), animal fats, or lipids of microalgae (renewable organic elements). Industrial production of biodiesel is more expensive than obtaining diesel fuel from oil. The substance is safe and biodegradable and reduces the content of substances that pollute the air (solid impurities, carbon monoxide, hydrocarbons). It is used in its pure form (for convertible internal combustion engines) and as an additive to hydrocarbon diesel fuel (for non-convertible internal combustion engines).

Hydrogen fuel (an alternative to hydrocarbons) has a specific heat of combustion three times higher than gasoline and does not emit harmful substances during combustion. This fuel is a renewable product, as it is produced from water and turns into its condensate after combustion. However, hydrogen production is much more expensive than gasoline (energy consumption). In addition, its storage under pressure is explosive. Using hydrogen as a monofuel on a non-convertible engine reduces its power to 70%.

In a convertible internal combustion engine, the capacity can be increased to 117%, but at the same time, nitrogen oxides are emitted, and the engine life is reduced. A compromise solution can be mixtures of traditional fuel with hydrogen to improve the flammability of poor mixtures.

Multicomponent combustible mixtures (P series fuel) contain ethanol, gas condensate liquid, and an auxiliary solvent obtained from biomass. They have a high octane number and are used in vehicles with a universal fuel system in their pure form or mixed with gasoline in any ratio. Note that all alternative combustible fuels, except hydrogen, are non-renewable energy.

Power plant hybridization

The synthesis of HPPs, which use different types of energy sources and kinds of energy converters, allows you to get the car's best energy, environmental, and operational characteristics.

Almost all leading car manufacturers currently produce electric hybrids - EHEV (Engine Hybrid Electric Vehicle); therefore, it is probably too late to give them the status of a "concept." But, you can focus on progressive technologies of modular unification of electromechanical (mechatronic) car units. For example, combining the electric motor and part of the transmission into one module (electric transmission) led to the appearance of universal modules for various purposes (Fig. 3).

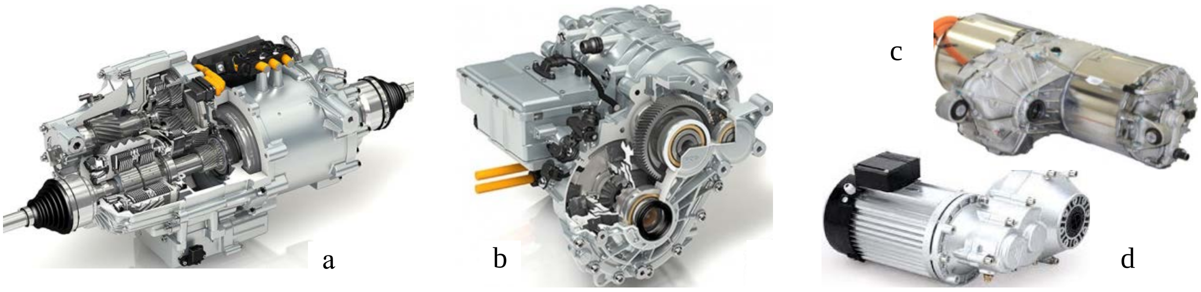


Fig. 3. Electric drive modules of industrial models: a – rear axle Driveline; b – central plant eDrive; c – drive axel; d – cardan unit Renault Zoe

Such a module can be used as the main one to drive an electric car or as an auxiliary one to add an electric drive to one of the axles, turning an ordinary vehicle into a hybrid with all-wheel drive. An example of applying a three-phase asynchronous unit is the Volt hybrid car from Chevrolet. The vehicle with Mitsubishi's three-phase synchronous motor i-MiEV is exclusively electric [6].

The second approach in implementing the electric drive of a car is the use of motor-wheel technology, which provides several advantages:

- the absence of bulky transmission;
- excellent drive dynamics (torque up to 700 N·m at low revs);
- maneuverability of the car due to independent control of each wheel;
- a simplified braking energy recuperation system;
- ensuring active traffic safety (implementation of algorithms of electronic braking systems, dynamic stability of the car, assistance to the driver).

Along with this, motor-wheels have significant disadvantages:

- the excess mass of the mechanisms that are placed inside the rim reduces comfort and controllability, increases wear, and reduces the suspension efficiency;
- increased requirements for tightness;
- significant costs for the repair of the motor-wheel or its replacement.

Motor-wheel systems are implemented according to several options, which differ in the construction principle and degree of integration (Fig. 4).

So, for example, the Active Wheel traction motor of the Michelin company (Fig. 4, a) is used in the design of the Volage sports car. It weighs only 7 kg, which makes it possible to achieve an acceptable wheel weight of 11 kg. The traction electric motor works in generator mode during braking, producing electricity to power the TAB. The suspension consists of a steel spring and electric shock absorbers. The motor controlling the shock absorbers is also responsible for turning the wheel [7-9].

The Schaeffler company introduced the hub traction electric drive - E-Wheel Drive (electric all-wheel drive), developed in cooperation with the Ford company (Fig. 4, b). Two electric motors installed in the rear wheel arches of a Ford car have a power of up to 40 kW each and develop a torque of up to 700 N·m.

Fig. 4. Variants of motor-wheel constructions: a – active wheel-suspension of discrete layout Active Wheel; b – built-in hub electric drive E-Wheel Drive; c – disk electric motor; d – Duyunov’s motor-wheel; e – Shkondin's motor-wheel

The Duyunov model motor-wheel is built according to the principle of an asynchronous motor where permanent magnets are not used (Fig. 4, d). The design is developed based on innovative technologies of combined windings. There are advantages such as low cost, excellent rolling, low noise level, extended service life, and increased reliability.

The motor windings are integrated into a six-phase motor according to the "Slavyanka" scheme (a combination of "star" and "delta"), the phases of which are connected to the network in three stages. The structural originality of Duyunov's engine is that the stator of the engine is located inside (the hub), and the short-circuited rotor rotates outside. The advantages of the original EM compared to conventional asynchronous ones: high coefficient of performance in the load range of 25...150% (reduction of electricity consumption by 15...50%); an increase in the maximum torque by 10...100%; increase in starting torque by 20...50%; reduction of starting currents by two times; noise level reduction by 6...7 dBA; decrease in the heating temperature of the windings [9].

In Shkondin's motor-wheel, the stator is also placed inside the rotor (Fig. 4, e). The armature windings are placed on the rotor, and the excitation magnets are on the stator.

The main advantages are a high coefficient of performance, simplicity of design, and relatively low cost. Disadvantages include poor thermal regime, difficulty in adjusting rotation speed, and the presence of a mechanical commutating device [10].

This latter drawback is eliminated in the brushless version of the engine, where the armature windings are placed on the inner stator, and the pole magnets are placed on the outer rotor.

A classification structure can be made based on general characteristics for conceptual HPPs in which compressed air energy is used (Fig. 5).

Such concepts include the following compositions:

- EHPV (Engine Hybrid Pneumatic Vehicle) with an alternative internal combustion engine [11];
- EHHV (Engine Hydraulic Hybrid Vehicle) with hydraulic drive and alternative internal combustion engine [12-15];

- PHEV (Pneumatic Hybrid Electric Vehicle) with an alternative electric motor (EM) [16].

Cars on compressed air are much cheaper than their purely electric or hydrogen rivals, with approximately equal technical parameters (size, speed, range). In addition, air cylinders have a longer service life than chemical electricity batteries.

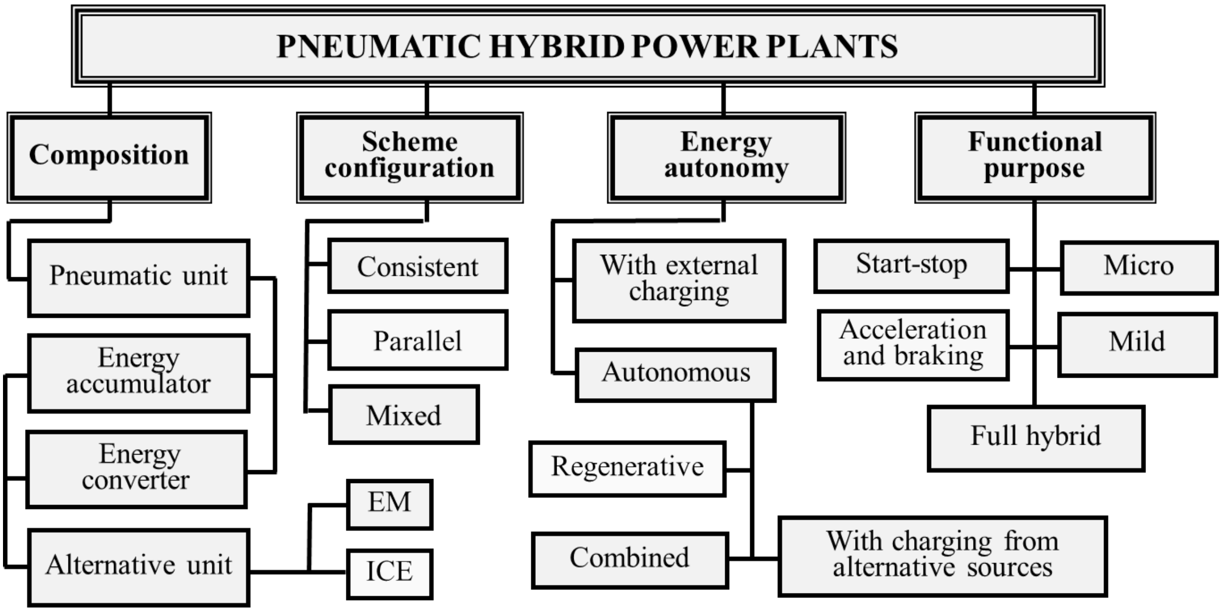


Fig. 5. Classification structure of automotive HPP

The advantages of the pneumatic drive can be added [8, 12]:

- environmental friendliness (there are no harmful emissions and no oxygen is burned);
- low cost of drive and "fuel";
- the possibility of refueling the car at home;
- the possibility of using an energy recuperator.

The main operating advantage of pneumatic motors is obtaining maximum torque and coefficient of performance when motion begins (no air consumption). As acceleration occurs, these indicators decrease significantly. Disadvantages of a pneumatic drive include:

- low coefficient of performance (5...7%) in comparison with internal combustion engines (18...20%);
- the need for an external heat exchanger;
- low driving performance of pneumatic vehicles (range, power);
- low energy density (specific energy capacity);
- pressure leakage in the construction of pneumatic equipment;
- a large cylinder is needed for air refueling.

For comparison, air at a pressure of 30 MPa has an energy density of about 50 kWh per liter, and ordinary gasoline has 9411 kWh per liter. That is, gasoline as a fuel is almost 200 times more efficient.

The technology of pneumatic hybrids involves the use of alternative designs of pneumatic motors of different operating principles (volumetric, rotary, combined), of various types (vane, piston) and purpose (general use, automotive and original designs), which differ in specific energy indicators and operating characteristics [17, 18] (Fig. 6).

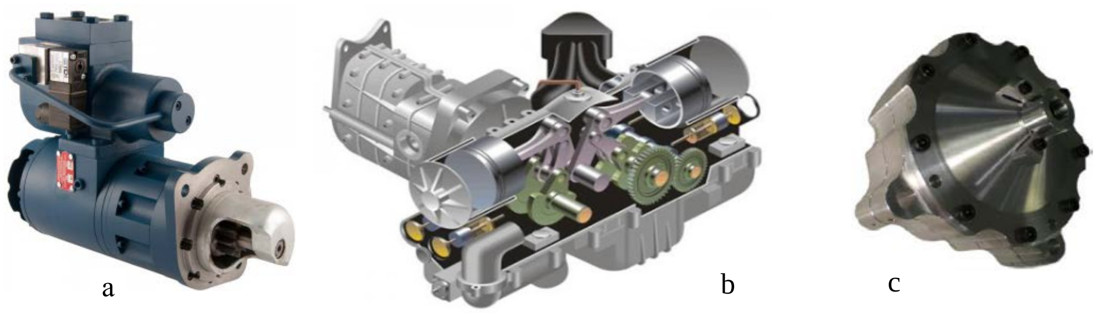


Fig. 6. Designs of pneumatic motors: a – rotary vane as part of the pneumatic starter; б – volume piston from Guy Negre; б – combined vane from Angelo Di Pietro

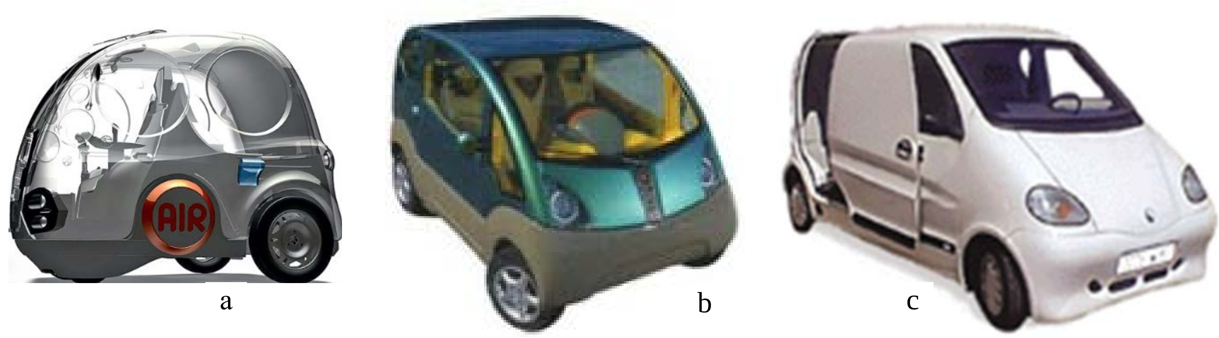


Fig. 7. Pneumatic vehicles with a Guy Negre's engine: a – three-wheeled Air Pod; b – three-seater Tata Mini CAT; c – cargo Multicar

Currently, based on Guy Negre's engines, manufacturers of foreign firms MDI (Motor Development International) have created small-class pneumatic vehicles for various purposes: the multi-purpose family one, the Multi pickup and minivan, the City taxi, the city Mini [19] (Fig. 7).

A two-seater Air Pod weighing 220 kg, equipped with a 4 kW pneumatic engine, can accelerate to 75 km/h (Fig. 7, a). It has a range of up to 200 km. The vehicle is controlled using a joystick. To ensure smooth operation and optimize energy consumption, the Air Pod motor uses a simple electromagnetic distribution system that controls airflow into the motor. In addition, the engine's air supply system is equipped with a dynamic gearbox with a variable volume.

Mini CAT (Compressed Air Technology) city car with a plastic body weighing about 550 kg, designed to transport three people at a speed of up to 110 km/h (Fig. 7, b). A four-cylinder engine with a volume of 800 cm^3 and a container under a pressure of 30 MPa develops a power of about 18 kW at 4000 min^{-1} and provides a mileage of 150 km. Exhausted cold air while the car is moving can be used in the air conditioning system. The engine is also designed to run on conventional fuel with operative switching on demand.

Multicar cargo single-seater develops a speed of up to 100 km/h. One refueling is enough for 200 km. Capable of transporting up to 300 kg of cargo commensurate with its weight of 210 kg (Fig. 7, c).

The serial One CAT pneumatic vehicle contains up to 300 liters of compressed air under a pressure of 30 MPa in containers, can reach a speed of over 64 km/h, and provides a mileage of up to 210 km. The cargo version of One CAT, with a weight of 210 kg, allows you to transport up to 300 kg. The braking system used on cars of this class will enable you to recuperate up to 13% of compressed air energy. For example, we will give the characteristics of pneumatic transport with Angelo Di Pietro's pneumatic motors of industrial developments for various purposes [20, 21] (Fig. 8).

a b c

Fig. 8. Pneumatic transport from Engineair: a – motorcycle O2 Pursuit; b – cargo transporter Gator; c – two-seater car

The O2 Pursuit motorcycle uses an 11 kg engine powered by air from a diving cylinder (Fig. 8, a). The range of one refueling is up to 100 km; the maximum speed is up to 140 km/h. The Gator transporter from the Engineair company is the first compressed air vehicle in Australia that entered real commercial operation (Fig. 8, b). The load capacity is up to 500 kg, the volume of air cylinders is 105 liters, and the mileage on one refueling is up to 16 km. Moreover, refueling takes several minutes. Similar cars for golf clubs develop a speed of up to

50 km/h, and in standard operating modes, one air refueling ensures transportation within an hour.

Due to the low specific energy capacity, pneumatic vehicles have found wide applications as intra-factory, airport, and city transport for communal purposes. If we add an internal combustion engine or EM to the power plant, we will get hybrids combining both alternative engines' advantages.

It should be noted that power plants for driving a car using compressed air energy can be pneumomechanical or pneumohydraulic systems based on the principle of operation. In the second case, the system uses a liquid as a transmission link. This solution eliminates losses of pressure energy on leaks (increasing the drive coefficient of performance).

The pneumohydraulic drive consists of a reversible hydraulic machine (hydraulic unit), which, in the status of a pump, transfers liquid from the tank into a hydraulic accumulator with gas support, thereby increasing the energy of compressed gas. In the status of the motor, the torque on the shaft of the hydraulic unit is created by the pressure of the liquid squeezed out of the hydraulic accumulator by the expanding gas support. Switching the status of the hydraulic unit is carried out with the help of electric valves under electronic control. At the same time, information from pressure sensors in the gas support and the level (volume) of the working liquid in the tank is used.

Thus, the energy resources of the hydraulic system are limited by the volume of the working liquid and the gas pressure in the hydraulic accumulator support chamber. Therefore, hydraulics is acceptable only for braking energy recuperation systems or work as part of the HPP.

PHEV power units from different manufacturers have their features. So, for example, a pneumatic convertible engine and a reversible electric machine are used in the power plant of the Energine parallel hybrid from South Korea. When the car is moving at a constant speed of more than 20 km/h, the electric motor is the main one, and the vehicle starts, picks up speed, and overcomes hills on pneumatic traction. The Energine hybrid accelerates only on pneumatic traction and maintains a maximum speed of 120 km/h for an hour. The power unit is built based on Guy Negre’s four-cylinder pneumatic engine of the CAT series. The composition of the HPP includes a reversible pneumatic unit and an integrated reversible alternating current electric machine as part of the transmission. In addition to the described functions, the HPP control system allows refueling cylinders from the compressor station and the household electrical outlet using a pneumatic unit in the status of a compressor, driven by an electric machine, as a compressor drive. It should be noted that options for creating HPPs are not limited to the considered examples. Technical progress involves using alternative energy sources and new methods of energy transformation, which allow the improvement of the car's power plant's structure and ways of managing the operating modes of vehicles.

Alternative energy sources use

TAB is the primary source of electrical energy in electric vehicles and electric hybrids. It consists of many individual batteries connected in series. A 300...700 V voltage is formed at the TAB output with a capacity of about 60 kWh, comparable to the power of a traction engine (up to 100 kW). Lithium-ion batteries are most often used in electric vehicles. The average period of operation of such TABs is 8 years, and the battery's cycle life is several thousand cycles. Such TABs have an increased specific energy capacity (0.8...2.6 kWh/kg), minimal self-discharge, and improved charging characteristics [21-23].

The main limitation of lithium-ion batteries is a narrow range of operating temperatures (25...45ºC) and high cost. Low temperatures cause a loss of capacity; high temperatures lead to the destruction of the structure.

An electrochemical reaction between hydrogen and oxygen (reverse electrolysis) takes place in the fuel cell with the participation of catalysts. As a result of this reaction, an electric potential difference between the element's electrodes is formed. The release of heat and water accompanies the reaction. Hydrogen is contained in the fuel tank to generate electricity in a car, and oxygen comes from the air. Currently, many leading car manufacturers are developing vehicles with fuel plants. So, for example, a hydrogen car built based on a Mirai (Toyota) front-wheel drive electric car with a 112 kW electric motor is equipped with a fuel plant with a reserve of 5 kg of hydrogen in tanks (120 liters under a pressure of 70 MPa), which provides a range of about 400 km. (Fig. 9).

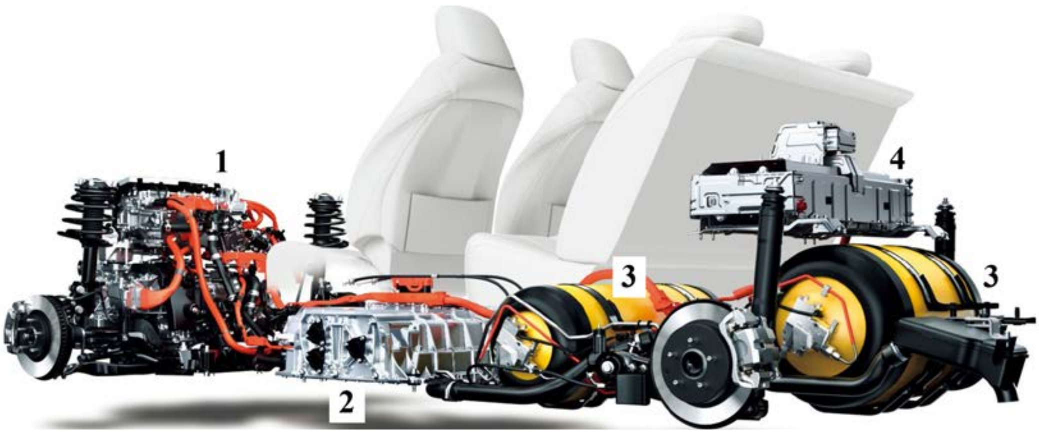


Fig. 9. Layout of the Toyota Mirai hydrogen vehicle chassis: 1 – electric motor; 2 – block of fuel cells; 3 – tanks with hydrogen; 4 – electric battery

It takes 3 minutes to refuel such a car with hydrogen. The power unit contains 370 DC hydrogen fuel cells and boosts an inverter (up to 650 V). The maximum speed of the vehicle reaches 175 km/h. For energy accumulation of the fuel unit and recuperative braking, a 21 kWh nickel-metal hybrid TAB is used [24].

Energy stored in liquid nitrogen (78% air) and compressed air (atmospheric renewable resources) can be used to enable vehicle movement. In this case, two ways of converting types of energy are considered - direct conversion using a pneumatic motor and two-stage conversion with a generator plant and an electric motor (serial hybrid).

The cryogenic power plant [25] consists of a cryogenic tank 1, a gasifier 2, an air heat exchanger 3, and a pneumatic motor 4 (Fig. 10).

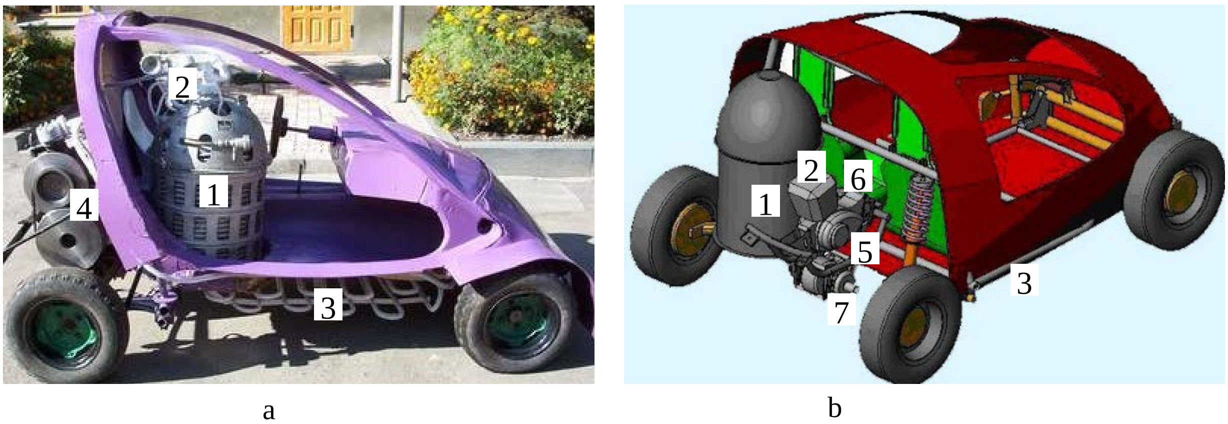


Fig. 10. Cryomobile designs: a – with a pneumatic drive; b - with an electric drive

The pneumatic drive of the wheels (Fig. 10, a) or the generator 6 (Fig. 10, b) is implemented with the help of a piston 4 or a vane (rotary) pneumatic motor 5. In the HPP with an electric drive 7, a buffer energy store is provided for the braking energy recuperation system. Cryomobiles with an electric drive in many aspects can be compared with electric hybrids, which are charged. Moreover, some advantages can be noted:

- cheap, non-explosive, and non-flammable raw materials;
- the best environmental indicators during the disposal and restoration of thermal tanks in comparison with electric batteries;
- fast charging compared to electric batteries;
- use of internal combustion engine collateral heat (in hybrids with internal combustion engine).

Several factors cause the disadvantages of cryogenic power plants:

- high energy costs for the production of liquid nitrogen (up to 1 kWh/l) and additional costs for equipment (thermostatic cylinder, gasifier, heat exchanger);
- low energy density of liquid nitrogen compared to hydrocarbon fuels;
- the negative impact of the by-product of nitrogen production from atmospheric air (liquid oxygen) on the surrounding organic matter;

- danger of direct contact with the human body (frostbite);
- restructuring of some constructive materials under the influence of low temperatures;
- icing of heat streamlines;
- lack of gas station infrastructure.

The listed factors lead to an increase in the mass of the vehicle, an increase in the complexity of the structure, a decrease in the coefficient of performance, and an increase in the cost of the power plant.

Solar energy is a non-limited product of the energy environment of space. The main problem with mobile solar energy sources is the limited surface area of the vehicle, which makes it challenging to obtain sufficient electrical power with the help of solar cells. Their coefficient of performance is about 20%. An electric car with solar cells assembled into a battery also has a storage (buffer) battery in its composition.

At the current level of scientific and practical achievements, it is shown that a real passenger solar car can drive a couple of dozen kilometers on the energy produced by a solar battery during daylight hours. Moreover, a solar panel with a capacity of several hundred watts, an electric motor with a capacity of about 2 kW, and a storage battery of a comparable capacity are needed to drive the vehicle. However, the low mileage and insufficient power of the drive on the solar potential do not satisfy consumer demands for a modern car's driving qualities and operating conditions. Therefore, the further development of solar energy in the vehicle consists of hybridizing the source of electrical energy. Solar batteries have become an additional means of replenishing the TAB energy of electric vehicles.

Prototypes and even small-scale versions of electric cars with charging from the "free" sun are being tested [26]. Due to their specificity, the designs of such electric vehicles are outwardly different from cars with traditional bodies (Fig. 11).

a b

Fig. 11. Designs of electric cars with solar batteries: a – Eclectic; b – Astrolab

An electric car with solar cells Eclectic of the French company Venturi (Fig. 11, a) provides a daily mileage without recharging the storage (traction) battery, up to 50 km at an average speed of 50 km/h. With the help of solar panels with an area of 2.5 m² (300 W), you can accumulate enough energy to run up to 10 km during daylight. If necessary, the nickel-metal hydride TAB with a capacity of 9 kWh can be charged from a regular socket in 5 hours. In addition to solar energy, Eclectic can use wind energy (distance up to 15 km/day). The concept uses an asynchronous electric motor with a capacity of 11 kW and a torque of 45 Nm. The car weighs 400 kg, and the price starts from 20 thousand dollars.

The next concept model, Venturi Astrolab (Fig. 11 b), reached the commercial level with improved performance: capacity of power plant of 16 kW (torque 50 Nm), maximum speed of 120 km/h, mileage up to 110 km. At the same time, the area of photovoltaic elements with a total power of 600 W increased to 3.6 m^2, and the capacity of the TAB decreased to 7 kWh (weight 110 kg). The car's total weight remained unchanged, but the price jumped to 92 thousand euros. Further improvement of solar electric vehicles is by increasing the efficiency of solar panels and reducing the capacity of the TAB at a given capacity of power plant. Developers of competing companies expect their electric concepts to achieve up to 20,000 km of mileage per year shortly, only on the energy of the sun. Moreover, the driving qualities of the vehicle will satisfy the requirements of a broad class of cars.

In the not-so-near, nuclear reactors operating on atomic thorium can be added to the list of considered energy sources for vehicles. The energy density of such fuel allows the car to be used at one "starting refueling" (8 grams per million kilometers of mileage) [27]. However, discussing the cost of obtaining an energy product and the safety of using such concepts is not yet necessary.

Finally, electromagnetic fields (geomagnetic, ground, near-Earth, and space emitters) can be used as an energy product to power mobile objects in the distant future [28]. Energy from the ether can be received directly onboard the car or transported centrally. In the other case, gas stations are transformed into distributed infrastructure objects as a complex of antenna resonators-receivers, frequency converters, and directional energy translators [29]. The last ones will transmit energy to the vehicle through electromagnetic oscillations of a fixed (carrier) frequency during its movement. Thus, the frequency regulation of "contactless refueling" with wave energy will allow us to minimize the costs of implementing the resonator-receiver on board the vehicle.

Conclusion

An analysis of the directions of the development of road transport from the standpoint of the use of alternative energy sources was carried out, taking into account the factors that comprehensively determine the economic and environmental indicators at the stages of production and processing of fossil raw materials, production of power plants and conversion, transformation, and transportation of energy in the field of transport technologies.

The characteristics of the development direction of power plants for motor vehicles are provided. Ways of improving the characteristics of alternative fuel types for their use in motor vehicles have been studied. An analysis of hybridization methods for the main power plants used in motor vehicles was conducted.

A study on using alternative energy sources in motor vehicles was conducted.

Energy sources for promising vehicles must be selected in the «3/4-E» format (ecology, economy, operational/(energy) characteristics), taking into account comprehensive efficiency indicators throughout the energy chain, starting with obtaining energy raw materials and ending with the transport process.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

1. Gnatov, A., Argun, S., & Rudenko, N. (2017). Smart road as a complex system of electric power generation. In 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON) (pp. 457-461). IEEE.
2. A review on electric vehicles: Technologies and challenges. / Sanguesa J. A. et al. Smart Cities, 2021. 4 (1), P. 372-404.
3. Nick Hazleton. Everything You Should Know About The Compressed Air Car. (2022). URL: https://www.hotcars.com/air-fuel-car-everything-should-know/ (дата звернення 23.10.2023).
4. Hnatov, A., & Arhun, S. (2017). Energy saving technologies for urban bus transport. International journal of automotive and mechanical engineering, 14(4), 4649-4664.
5. Рогозін, І. В., Новічонок, С. М., Гнатов, А. В., & Рогозіна, А. І. (2018). Спосіб розрахунку основних параметрів гібридного силового агрегату для спеціалізованих автотранспортних засобів. Vehicle and electronics. Innovative technologies, (13), 5-12. Rohozin, I. V., Novichonok, S. M., Hnatov, A. V., & Rohozina, A. I. (2018). Sposib rozrakhunku osnovnykh parametriv hibrydnoho sylovoho ahrehatu dlia spetsializovanykh avtotransportnykh zasobiv. [The method of calculating the main parameters of a hybrid power unit for specialized motor vehicles]. Vehicle and electronics. Innovative technologies, (13), 5-12. [in Ukrainian].
6. Мехатронні системи автомобіля. Частина 1. Силовий привід: підручник / Ю.М. Бороденко, А.В. Гнатов, Щ.В. Аргун. – Харків : Мачулін, 2023. – 300 с. Mekhatronni systemy avtomobilia. Chastyna 1. Sylovyi pryvid [Mechatronic systems of the car. Part 1. Power drive]: textbook / Yu.M. Borodenko, A.V. Hnatov, Shch.V. Arhun. – Kharkiv : Machulin, 2023. – 300 p. [in Ukrainian].
7. Arhun, S., Hnatov, A., Mygal, V., Khodyriev, S., Popova, A., & Hnatova, H. (2020, April). An Integrated System of Alternative Sources of Electricity Generation for Charging Urban Electric Buses. In 2020 IEEE 40th International Conference on Electronics and Nanotechnology (ELNANO) (pp. 619-624). IEEE.
8. Розробка комбінованої енергетичної установки на базі пневмодвигуна з використанням поновлювальних джерел енергії для міського автотранспорту. Заключний: науково-дослідна робота / Гнатов А. В., Аргун Щ. В. та ін. Харків : ХНАДУ, 12.2022. № держреєстрації 0121U109611. 321 с. Rozrobka kombinovanoi enerhetychnoi ustanovky na bazi pnevmodvyhuna z vykorystanniam ponovliuvalnykh dzherel enerhii dlia miskoho avtotransportu [Development of a combined power plant based on a pneumatic engine with the use of renewable energy sources for city vehicles]. Hnatov A. V., Arhun Shch. V. ta

in. Kharkiv : KhNADU, 12.2022. № derzhreiestratsii 0121U109611. 321 p. [in Ukrainian].
9. Protean electric's in-wheel motors could make EVS M. URL: https://spectrum.ieee.org/protean-electrics-inwheel-motors-could-make-evs-more-efficient (дата звернення 23.03.2023).
10. In-wheel electric motors. URL: https://www.proteanelectric.com/wp-content/uploads/2018/04/In_Wheel_Electric_Motors_AFraser_ProteanV4.pdf (дата звернення 23.03.2023).
11. Nie C. et al. (2022) Pipe architecture optimization of the parallel Hydraulic-pneumatic hybrid system using a hydraulic transformer. Energy Conversion and Management. T. 266. 115858.
12. Fijalkowski B. T. (2011) Automotive Mechatronics. Operational and Practical Issues. Volume I. Springer Heidelberg Dordrecht London New York, 593 p.
13. Wasbari F. et al. (2017) A review of compressed-air hybrid technology in vehicle system. Renewable and Sustainable Energy Reviews. T. 67. P. 935–953.
14. Nie C. et al. (2022) Pipe architecture optimization of the parallel Hydraulic-pneumatic hybrid system using a hydraulic transformer. Energy Conversion and Management. T. 266. 115858.
15. Kuņicina, N., Zabašta, A., Romānovs, A., Pečerska, J., Ribickis, L., Hnatov, A., Shchasiana, A., Dziubenko, O., Rudenko, N., Borodenko, Y., Danylenko, K., Morkun, N., Zavsiehdashnia, I., Sistuk, V., Monastyrskyi, Y., Ruban, S., Tron, V., Peuteman, J. (2022): підручник/ Cyber-Physical Systems for Clean Transportation. Rīga: RTU Izdevniecība, 391 p.
16. S. Palani. Performance Analysis of Electro-pneumatic Hybrid Vehicle with ANSYS. (2022). URL: https://link.springer.com/chapter/10.1007/978-981-19-4606-6_24 (дата звернення 23.10.2023).
17. Korbut M., Szpica D. (2021) A review of compressed air engine in the vehicle propulsion system. Sciendo. Acta Mechanica et Automatica, 2021. Vol. 15, № 4. P. 215–226.
18. Amey D. More1. Air Powered Vehicle. (2021) International Research Journal of Engineering and Technology (IRJET). Volume: 08 Issue: 09 | Sep P. 1776–1782. URL: https://www.irjet.net/archives/V8/i9/IRJET-V8I9283.pdf (дата звернення 23.03.2023).
19. Zwierzchowski J. (2017) Design type air engine Di Pietro. EPJ Web of Conferences. EDP Sciences, T. 143. P. 02149.
20. Florin Tiby. O2 Pursuit Air-Powered Motorcycle Does 87 mph. (2012). https://www.autoevolution.com/news/o2-pursuit-air-powered-motorcycle-does-87-mph-photo-gallery-51467.html (дата звернення 23.10.2023).
21. Гнатов А. В., Аргун Щ. В., Трунова І. С. (2016) Теорія електроприводу транспортних засобів: підручник. Харків : ХНАДУ, 292 с. Hnatov A. V., Arhun Shch. V., Trunova I. S. (2016) Teoriia elektropryvodu transportnykh zasobiv [Theory of the electric drive of vehicles]: textbook. Kharkiv : KhNADU, 292 s. [in Ukrainian].
22. Hnatov, A., Patlins, A., Arhun, S., Kunicina, N., Hnatova, H., Ulianets, O., & Romanovs, A. (2020, September). Development of an unified energy-efficient system for urban transport. In 2020 6th IEEE International Energy Conference (ENERGYCon) (pp. 248-253). IEEE.
23. Гнатов А. В., Аргун Щ. В., Гнатова Г. А. (2019) Тягові характеристики силової установки електробуса. Науковий вісник Херсонської державної морської академії. Т. 2, №. 21. С. 36-43. Hnatov A. V., Arhun Shch. V., Hnatova H. A. (2019) Tiahovi kharakterystyky sylovoi ustanovky elektrobusa. [Traction characteristics of the electric bus power plant]. Naukovyi visnyk Khersonskoi derzhavnoi morskoi akademii. 2019. T. 2, №. 21. P. 36-43. [in Ukrainian].
24. Borodenko, Y., Ribickis, L., Zabasta, A., Arhun, S., Kunicina, N., ZHIRAVETSKA, A., ... & Kunicins, K. (2020). Using the method of the spectral analysis in diagnostics of electrical process of propulsion systems power supply in electric car. Przegląd Elektrotechniczny= Electrical Review.
25. Kravchenko M. B. (2017) Application of the Open Cycle Stirling Engine Driven with Liquid Nitrogen for the Non-Polluting Automobiles / Refrigeration Engineering and Technology. T. 53, №. 5. P. 23-32.
26. Technical and economic calculation of a solar-powered charging station for electric vehicles. / Hnatov A. V., Arhun S. V., Hnatova H. A., Sokhin P. A. Автомобільний транспорт. Харків : ХНАДУ, 2021. Вип. 49. P. 71-78.
27. A review on electric vehicles: Technologies and challenges. / Sanguesa J. A. et al. Smart Cities, 2021. 4(1), P. 372-404.
28. Patlins, A., Hnatov, A., Arhun, S., Hnatova, H., & Saraiev, O. (2022, May). Features of converting a car with an internal combustion engine into an electric car. In 2022 IEEE 7th International Energy Conference (ENERGYCON) (pp. 1-6). IEEE.
29. Стеблина Д. В. (2020) Технологія бездротової передачі електроенергії та її продукування за рахунок потенціалу електромагнітного поля землі. / Відновлювана енергетика та енергоефективність у XXI столітті: В 42 матеріали XXI міжнародної науково-практичної конференції (Київ, 14-15 травня 2020 р.). Київ: Інтерсервіс, 2020. 823 с. Steblyna D. V. Tekhnolohiia bezdrotovoi peredachi elektroenerhii ta yii produkuvannia za rakhunok potentsialu elektromahnitnoho polia zemli. [Technology of wireless transmission of electricity and its production due to the potential of the earth's electromagnetic field] / Vidnovliuvana enerhetyka ta enerhoefektyvnist u XXI stolitti: V 42 materialy

XXI mizhnarodnoi naukovo-praktychnoi konferentsii (Kyiv, 14-15 travnia 2020 r.). Kyiv: Interservis, 823 p. [in Ukrainian].

Borodenko Yuriy[1], Assoc. Prof., Ph. D. (Phys.-Maht.), Head of Vehicle Electronics Department,
Phone:. +38 (098) 362-91-12,
e-mail: docentmaster@gmail.com
ORCID: https://orcid.org/0000-0002-2491-6799
Hnatov Andrii[1], professor, Doct. of Science, Head of Vehicle Electronics Department,
Phone +38 (066)-743-08-87,
e-mail: kalifus76@gmail.com,
ORCID: https://orcid.org/0000-0003-0932-8849
Arhun Shchasiana[1], professor, Doct. of Science, Vehicle Electronics Department,
e-mail: shasyana@gmail.com,
ORCID: https://orcid.org/0000-0001-6098-8661
Sokhin Pavlo[1], postgraduate, Vehicle Electronics Department,
Phone. +38 (063) 347-34-33,
e-mail: info@elektrocar.com.ua,
ORCID: https://orcid.org/0000-0002-2823-2239

[1]Kharkiv National Automobile and Highway University Yaroslava Mudrogo str., 25, Kharkiv, Ukraine, 61002

Енергетичні аспекти розвитку автомобільного транспорту

Анотація. Проблема. *Основними завданнями вдосконалення автомобільного транспорту є підвищення його паливно-економічних та екологічних показників. Під паливом, у широкому сенсі, розуміють енергоносії, які використовуються для приведення силової установки автомобіля в дію. Потенційні енергоносії розосереджені в надрах землі, на її поверхні, у атмосферному повітрі, і навіть у космосі. Причому, деякі з них існують у різних субстанціях. Ефективність використання енергетичного продукту, з одного боку, оцінюється його енергоємністю, з іншого – витратами на його одержання (транспортування) і якістю перетворення на споживчий вид енергії. Особлива увага приділяється відновлюваним і не лімітованим видам енергетичного середовища.* ***Мета.*** *Метою дослідження є якісний аналіз напрямків розвитку автомобільного транспорту з позицій застосування альтернативних джерел енергії з урахуванням чинників які комплексно визначають економічні та екологічні показники на етапах добичі і переробки викопної сировини, виробництва енергетичних установок та перетворення, трансформації і транспортування енергії в галузі транспортних технологій.* ***Методологія****. Перший напрямок полягає в адаптації (конвертації) конструкції теплових ДВЗ під альтернативні види рідкого або газоподібного палива. Перевагою такого підходу є мінімальні витрати на конвертацію двигуна та виробництво палива. Другий підхід передбачає використання гібридних силових установок композиція яких складається з основного і допоміжного двигуна, джерела або накопичувача енергії, перетворювача енергії, системи рекуперації при гальмуванні. Третій напрямок це використання не традиційних джерел енергії.* ***Результати.*** *Визначені напрямки розвитку силових установок автотранспортних засобів, пов'язаних з підвищенням щільності енергії вуглеводних видів палива, застосуванням гібридних силових установок і використанням альтернативних джерел енергії. Дана якісна оцінка розглянутим підходам.* ***Оригінальність.*** *Розглядається комплексний підхід до оцінки ефективності використання альтернативних видів енергії на автомобільному транспорті, з боку енергетичних, економічних та екологічних показників.* ***Практичне значення****. Отримані результати можуть розглядатися як рекомендації при складанні планів розвитку галузей здобичі викопних і трансформації інших енергетичних ресурсів, розробці технологій автотранспортних засобів та транспортної інфраструктури з урахуванням природних і промислових потенціалів країни.*

Ключові слова: *джерело енергії, енергетична щільність палива, альтернативні приводи, гібридна силова установка, тягова батарея, паливні елементи, сонячні батареї, кріогенні установки, автомобільний транспорт.*

Бороденко Юрій Миколайович[1], к.ф-м.н., доцент. каф. автомобільної електроніки,
тел. +38 (098) 362-91-12,
e-mail: docentmaster@gmail.com
ORCID: https://orcid.org/0000-0002-2491-6799
Гнатов Андрій Вікторович[1], д.т.н., проф., завідувач каф. автомобільної електроніки,
тел. +38 (066) 743-08-87,
e-mail: kalifus76@gmail.com,
ORCID: https://orcid.org/0000-0003-0932-8849
Аргун Щасяна Валіковна[1], д.т.н., проф. каф. автомобільної електроніки,
тел. +38 (099) 378-04-51,
e-mail: shasyana@gmail.com,
ORCID: https://orcid.org/0000-0001-6098-8661
Сохін Павло Андрійович[1], аспірант кафедри автомобільної електроніки,
тел. +38 (063) 347-34-33,
e-mail: info@elektrocar.com.ua
ORCID: https://orcid.org/0000-0002-2823-2239

[1]Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, Україна, 61002.