# ТЕХНИЧЕСКИ УНИВЕРСИТЕТ ВАРНА

## КАТЕДРА
## ТРАНСПОРТНА ТЕХНИКА И ТЕХНОЛОГИИ

# ТРАНСПОРТ, ЕКОЛОГИЯ УСТОЙЧИВО РАЗВИТИЕ

## XXXI НАУЧНО-ТЕХНИЧЕСКА КОНФЕРЕНЦИЯ С МЕЖДУНАРОДНО УЧАСТИЕ




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# A METHODOLOGY FOR PREDICTION OF UNBURNED FUEL EMISSIONS FROM LARGE GAS ENGINES BASED ON SIMULATION

**Dimitar Dimitrov, Gernot Kammel, Erich Egert, Constantin Kiesling, Nicole Wermuth**

**Abstract.** The main subject of this paper is the development of a methodology for prediction of the unburned fuel emissions from large gas engines, including 1D and 3D simulation, as well as experimental investigations on a single cylinder research engine. The paper focuses on the prediction of the unburned fuel mass from the combustion process and from the scavenging process during the valve overlap phase. The calibration of the sub-models is based on measurements on a single-cylinder research engine with a displacement of approximately 6 liters. The simulation results are validated with experimental measurements on the same research engine.
**Keywords**: gas fueled engines, unburned hydrocarbons, simulation.

## 1. Introduction

The trend towards high power output, higher efficiencies as well as more stringent emission legislation is greatly pushing the development of large gas engines. The current trend is towards lowering emission limits for large combustion engines. Pollutant emissions from large engines and nitric oxide emissions ($NO_x$) in particular are currently strictly regulated. Whereas the current German TA Luft legislation [1] for gas engines defines the maximum nitric oxide emissions as 500 mg/m$^3$ (norm) @ 5% $O_2$, the trend is towards a further reduction to 250 mg/m$^3$ (norm) @ 5% $O_2$ (Gothenburg Protocol [2]) or 75 mg/m$^3$ (norm) @ 15% $O_2$ (EU Directive 2010/75/EU [3]), whereas 75 mg/m$^3$ (norm) @ 15% $O_2$ is equivalent to 200 mg/m$^3$ (norm) @ 5% $O_2$. In certain European regions, even emissions below 100 mg/m$^3$ (norm) @ 5% $O_2$ are required [4]. Lean-burn gas engines can reach these $NO_x$ limits, but this often leads to comparatively high unburned hydrocarbon (HC) emissions [5]. Methane as the main component of natural gas makes up the largest amount of hydrocarbon emissions and its impact on the greenhouse effect is around 25 times higher than that of $CO_2$. It is thus essential to reduce the level of HC emissions from the engines to a minimum [6].

There exist three main sources of HC emissions in lean-burn gas engines: scavenging, incomplete combustion and crevices in the combustion chamber [5, 7, 8]. Scavenging refers to the flow of unburned mixture from the intake port to the main combustion chamber and then to the exhaust port during the valve overlap period. This process is favored by the pressure difference between the intake and exhaust port. Another source of HC emission is the incomplete combustion, mostly caused by flame quenching near the cylinder walls. This process is promoted by low pressures and temperatures at the end of combustion and by an increase in the excess air ratio. The third source are crevices in the combustion chamber, where no combustion occurs [5]. Such crevices are between piston top and liner, piston ring and piston and near the cylinder head gasket. During the exhaust stroke the pressure in the combustion chamber drops and the unburned fuel from the crevices flows into the exhaust ports, mixed with the burned mixture.

This work presents a methodology for the prediction of HC emissions in general, as well as the split of emissions from the combustion process and from the scavenging process. The HC emissions from the scavenging process are represented by a 1D simulation model with a calibrated scavenging sub-model. The emissions from incomplete combustion and crevices are modeled in the 1D-framework via a conversion rate in the combustion chamber. The required conversion rate is described by a polynomial function, which is fitted to a measurement database obtained from SCE measurements. Phenomena related to flame propagation and the generation of unburned fuel in specific zones of the combustion chamber are described using 3D-CFD simulation. The comprehensive measurement data base enables precise calibration of the sub-models used. The verification of the simulation results shows an accurate agreement with the measurements.

## 2. Experimental investigations

Measurement data is required for the development and calibration of simulation models as well as for the calculation of the rates of heat release for direct specification in 1D simulation. The database for the calibration of the conversion rate in the combustion chamber and the scavenging sub-model consists of 64 steady-state single-cylinder research engine operating points. Additional 16 measured operating points were used to verify the overall HC emission prediction methodology. The available database includes measurements of different parameter variations: indicated mean effective pressure (IMEP), $NO_x$, and ignition timing. Compression ratio was varied by means of different hardware variants. The required rate of heat release curves for the 1D simulation were derived from the measured pressure curves.

All experimental investigations presented in this paper were carried out on a high-speed four-stroke single cylinder research engine (SCE) with a displacement of about 6 liters. A prechamber spark ignition concept and a camshaft with early intake valve closing (IVC) timing, also known as Miller valve timing, were used. Table 1 summarizes the engine specification.

**Table 1.** SCE specification

| Parameter | Value/type |
|---|---|
| Working principle | 4-stroke |
| Displacement | ca. 6 L |
| Engine speed | 1500 rpm |
| Valve timing | Miller intake valve timing |
| Ignition concept | prechamber spark ignition |

A mock-up of the SCE is shown in Figure 1. Charge air is supplied to the engine by an electrically driven compressor. The air humidity is controlled by means of a steam generator that admixes water steam to the cooled, dehydrated and re-heated air. Cooling water and lubricating oil are conditioned before being supplied to the engine. A back pressure flap in the exhaust piping is used to set the back pressure generated by the turbine of a turbocharger on a multi-cylinder engine. The exhaust gas analysis is performed with an AMA i60 exhaust gas measurement system from AVL List GmbH. The sampling point for HC emissions is located in the exhaust pipe, 200 mm from the cylinder head. Time-based measurement data is recorded and processed by the software Tornado from Kristl, Seibt & Co GmbH; crank angle-resolved data is recorded and processed using the indicating system IndiSet Advanced Gigabit and the software package IndiCom from AVL List GmbH.

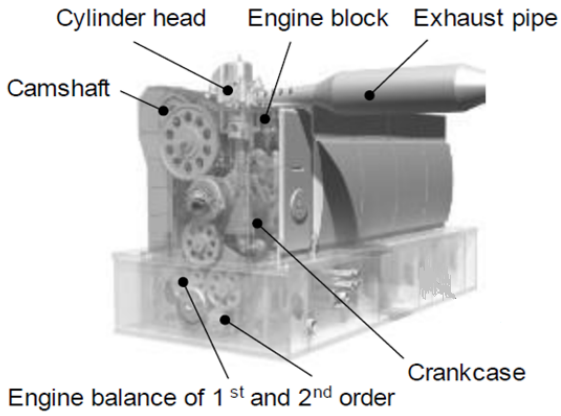



**Fig. 1.** Computer aided design mock-up of the employed SCE

## 3. Predicting HC emissions using simulation

For a detailed analysis of the mixture formation and to generate the boundary conditions required for the 3D-CFD simulation, a 1D single cylinder engine model has been used. This model corresponds to the engine integrated on the test bed. Figure 2 shows the topology of the model in the commercial software package GT Power. The objective pursued with the model is to determine the conditions during the entire cycle not only in the main combustion chamber, but also in the prechamber as precisely as possible. Therefore, besides the main chamber the prechamber and the related gas valve are depicted in detail in the 1D model. Air and fuel are mixed in the intake system. The prechamber mixture flows through the gas rail and the prechamber gas valve. The model uses measured pressure traces from the measured operating points for the intake as well as the exhaust manifold and in front of the PCGV. All measured operating points from the database were simulated using the 1D SCE model.

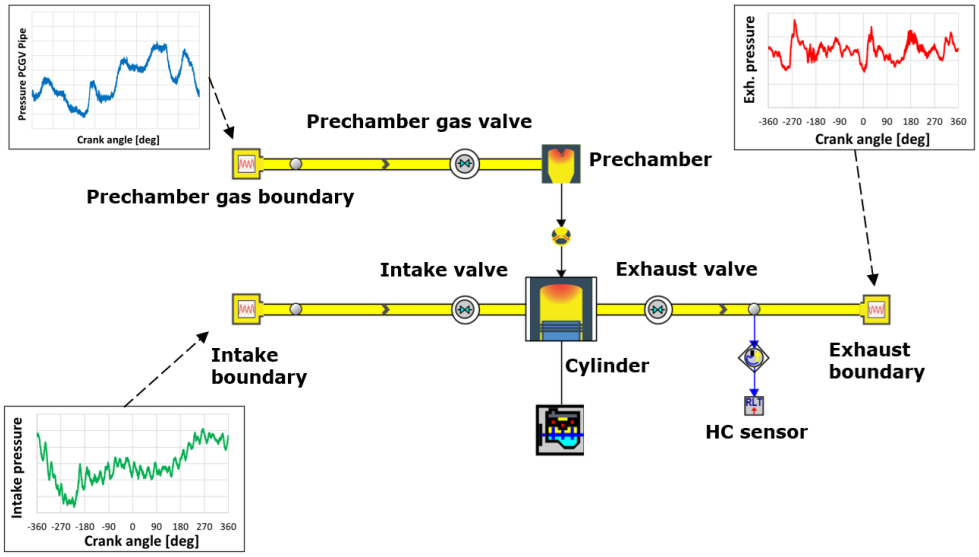



**Fig. 2.** Topology of the 1D model of the employed single-cylinder engine with a prechamber

The goal of the calibrated 1D model is to predict the unburned fuel fraction in the exhaust gas for operating points with different boundary conditions than the measured ones, e.g. $NO_x$ level or IMEP. In this case, the rate of heat release curve, which is decisive in particular for combustion phasing, is derived from measured operating points with similar boundary conditions. The unburned fuel sensor in the simulation model is located in the exhaust pipe, at the same location as at the test engine. In order to understand and predict the different contributors to HC emission, a model is developed that differentiates between the two sources: incomplete combustion in the combustion chamber and scavenging during the valve overlap period. The unburned fuel fraction from the combustion is considered in the combustion sub-model, and the unburned fuel fraction from valve overlap – in the scavenging sub-model.

The scavenging sub-model is calibrated based on measured operating points with constant excess air ratio (EAR) and nearly the same in-cylinder process, but with different scavenging gradients and different measured HC emissions. It is expected that the unburned fuel mass from the combustion is nearly constant, because of the constant EAR. The measured HC difference is due to the different scavenging gradients. It is assumed that the entire HC amount is generated in the combustion chamber at scavenging gradient equal to zero. An operating point with zero scavenging gradient is simulated and the fuel conversion rate in the combustion chamber is calibrated. In the next step, the two measured operating points are simulated using the already calibrated conversion rate and the scavenging sub-model is adjusted using the measured HC values.

The HC values from incomplete combustion result from the difference between the measurement and the values of the calibrated scavenging sub-model and were determined for

each operating point of the experimental database. Subsequently a sub-model for the fuel conversion rate was developed that considers both flame quenching and crevices effects. It is assumed that the in-cylinder fuel conversion rate is a function of characteristic parameters for flame quenching and crevices: 50% mass fraction burned point, pressure and temperature at the end of combustion and EAR. The end of combustion is defined as the 90% mass fraction burned point. Using the software MODDE from Sartorius AG, a quadratic function with the corresponding coefficients was found that describes the fuel conversion values of the operating points from the database.

In this methodology, CFD simulation is used as an additional tool to explain some specific phenomena of HC formation. The CFD simulations are based on selected operating points of the single-cylinder research engine. From the SCE measurement data, the initial and boundary conditions were derived using 1D simulation modeling. The CFD simulations are based on AVL FIRE, using the ECFM combustion model to calculate turbulent flame propagation. Validation was performed by comparing the pressure, temperature and combustion curves, with the measurement and 1D simulation. With help of the simulation results, it is possible to obtain a detailed understanding of specific phenomena observed on the SCE. E.g., differences in HC emission due to a variation of ignition timing can be explained by the differences in penetration of the prechamber jets into the main chamber and related differences in flame front propagation. In particular zones that are late or not at all captured by the flame can be subject to large local amounts of unburned fuel.

## 4. Verification of the simulation results

For verification of the forecast quality of the model, 16 additional measured operating points with high NOx levels at different IMEPs and compression ratios were used. Figure 3 shows the HC emissions of these 16 operating points. The agreement between measurement and prediction is accurate. All operating points are in the range of 50 ppm and the root mean squared error (RMSE) is 23 ppm.

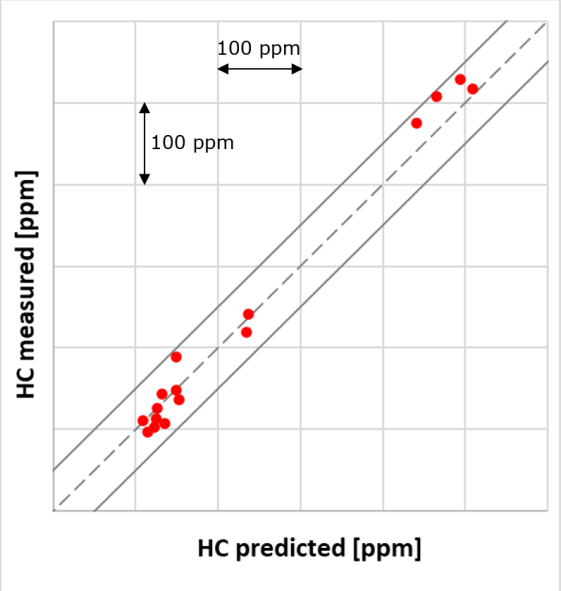



**Fig. 3.** Measured vs. predicted HC emission values for the SCE operating points used for model verification.

## 5. Summary and outlook

This paper presented methodology for the prediction of HC emissions of large gas engines consisting of a 1D simulation model that depicts both HC emissions from the scavenging process as well as emissions from incomplete combustion and crevices. The latter are modeled in the 1D-framework via a polynomial function that describes the conversion rate in the combustion chamber. The simulation models were calibrated and validated on the basis of SCE

measurement data. In addition, 3D-CFD simulation can be employed to analyze specific phenomena with regard to flame propagation and HC emission formation. The overall methodology can be further developed to depict post-oxidation phenomena in the exhaust manifold.

**Acknowledgments**

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За контакти (for contacts):
Dipl.-Ing. Dr. techn. Dimitar Dimitrov
Large Engines Competence Center
Address: Inffeldgasse 19, 8010 Graz, Austria
phone: +43 316 873 30 131
e-mail: Dimitar.Dimitrov@lec.tugraz.at

# ДИАГНОСТИКА НА ЗАХРАНВАЩИТЕ СИСТЕМИ НА ХИБРИДЕН АВТОМОБИЛ

# DIAGNOSING THE POWER SYSTEMS OF A HYBRID CAR

**Alexey Bazhinov** [1], **Tetiana Bazhynova** [2]

**Abstract.** Methods for determining the effective operability of the power plant of a hybrid car at the stage of operation are given. An analysis of failures and malfunctions that occur in the hybrid power plant of a car has been carried out. Additional diagnostic operations and replacement of spare parts not provided by the manufacturer during maintenance (MOT) are given.

**Keywords**: electric vehicle, hybrid vehicle, fire safety, battery, thermal runaway, ignition, fire extinguishing methods, lithium-ion batteries, high-voltage systems, thermal control, safety standards.

## 1. Introduction:

Diagnosing, repairing vehicles with hybrid power plants (GSU) is a problem. Gas control systems, coupled with electronic control units and other components, have a complex system that requires special approaches to determining the technical condition and repair. This problem occurs when operating hybrid vehicles. In addition, road safety also depends on the technical condition of the car. The technical regulations do not have information on determining the technical condition of a hybrid car. When designing service stations and organizing repair work, normative and reference literature is used, but it is not possible to use this literature for cars with a hybrid power plant, because other methods of work are required. The service personnel of service stations do not have sufficient qualifications to carry out diagnostic and repair work on hybrid vehicles. The increase in the production of hybrid vehicles conditions ...

## 2. Presentation:

The on-board network of cars has been constantly improved in recent years. At the same time, the requirements for the battery are increasing. An emergency caused by a dead battery or problems in the on-board power grid can have various causes, which in most cases do not relate to the battery itself. Therefore, replacing a high-voltage battery for a long time eliminates the problem only in the rarest cases. The test block for diagnosing the power system helps in finding the cause. The purpose of diagnosing the power system is to determine the cause of the malfunction as accurately as possible. The test unit reads all the necessary data from the corresponding ECCs and, after evaluating these data, gives out a possible cause that leads to a battery discharge or problems in the on-board energy network, or general information. The amount of this information may vary. If there are several possible causes of malfunctions, they are sorted by mileage (the last event is in first place in the list).

Car malfunction: the car does not go into standby mode; the car constantly comes out of a state of rest; too high a quiescent current at rest; poor charging balance; battery failure. Unfavorable operating parameters: parking lights or emergency lights have been turned on for too long; For too long, pin R or pin 15 has been switched on; long downtime; the average trip is unprofitable (operating the car over short distances); frequent or prolonged switching on of consumers of quiescent current (for example, a radio receiver or rear entertainment system), which can also cause an obstacle to the transition to a state of rest and increased current consumption. We will conduct a study of the data from the diagnostic unit of the car, which is analyzed and read. The analyzed data is, in particular, information from the error storage device in the central network converter or from the error storage device in diagnostics, contact management.

Various information is recorded in the memory device of the history of the power system, which can help in finding the causes of problems with the on-board energy network. The information stored in the energy system history storage device is in particular: an overview of trips in the last 5 weeks. The trip overview is stored in the memory of the power supply history using 6

data sets. Each data set contains the following information: the start time of the registration of the data set, the distance traveled in km during registration, the number of trips on different sections; A new dataset is triggered when the time interval between the current time and the start time of logging the current dataset exceeds 7 days. Thus, the analysis time interval is usually approximately 35 days., unless the car has been at rest for a longer amount of time; the old dataset is overwritten as soon as all 6 datasets in the device are filled; the maximum number of activations during the rest period (contact R excluded) ..

The motor control system or EDME system stores various diagnostic data used in power diagnostics: the results of the last 24 resting current checks; the last recorded battery replacement; the degree of charge of the tab for the last 5 days; mileage in the last 5 days.; time and duration of the last 4 restrictions or disconnection of current consumers; Measurement data to monitor battery status with advanced intelligent battery sensor: Recognition of faulty battery cells, residual capacity. Let's conduct a study of error memory in the engine control system and in EDME. The motor control system or EDME system stores an error code when the quiescent current is exceeded, the battery is discharged deeply, and the current consumers are limited or disconnected. The error memory device in the light control system works as follows.

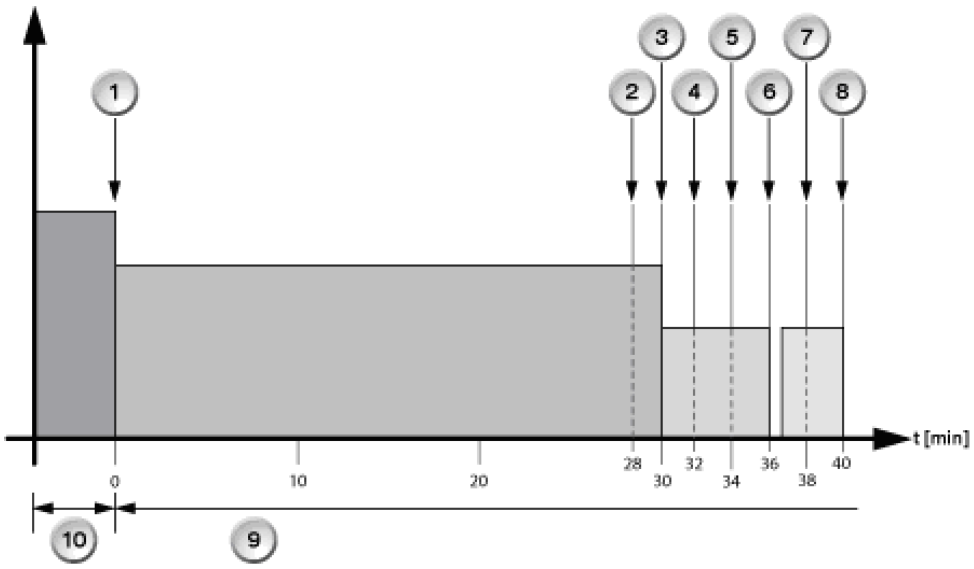



**Fig. 1.** Disturbance of the transition to a state of rest

Disruption of the transition to a resting state Explanation: 1 Pin R switched on 2 Registration of the consumer or consumers in the central network converter module 2 min before the disconnection of pin 30B 3 Disconnection of pin 30B (with the car open or the boot lid open, 30 min after disconnection of pin R) 4 2 min after deactivation of pin 30B: Registration of the consumer or consumers in the central intermediate converter. The central intermediate converter sends a power off command 5 2 minutes after the power off command: Registration of the consumer or consumers in the central intermediate converter. The central network converter requests a pin reset 30F 6 2 min after the request, the central network converter module of the contact control unit resets the pin 30F 7 2 min after the power off command: registration of the consumer or consumers in the central network converter. Central...

Unreasonable activation is shown in Fig. 2.

Unjustified activation Explanation: 1 Pin R switched on 2 Disconnection of pin 30B (with the car open or trunk lid open, 30 min after disconnecting pin R) 3 After disconnecting pin 30B, the central intermediate converter registers 5 times the same wake-up cause or 16 activations. The central intermediate network converter then requests a pin reset 30F. Pin control unit performs a pin reset 30F 4 After resetting the pin 30F, the central intermediate network converter registers the activation that has already occurred; or registered 16 activations since pin 30B was disconnected.

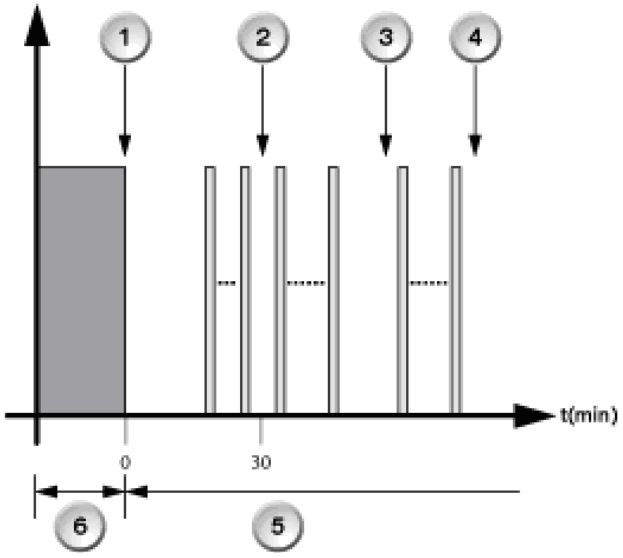



**Fig. 2.** Unreasonable activation

## 3. Conclusion:

The problem of increasing the efficiency of operation of functional systems of a hybrid power plant on the basis of a new concept of diagnosing the technical condition of hybrid cars has been solved, providing a unified approach to the study of diagnostic parameters depending on the structure scheme and design features of the gas turbine system, which uses the characteristics of diagnostic parameters when using energy indicators. The effectiveness of diagnosing the technical condition of a hybrid car significantly depends on the chosen control strategy of the GSU - respectively, its operating mode and control of the energy distribution between the internal combustion engine, traction battery, depending on the technical condition of the components of the car. Conclusion: The problem of increasing the efficiency of operation of functional systems of a hybrid power plant on the basis of a new concept of diagnosing the technical condition of hybrid cars has been solved, providing a unified approach to the study of diagnostic parameters depending on the structure scheme and design features of the gas turbine system, which uses the characteristics of diagnostic parameters when using energy indicators. The effectiveness of diagnosing the technical condition of a hybrid car significantly depends on the chosen control strategy of the GSU - respectively, its operating mode and control of the energy distribution between the internal combustion engine, traction battery, depending on the technical condition of the components of the car.

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За контакти:

[1] Bazhinov Alexey, Prof., doct. texn. nauk, Kharkiv National Automobile and Highway University, Ukraine, phone 80983379445, e-mail: alexey.bazhinov@gmail.com

[2] Bazhynova Tetiana, Prof., doct. texn. nauk, Kharkiv National Automobile and Highway University, Ukraine, phone 80983379445, e-mail: alexey.bazhinov@gmail.com

# ОПАСНОСТ ОТ ПОЖАР В СИСТЕМИТЕ ЗА СЪХРАНЕНИЕ НА ЕЛЕКТРИЧЕСКИ И ХИБРИДНИ ПРЕВОЗНИ СРЕДСТВА

# FIRE HAZARD OF STORAGE SYSTEMS OF ELECTRIC AND HYBRID VEHICLESI

**Kravtsov Mykhailo[1], Bazhynov Oleksiy[2], Petrenko Natalia[3], Petrova Olena[4]**

**Abstract.** The object of the study is the fire hazard of Li-ion batteries of electric and hybrid vehicles, which arises due to the peculiarities of their design, the use of high-voltage electrical systems and the potential risk of their thermal acceleration. The subject of the study: is the regularities of the emergence, development and prevention of fire hazard in electric and hybrid vehicles, in particular the mechanisms of thermal acceleration of battery packs, ignition risk factors, as well as methods of their prevention and extinguishing. The purpose of the study: analysis and assessment of the fire hazard of Li-ion batteries of electric and hybrid vehicles, development of recommendations for increasing their safety and the effectiveness of fire extinguishing methods. Methodological basis of the study: is based on a comprehensive approach to the analysis of the fire hazard of Li-ion batteries of electric and hybrid vehicles, including theoretical, experimental and analytical methods. Relevance of the article: the growing popularity of electric and hybrid vehicles in the world is accompanied by new challenges, in particular the increased fire hazard associated with the use of high-voltage batteries. Cases of electric and hybrid vehicle fires, in particular due to thermal acceleration of lithium-ion batteries, require a detailed study of the causes, mechanisms of fire development and the effectiveness of existing methods of extinguishing it. Practical significance of the article: the results of the study are important for improving the level of fire safety of electric and hybrid vehicles, in particular in the aspects of - developing recommendations for automakers: optimizing the design of battery packs to reduce the risk of ignition; using new materials with increased heat resistance and insulating properties; improving the temperature monitoring and cooling system of batteries; assessing the effectiveness of various methods of extinguishing battery fires; developing specialized fire extinguishing agents for electric vehicles; improving the algorithms of fire services in case of electric vehicle fires, etc. The results obtained can be used by car manufacturers, rescue services, regulatory authorities and scientific institutions to improve the safety of electric vehicles.

**Keywords**: electric vehicle, hybrid vehicle, fire safety, battery, thermal runaway, ignition, fire extinguishing methods, lithium-ion batteries, high-voltage systems, thermal control, safety standards.

## 1. Introduction

In today's world, electric and hybrid vehicles are playing an increasingly important role in the transportation industry, helping to reduce emissions and reduce dependence on fossil fuels. However, along with their advantages, electric vehicles have a number of specific risks, among which fire hazard is of particular concern.

The main source of potential ignition in electric vehicles is high-voltage batteries using lithium-ion or other modern energy storage technologies. Their ignition can occur due to: thermal runaway (uncontrolled temperature increase due to chemical reactions); mechanical damage during traffic accidents; overheating or short circuit in high-voltage systems; external factors such as flooding or prolonged exposure to high temperatures.

Despite the development of safety technologies, extinguishing fires in electric vehicles and hybrids remains a difficult task, as traditional fire extinguishing methods are not always effective. Additional difficulties are created by the possibility of re-ignition of Li-ion batteries even after the primary source of fire has been eliminated.

Thus, the study of the mechanisms of fire occurrence in electric vehicles, the analysis of existing methods of preventing fires, and the search for effective solutions to combat such fires is an urgent scientific and practical task.

The purpose of the study is to investigate the mechanisms of ignition of Li-ion batteries and assess the effectiveness of existing methods of extinguishing them in order to develop recommendations for improving their safety. To achieve this goal, it is necessary to solve the following tasks:

- analyze the main causes of ignition of batteries;
- investigate the mechanisms of fire development and the possibilities of its localization;

- assess the effectiveness of modern methods of fire extinguishing of electric vehicles;
- develop recommendations for increasing the level of fire safety of electric vehicles.

The results obtained can be used to improve the designs of electric vehicles, develop new methods of fire extinguishing and update regulatory requirements for fire safety of electric and hybrid vehicles.

**2. Presentation:**

**Relevance of the topic**

With the development of technology and the popularization of electric and hybrid vehicles, the problem of fire safety of these vehicles is becoming extremely important. Compared to traditional cars, electric and hybrid have significant design differences, in particular the use of large batteries, electric power plants and new technologies for managing energy flows, which can become a source of potential danger.

Over the past few years, there has been an increase in the number of incidents related to fires in electric and hybrid vehicles, which raises the question of the inadequacy of existing methods of prevention and response to such situations. The problem is complicated by the lack of universal standards and recommendations on fire safety for these new types of vehicles, as well as the need to develop new protection technologies and extinguishing methods.

Fires caused by problems with batteries or electrical components have specific features that require a special approach to safety, as well as taking into account factors such as high temperatures and chemical activity of battery cells. Therefore, the importance and relevance of studying the concept of fire hazard of such vehicles is growing in the context of their widespread introduction into the market and increasing use.[1-5].

**Battery Problems**

Li-ion batteries can overheat or short-circuit, which can lead to damage. If the battery does not have an effective cooling system or internal damage occurs, this can cause the battery to ignite. Thermal Failures: Overheating of a battery can lead to thermal decomposition or even explosion. (Li-ion) batteries can cause thermal decomposition of the active materials, which releases heat and gases. If the temperature increases further, the battery may self-ignite or even explode. This chain of events is called thermal runaway - an uncontrolled increase in temperature that can have serious safety consequences.

One of the critical problems in the operation of lithium-ion batteries is the possibility of thermal failure. If the battery overheats, thermal decomposition of the electrolyte and active electrode materials can occur, accompanied by the release of heat and flammable gases. If the temperature continues to rise, this can trigger the process of thermal runaway - an uncontrolled exothermic reaction that leads to spontaneous combustion or explosion of the element. To prevent such failures, thermal monitoring systems, heat exchange and active cooling, as well as structural safety elements, in particular pressure valves and flameproof shells, are used [6-9].

If a lithium-ion battery overheats, chemical reactions can begin inside it, releasing a lot of heat and gases. This can cause thermal runaway - a process when the temperature rises rapidly and leads to ignition or explosion. To avoid this, cooling systems, temperature control and safety valves are installed in the batteries that reduce the risks. Danger of overheating of Li-ion batteries: overheating → chemical reactions → release of heat and gases; thermal runaway, uncontrolled increase in temperature, possible ignition or explosion (fig.1).

High temperatures can cause “thermal runaway,” where the battery begins to release large amounts of heat and gases, increasing the likelihood of a fire or explosion.

Causes of temperature rise that can lead to thermal runaway: Overcharging: Excessive voltage leads to chemical instability in the battery cells. Deep discharge: Can cause internal short circuits during the next charge cycle. Internal short circuit: Due to manufacturing defects or mechanical damage — causes a sharp increase in temperature. High ambient temperature: Especially dangerous in combination with poor ventilation. Intensive load (e.g. in transport): Rapid charging/discharging at high currents also contributes to heating (fig.2).

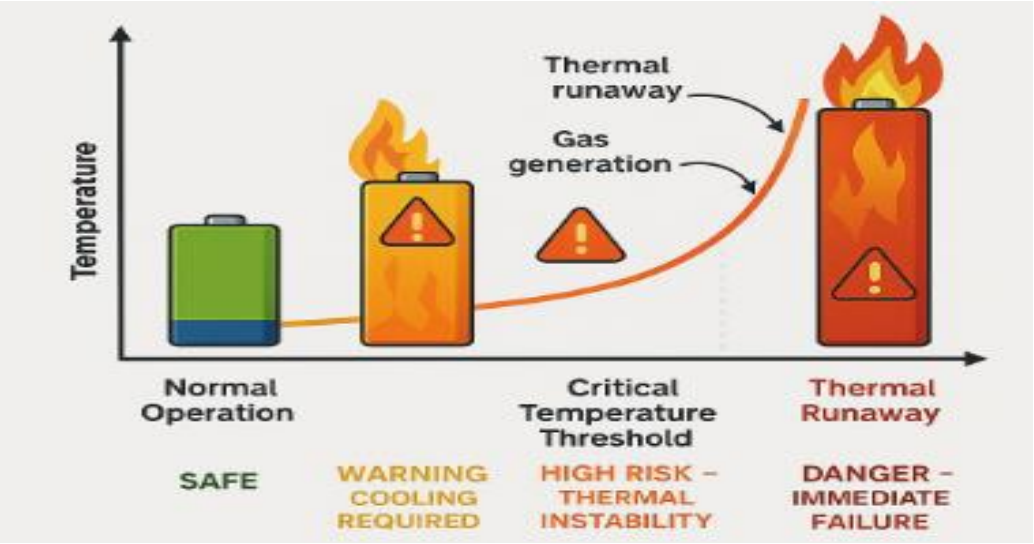
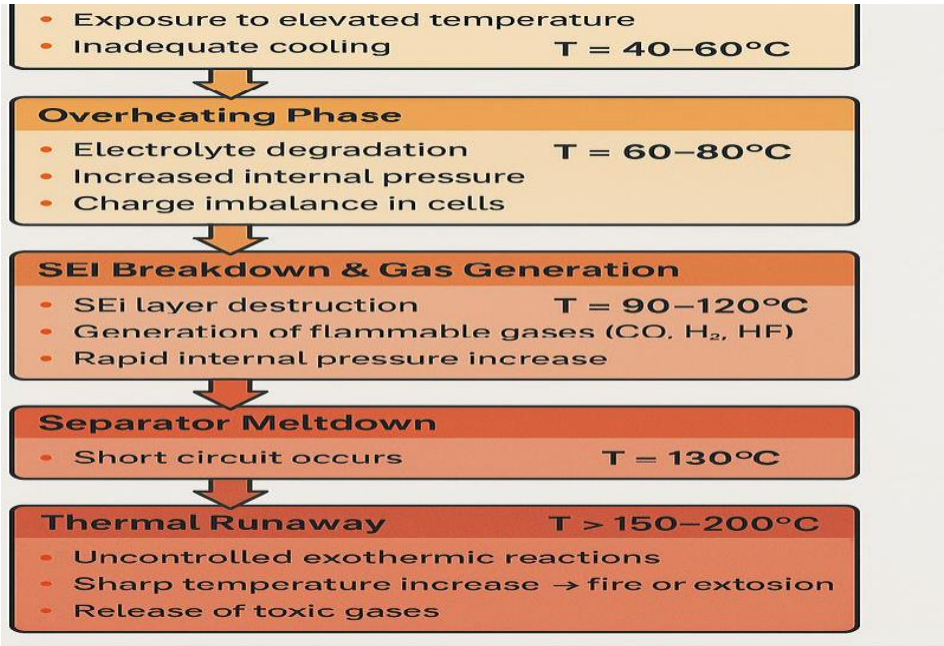



**Fig. 1.** Proper thermal management, cooling systems, and cell monitoring are essential to prevent catastrophic Li-ion battery failure




**Fif. 2.** Temperature rise diagram that can lead to thermal runaway of lithium-ion batteries

Manufacturing defects and aging of Li-ion batteries: Poor quality batteries or their aging can cause a hazard. Damage to the outer shells of the batteries or internal components can lead to electrolyte leaks, making the battery vulnerable to fire. Manufacturing defects of Li-ion batteries: Contamination: The ingress of metal particles during manufacturing (e.g. nickel or iron) can cause an internal short circuit, leading to local overheating and, in the worst case, thermal runaway. Uneven application of electrode materials, variations in the thickness of the active material layer can reduce battery efficiency and cause local degradation. Insufficient moisture control - moisture reacts with the electrolyte to form HF (hydrogen fluoride), which damages the electrodes and shortens the battery's service life. Damage to the separator that separates the anode and cathode. Its mechanical damage or incorrect structure can lead to short circuits. Electrode mismatch - poor alignment of the anode and cathode or errors in the chemical composition lead to overloads, uneven wear and low capacity. Aging of Li-ion batteries: calendar aging (even without use); oxidation of the electrolyte over time; decomposition with the formation of passivating layers (SEI - Solid Electrolyte Interphase); change in cathode chemistry, for example, loss of oxygen from materials such as NMC. Cyclic

aging (during charge/discharge): growth of the SEI layer on the anode → lithium consumption → loss of available Li; mechanical cracking of the electrodes due to volume changes during cyclic operation; lithium disproportionation - deposition of metallic lithium on the anode (especially during fast charging). Thermal aging: high temperatures accelerate electrolyte degradation, destruction of the SEI, cross-reactions between components; gas formation. Formation of gases ($CO_2$, $H_2$) due to electrolyte decomposition → swelling of cells → increased risk of damage or ignition (fig.3)

The main effects of aging: decrease in capacity (Ah); increase in internal resistance (IR); decrease in current output; voltage drop under load; increase in the risk of danger (overheating, swelling, ignition) [10-15].

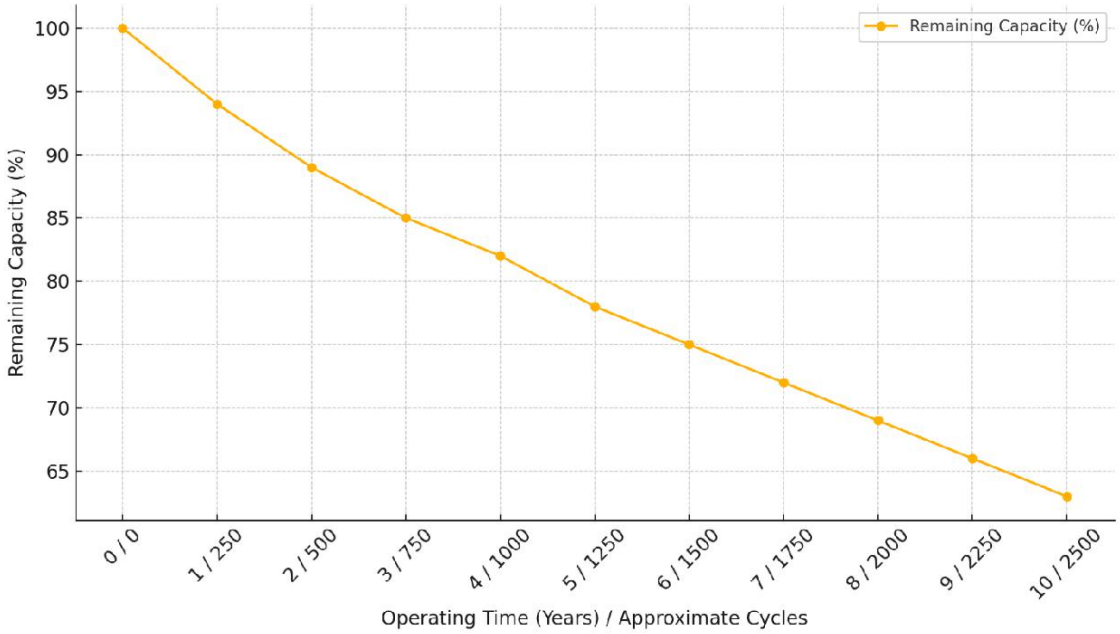



**Fig. 3.** Li-ion battery aging chart

The graph shows how the residual capacity (%) decreases depending on the years of operation and the number of cycles (approximately 250 cycles per year) (fig.4.).

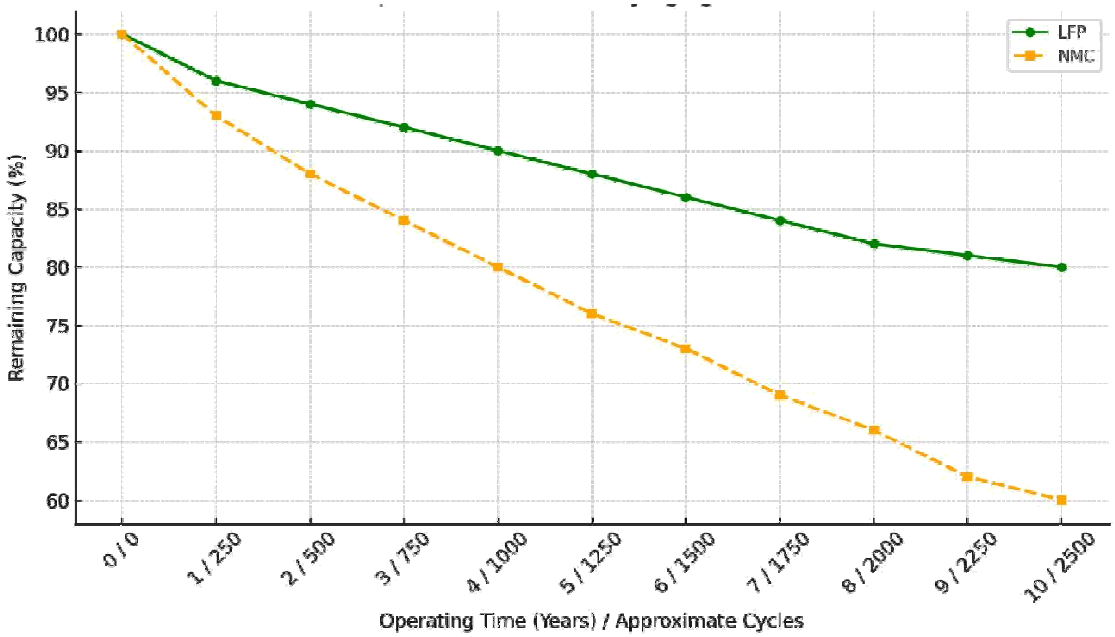



**Fig. 4.** Comparison chart of aging of Li-ion batteries LFP vs NMC

LFP: ages more slowly, retains over 70% capacity even after 10 years or 2500 cycles. Ideal for long life. NMC: more energy dense, but degrades faster - can drop to ~60% after 10 years (fig.5.).

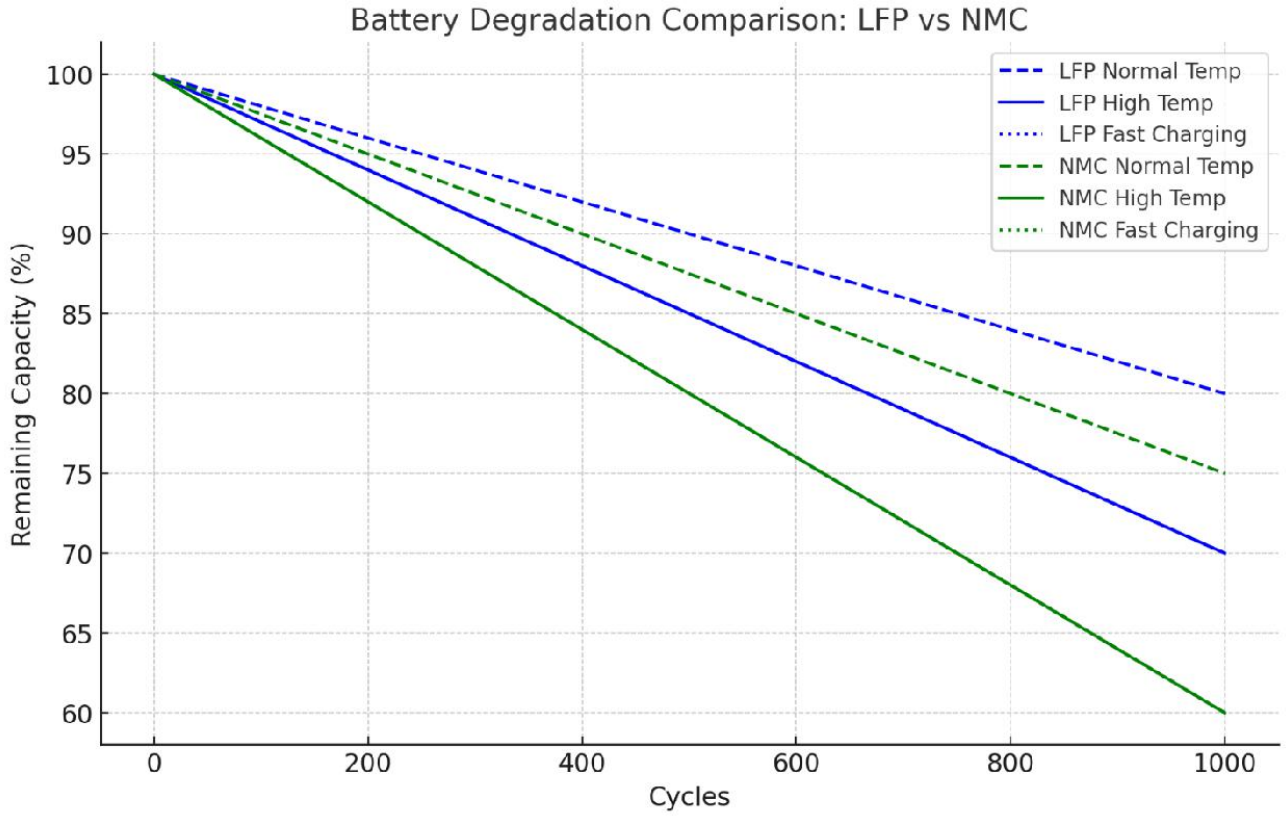



**Fig. 5.** Battery Degradation Comparison: LEP vs NMC

A graph showing the comparison of the aging of LFP and NMC batteries under the influence of temperature and fast charging:

LFP Normal Temp and NMC Normal Temp are the aging of batteries at standard temperatures.

LFP High Temp and NMC High Temp are the aging at high temperatures, which accelerates degradation. LFP Fast Charging and NMC Fast Charging are the effects of fast charging, which also accelerates aging.

This graph shows how temperature and fast charging affect the decrease in battery capacity over time.

**Electrical components and systems**

Overload and damage to electrical wiring: In electric and hybrid vehicles, high-voltage electrical systems must have reliable insulating materials, but damaged cables, incorrect connections or poor quality components can cause short circuits and short circuits, which increase the risk of fire.

Use of high-voltage systems: Electric vehicles use high-voltage systems to power electric motors and chargers. If these systems are damaged, there is a risk of electric shock or short circuits, which can cause fire.

Accidental injuries: Drivers and passengers in electric and hybrid vehicles may be at additional risk in the event of an accident due to the design of the batteries and electrical systems. Damage to the battery during an accident can lead to electrolyte leakage, fire or even explosion [16-24].

Calculation of damage to a lithium-ion battery during an accident is a complex engineering task that takes into account mechanical loads, the design of the battery module, the characteristics of the materials and the type of accident. The general approach to such an

analysis: input data - battery design: type of cells (cylindrical, prismatic, pouch); number and location of cells; mechanical protection (housing, frame, shock-absorbing materials). Accident data: type of impact (frontal, side, rear, rollover). Collision speed. Impact geometry (contact point, impact angle). Material characteristics: mechanical strength of the housing. Plasticity, elastic modulus, ultimate strength of battery cells. Parameters of internal connections (welding, conductors). Calculation methods Finite element analysis (FEM/FEA): CAD model of the battery pack. Application of impact load. Analysis of deformations, stress distribution, fractures. Example software: Ansys, Abaqus, LS-DYNA. Damage criteria: cell penetration → possibility of short circuit. Plastic deformation of the housing → thermal risk. Exceeding the strength limit of welded joints → failure of current paths.

**Table 1.** Damage risk assessment

| Parameter | Safety limit |
|---|---|
| Cell deformation | ≤ 5% |
| Case voltage (aluminum) | ≤ yield point [~250 МПа] |
| Temperature after impact | [≤ 60°C] |
| Probability of short circuit | [< 1%] |

Physical testing (model validation): Battery crash tests: side impact, drop, compression. Temperature, current, voltage recording. Estimation of residual capacity after an accident. Example calculation (simplified). Assume: car mass: 1500 kg; Impact speed: 50 km/h. Impact kinetic energy:

$$E = \frac{1}{2} \cdot mv^2 = \frac{1}{2} \cdot 1500 \cdot \left( \frac{50}{3.6} \right)^2 = 289.351 \text{ Дж} \quad (1)$$

If 15% of the energy is transferred to the battery pack:

Ebattery=0.15 ⋅ 289 351≈43 402.65 Дж

Converting energy into kWh. We have: E=43 403 J

1 kWh = 3,600,000 J

E=43 403:3 600 000≈0.01206 kW

This is approximately 0.0121 kWh.

Percentage of typical battery:

For example, for a 60 kWh battery: 0.012160 ⋅ 100≈0.0202 This is only ~0.02% of the full capacity of the 60 kWh battery

Conclusion: even during emergency braking with the transfer of 15% of kinetic energy to the battery, this is a very small part of the total battery life. But in multiple cases or in recuperation conditions, the energy can accumulate more significantly [25- 7].

Energy transfer to the battery pack (15%) depending on vehicle speed

Let's assume: mass of the car = 1500 kg. We calculate the energy at speeds from 10 to 130 km/h with a step of 10 km/h (fig.6.).

$$E = \frac{1}{2} \cdot mv^2, \text{ v to m/s, } E_{battary} = 15\% \text{ on E} \quad (1)$$

A graph showing how much energy (in kWh) is transferred to the battery pack when a vehicle is braking at various speeds, if 15% of the kinetic energy is returned to the battery (e.g. through regenerative braking) (fig. 7).

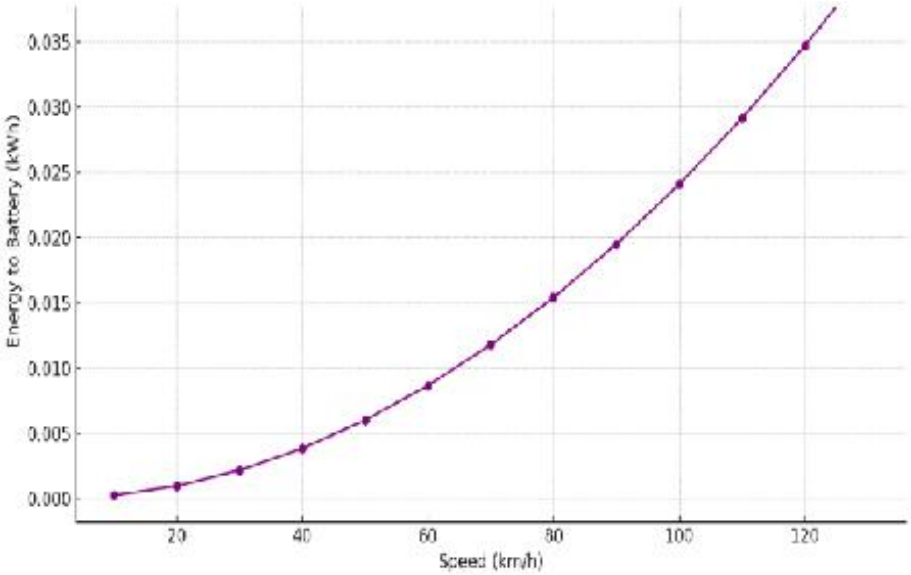



**Fig. 6.** Graph of the amount of energy (kWh) transferred to the battery

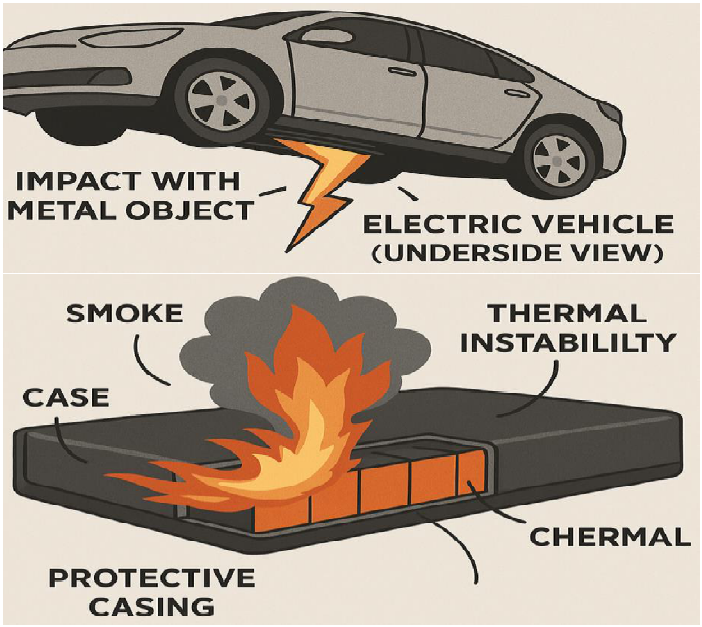



**Fig. 7.** Electric vehicle (bottom view): impact of a metal object on the lithium-ion battery

Top part — bottom view of the electric vehicle - this area of the image shows the car from below: the body of the electric vehicle (blue): conditionally transparent to show the location of the battery. Battery pack: located under the floor, in the center, has a protective cover. Metal object (yellow/orange spike): hits the battery from below — for example, a piece of debris from the road, reinforcement or other sharp object.

Central area — penetration point - penetration of the battery case: the spike penetrates the metal shell. Damaged internal structure: the spike reaches the internal elements of the battery.

Calculating damage to a lithium-ion battery when hit by a metal object is complex and requires taking into account several factors: the mechanical properties of the battery, its design, the characteristics of the impact, as well as the properties of the material that makes the impact. Here are some basic steps for such a calculation: determining the impact force, first you need to calculate the impact force that affects the battery. To do this, we use the basic equations of mechanics:

$$F = \frac{m \cdot \Delta_v}{\Delta_t} \tag{3}$$

where:
F – impact force (N);
м - mass of the metal object (kg);
$\Delta_v$ - change in velocity (m/s) – the difference between the velocity before and after the collision;
$\Delta_t$ - contact time (s), which should usually be very short, but depends on the material and impact conditions (fig. 8).

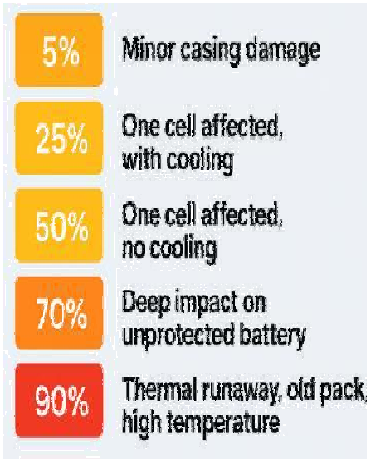



**Fig. 8.** Possibility of ignition or explosion of a lithium-ion battery

Assessing the likelihood of a fire or explosion where an impact could cause a battery cell to overheat, which in turn could lead to a fire or even an explosion. Assessing the likelihood of such an outcome requires knowledge of the thermal properties of the battery materials, their thermal resistance, and critical temperatures for safety.

What happens when an impact occurs: mechanical damage to the cell (battery element): due to the penetration of a metal object, the following can occur: damage to the separator between the anode and cathode; short circuit between the electrodes (short circuit); a sharp increase in temperature inside the element: a large amount of heat is released due to resistance and chemical reaction. Thermal runaway is triggered: the temperature increases exponentially, to 500–800°C. Gas, smoke are released, and a flash is possible [28-29].

**Table 2.** Assessment of thermal effects from impact

| Factors | Description | Risk of fire/explosion |
|---|---|---|
| Deep mechanical penetration | A metal object penetrates several layers of protection and reaches the cell | High [60–80%] |
| Damage to the shell only | The casing is scratched or deformed, but the cells are not affected | Low [1–5%] |
| One cell damaged | One damage without domino effect | Medium [30–40%] |
| Old or degraded elements | Weakened protection, worse thermal stability | Elevated [40–60%] |
| Lack of cooling | Inability to absorb the heat that is generated | High [50–70%] |
| Availability of a cooling system | Liquid/air reduces temperature during an accident | Low–medium [5–25%)] |
| Protective gasket and thermal Breaks | Special elements limit heat spread | Risk reduction by [30–50%] |

When struck by a metal object, a large amount of heat can be generated due to mechanical compression and internal friction in the battery materials. This heat can damage the battery's internal components, causing overheating and potentially a fire.

Formula for heat load:

$$Q=\eta \cdot \sigma \cdot \varepsilon \cdot V \quad (4)$$

where:
Q — amount of heat (J),
η — coefficient of conversion of mechanical energy into heat (depends on the material, usually 0.5–1),
σ = 5.670374419×10$^{-8}$Wt/(м$^2$ · К$^4$) - mechanical stress in engineering is often measured in MPa, because Pascal;
ε — deformation (dimensionless),
V — volume of material in which deformation occurs (m³).
Heat transfer in the battery: after heat is generated by impact, it is transferred through the battery case to the elements contained within:

$$\rho c_p \partial t/\partial T=\nabla \cdot (k \nabla T)+q \quad (5)$$

where:
ρ — material density (kg/m³)
cp — specific heat capacity at constant pressure (J/(kg K))
∂T/∂t — partial derivative of temperature with respect to time, i.e. how quickly the temperature changes over time (K/s),
k — thermal conductivity coefficient (W/(m K)), may depend on spatial coordinates,
∇T — temperature gradient, a vector indicating the direction and rate of temperature change,
∇ · (k∇T)) — heat flux divergence, describes how heat "spreads" in space,
q — density of internal heat sources (W/m³), such as heat generated through reactions or electric current.
Physical meaning: left part: ρcp∂/T∂t is the change in the internal energy of the material over time (i.e., how much energy is stored or lost). Right part: ∇ · (k∇T)+q is the heat transfer through thermal conductivity and additional internal heat sources.

**Assessment of the probability of ignition or explosion**

Threat to rescuers: Electric and hybrid vehicle crashes and fires present additional challenges for rescuers. For example, battery fires can be difficult to extinguish with traditional methods, and electrical systems can remain live even after damage.

Insufficient safety infrastructure: Little research on fire safety aspects: Given the novelty of electric and hybrid vehicles, not all aspects of their safety have been studied and taken into account in standard emergency procedures. As a result, there may be a lack of effective infrastructure to quickly respond to accidents involving such vehicles. The need for specialized training for rescue workers: Rescue services may not have sufficient knowledge or specialized equipment to deal with fires in electric and hybrid vehicles, which requires additional training and educational programs.

Charging station issues: Charging station standards not meeting: If charging stations do not meet safety requirements or are used incorrectly, this can lead to connection problems or overheating of the chargers. This can also create potential fire risks in both the stations and the vehicles.

External factors: temperature fluctuations;: high or low temperatures can negatively affect the operation of batteries, reducing their efficiency or causing short circuits, which can cause fires. Moisture and corrosion or water ingress into the electrical components of a car can lead to

short circuits and the risk of fire, especially in places where components are not properly protected from water.

In general, despite their great advantages, electric and hybrid cars require special attention to safety, especially in the context of fire hazards. To reduce these risks, it is necessary to implement new safety standards, develop improved battery technologies, cooling and protection systems, and train emergency services to respond effectively to potentially dangerous situations [30-32].

**The main differences in the design of electric, hybrid and traditional cars**

Electric Vehicles (EV) - Drive: In electric vehicles, the engine is an electric motor powered by a battery. All moving components, including the wheels, are driven solely by electric energy. Power system: The main source of energy is a lithium-ion battery that stores energy obtained through the charging process from external sources. The battery can be charged via standard charging stations or home chargers. Emissions: These vehicles emit no CO2 or other pollutants because they do not have an internal combustion engine. Electric vehicles typically have a much simpler drivetrain and fewer moving parts than traditional vehicles. This reduces mechanical wear and tear and increases system reliability. Advantages include low operating costs, zero emissions, and high torque for fast acceleration. Disadvantages include limited range, long battery charging times, and dependence on charging infrastructure.

Hybrid Vehicles (HEV) - Drivetrain: Hybrid vehicles use a combination of an internal combustion engine (ICE) and an electric motor. The two engines can operate separately or together, providing different driving modes. Powertrain: In hybrid vehicles, the energy for the electric motor is stored in smaller batteries compared to electric vehicles. These batteries are charged through regenerative braking (when the vehicle brakes, the energy is generated and stored in the battery) or through the internal combustion engine.

Emissions: Hybrid vehicles reduce $CO_2$ emissions compared to conventional vehicles by using an electric motor to support propulsion, but they still emit emissions from the internal combustion engine.

Design: Hybrid vehicles have a more complex design than electric vehicles, as they combine two engines, a transmission, an electrical system and a fuel system. This can affect the cost and complexity of maintenance.

Advantages and disadvantages: Advantages include a longer driving range due to the use of both a battery and petrol/diesel. Disadvantages: Complex design and higher maintenance costs compared to electric cars.

Traditional cars (ICE – Internal Combustion Engine) - drive: In traditional cars, the main source of energy is an internal combustion engine (ICE), which runs on gasoline or diesel fuel. The ICE creates mechanical energy to propel the car.

**Table 3.** Advantages and disadvantages of cars

| Characteristic | Electric vehicle (EV) | Hybrid vehicle (HEV) | Traditional car (ICE) |
|---|---|---|---|
| Occasion | Electric motor | Electric and internal combustion engine | Internal combustion engine (ICE) |
| Energy | Lithium-ion battery | Battery and fuel combination | Gasoline or diesel |
| Emissions | No CO2 emissions | Reduced CO2 emissions, but still there | CO2 emissions and other pollutants |
| Travel range | Limited (depends on battery capacity) | Higher, thanks to the combined energy source | The largest while there is fuel |
| Infrastructure | Charging stations needed | Can be refueled with gasoline or diesel | Gasoline or diesel filling stations |
| Construction | Simple electric drive, no transmission | Complex design with two engines | A complex mechanical system with numerous components |

Power system: Power is provided by fuel stored in the tank. Energy is obtained by burning the fuel in the engine, which creates heat and mechanical energy.

Emissions: Traditional cars are major sources of $CO_2$, nitrogen oxides and other pollutants into the atmosphere.

Design: Traditional cars have a complex design, with numerous mechanical components such as the transmission, internal combustion engine, exhaust system, radiator and others.

Advantages and disadvantages: Advantages include a long history of development, affordability, quick refueling and relatively easy maintenance. Disadvantages include high pollutant emissions, greater dependence on fossil energy sources, and high fuel costs.

The choice between an electric, hybrid and traditional car depends on the consumer's needs, such as driving range, environmental requirements, infrastructure availability and personal preferences regarding cost and maintenance (fig. 9).

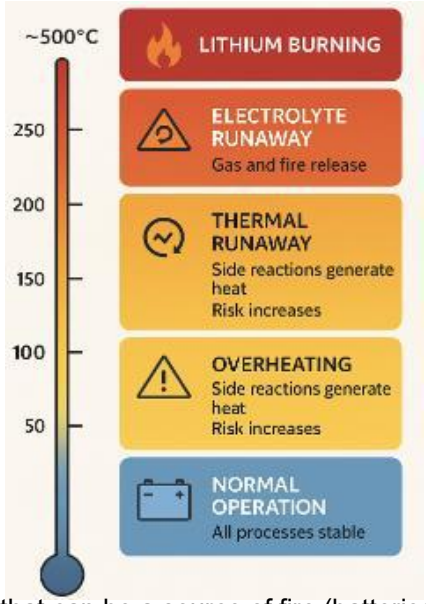



**Fig. 9.** Components that can be a source of fire (batteries, chargers, electrical systems)

There are several components in electric and hybrid vehicles that can become a source of fire, including overheating, short circuits, design defects, or improper operation. The main sources of fire hazards are batteries, chargers, and electrical systems.

Lithium-ion batteries are the primary source of energy in electric and hybrid vehicles, but they can also be a cause of fire due to several factors: Thermal failures: Lithium-ion batteries are prone to overheating, especially during intensive use if the battery is not adequately cooled. High temperatures can lead to thermal decomposition of the battery, causing a fire or even an explosion.

Internal short circuits in a battery can occur due to damage to internal components, such as the separators between the anode and cathode. This can cause excessive heat and, as a result, a fire. Mechanical damage to the battery resulting from an accident or impact can break its seal, lead to electrolyte leakage and potential ignition. Batteries that have been subjected to mechanical damage are particularly dangerous and can cause ignition due to leakage or overheating [33].

The process of a short circuit in a lithium-ion battery can be quite complex and depends on a number of factors: Mechanical damage: If the battery is mechanically damaged (for example, due to an impact or a breakdown), this can lead to damage to the insulation between the anode and cathode. As a result, the anode and cathode can come into direct contact, causing a short circuit. Overheating: Lithium-ion batteries can overheat due to improper use or insufficient cooling. Overheating can lead to the destruction of the separator (the material separating the anode and cathode) or damage to other elements of the battery. This can cause the separator to wear or shift, which can also cause a short circuit. Internal defects: The presence of defects in manufacturing, such as contamination or damage to materials, can also lead to a short circuit

inside the battery. Defective electrodes or the use of poor-quality materials can increase the likelihood of this process. Overcharging or overcharging: If a battery is charged outside of the permitted parameters (for example, when using an incorrect charger or a poor-quality charge controller), a dangerous condition can occur in which the temperature in the battery increases dramatically, which can also cause a short circuit. Chemical reactions: As a result of a short circuit, a chemical reaction can occur inside the battery, leading to even greater overheating and, ultimately, an explosion or fire. Physical mechanisms of short circuit: In a short circuit, the anode and cathode come into direct contact, either through a damaged separator or through the formation of a metal path that closes the circuit. This creates a short circuit, which leads to an instantaneous increase in current, overheating and potentially thermal breakdown. Statistical and thermal calculations: Thermal expansion: During a short circuit, a significant heat flow can occur in the battery, which exceeds the critical temperatures for the battery, causing thermal breakdown. It is worth considering the heat capacity of the materials and the rate of heat transfer. Electrical calculations: The current flow during a short circuit is usually very large, which can also be calculated using Ohm's law [34].

The current flow during a short circuit is usually very large, which can also be explained using Ohm's law:

$$\frac{dT}{dt} = \frac{P}{mc} I = \frac{V}{R} \tag{6}$$

where:
*I* - current strength;
*V* - battery voltage;
*R* - resistance (which in this case is reduced to a minimum during a short circuit).

**Thermal effects modelling**

Modeling thermal expansion processes and chemical reactions typically uses the equation for thermal temperature rise:

$$\frac{dT}{dt} = \frac{P}{mc} \tag{6}$$

where:
P — heat output,
m — mass,
c — heat capacity.

Improper use of chargers, overcharging, or using uncertified chargers can cause overheating and damage to the battery. Chargers for electric and hybrid vehicles play an important role in safety, but they can also be a source of danger:

Charger overheating: If the charger does not meet safety requirements or has design defects, this can lead to overheating. High temperatures in the charger can cause a fire, especially if the device does not have a proper cooling system or is used outside of specifications.

Faulty electrical connections: Poor contact, damaged or worn wires, connectors, or sockets on charging stations can lead to short circuits, which in turn can cause a fire.

Charging station standards that do not meet international safety standards: If charging stations or devices do not meet international safety standards, this can cause poor contact, which can cause overheating and fire during charging.

A vehicle’s electrical systems, including wiring, control modules, sensors, electronics, and transmissions, can be a source of fire hazards due to the following factors:Short circuits and overloads: Damaged or improperly connected wiring can cause a short circuit. This can occur due to manufacturing defects or improper maintenance of components, which can lead to a

short circuit in the vehicle’s electrical systems; Overheating of electrical components - Electrical components, including wiring, can overheat due to system overload, poor quality materials, or excessive use. Heating of wiring or contact points can lead to a fire.

Controller and modular system failures: Computer controllers and electronic systems that control various vehicle functions can fail due to software failures or overheating, which can be the source of a short circuit or overheating.

Failure to meet insulation and safety standards: Poor insulation of wires, electrical connections, or defects in electrical components can cause an increased risk of fire.

Other components: Cooling systems, modern electric and hybrid vehicles use specialized cooling systems for batteries and electrical components. If the cooling system fails or becomes contaminated, overheating can occur, increasing the risk of fire.

Engine ignition, although electric vehicles do not have a traditional internal combustion engine, in hybrid models, an internal combustion engine can become a source of ignition due to malfunctions in the fuel or exhaust system.

Prevention and safety. To reduce the risk of fire in electric and hybrid vehicles, it is necessary to: install systems for monitoring the temperature and condition of batteries; use certified chargers and standard charging stations; cooling and protection systems for batteries to avoid overheating; regular maintenance of electrical components to check their performance and safety; ensure reliable insulation of wiring and electrical connections; train rescuers and other security services in the specifics of responding to accidents involving electric and hybrid vehicles.

Strict safety standards and regular inspections of technical condition help reduce the likelihood of fires in such vehicles.

**Main causes of fires in electric and hybrid vehicles**

Short circuits in batteries are a serious safety issue that can lead to fire, explosion, or other hazardous situations. In lithium-ion batteries used in electric and hybrid vehicles, short circuits can occur for various reasons and have their own characteristics. Causes of short circuits in batteries: mechanical damage. Damage to the battery due to impact or accident can lead to deformation or violation of the integrity of the battery pack. If the internal components of the battery (electrodes or separators) are damaged, this can cause a short circuit, which will lead to overheating, ignition, or even an explosion.

Defects in the battery design - the manufacture of batteries can be accompanied by defects that are not always visible at first glance, such as cracks in the case, defects in the electrodes or separators that separate the anode and cathode. In the event of such a defect, the internal elements of the battery can come into contact with each other, which creates a short circuit.

Non-compliance with manufacturing standards, if the battery does not meet safety requirements or poor-quality materials are used, may cause a breakdown between components, which also contributes to the occurrence of a short circuit.

Overcharging the battery or using uncertified chargers can lead to overloading the battery. This can cause heating and damage to the internal elements of the battery, which in turn can lead to a short circuit. To prevent this, modern batteries are equipped with overload monitoring and protection systems.

Low quality or worn out battery, during operation of the battery, wear processes may occur that reduce its efficiency and increase the likelihood of a short circuit. Old batteries are more likely to develop damage or defects compared to new ones.

Moisture or contamination inside batteries can cause corrosion or electrical shorts between battery components. If moisture enters the battery through defects in the case or connection, this can lead to a short circuit. The consequences of a short circuit: overheating; Short circuits are often accompanied by a sharp increase in temperature. In lithium-ion batteries, this can cause thermal decomposition, which leads to the release of coolant and, as a result, to a fire or explosion of the battery; overheating or melting of the internal elements of the

battery can cause a fire. Fires that occur in batteries can be very intense and difficult to control, as lithium-ion batteries can produce toxic gases and even explode in a fire [35].

Explosion In some cases, a short circuit can cause a battery to explode. This can happen due to the accumulation of gases that are formed during overheating, or due to insufficient ventilation in the battery pack.

**Safety measures and prevention**

Modern batteries for electric and hybrid vehicles are equipped with various protection systems, such as thermal sensors, overload protection systems and circuit breakers. These systems automatically turn off the battery if it overheats or has a short circuit. Charging control, using certified chargers that meet the battery manufacturer's requirements, helps prevent overcharging or overloading the battery. Many cars also have built-in charging control systems that help avoid dangerous situations. Battery cooling: Cooling systems for batteries ensure that the optimal temperature is maintained during operation, which reduces the risk of overheating and short circuits.

Battery condition monitoring: Regular testing and checking the condition of the battery, as well as timely replacement of old or damaged batteries, can reduce the likelihood of a short circuit. Many manufacturers build in monitoring systems that signal possible malfunctions.

Improvements in battery design, including better materials for separators, cases and electrodes, as well as the use of more efficient cooling systems, can reduce the likelihood of short circuits. Short circuits in batteries are a serious safety risk, so proper operation, timely maintenance and the use of quality components are extremely important to minimize the likelihood of such incidents. Overheating of electrical components is one of the main causes of dangerous situations such as fires, explosions or system failures in electric and hybrid vehicles. This can occur due to various factors such as overloading, design defects, poor ventilation or improper use of systems. Given the high requirements for energy efficiency and power, overheating of electrical components requires special attention in the automotive industry. Causes of overheating of electrical components - overloading of electrical systems. Overloading of electrical systems, for example, when using the engine or battery at maximum power for a long time, can lead to overheating. This can occur due to intensive use of the vehicle in high temperatures or harsh operating conditions (for example, when climbing steep slopes or at high speeds).

In modern electric and hybrid vehicles, batteries and other electrical components such as motors or power inverters require an efficient cooling system. If the cooling system is not working properly or is defective (for example, contamination or loss of fluid), this can lead to overheating of the components. The cooling of batteries in electric vehicles is carried out using liquid or air systems, and their efficiency is critical for safety. An ineffective cooling system can lead to overheating and even a fire in the battery.

A short circuit in electrical components can cause excessive heat generation. For example, damaged wiring or connections can cause current to flow through the faulty areas, which in turn causes overheating. This process can be gradual and eventually lead to component damage or a fire.

Using poor quality materials for wiring, connections or other electrical components can cause them to overheat. Poorly insulated wires or poorly prepared connections can become a source of heat when electrical current flows, increasing the risk of overheating.

High loads on battery systems, increased engine power or intensive use of battery systems (for example, when fast charging or in difficult driving conditions) can cause the temperature in batteries and electrical components to rise to dangerous levels.

Non-optimal arrangement of components In some cases, overheating can be the result of improper arrangement of electrical components in the vehicle's design. For example, components that generate a lot of heat may be located too close to each other or without sufficient space for ventilation, resulting in overheating, damage to electrical components; continuous overheating can lead to damage to electrical components such as batteries,

inverters, controllers or wiring. High temperatures can weaken insulation or disrupt the proper functioning of components, ultimately leading to failure.

Fires and Explosions In the case of lithium-ion batteries, overheating can lead to thermal decomposition, which releases heat, toxic gases, and possibly an explosion. Fires caused by overheating can be difficult to control, especially in the confined spaces of a vehicle.

Cooling system malfunctions, improperly functioning, or inefficient cooling systems can cause them to malfunction, further complicating the overheating situation. This can damage other components and increase the risk of an accident or fire.

Overheating can reduce the efficiency of a vehicle’s electrical systems and shorten their lifespan. For example, a battery that overheats frequently can wear out faster, reducing its capacity and reducing the range of its range. Measures to prevent overheating include effective cooling. Cooling systems for batteries and other electrical components must be designed to handle high thermal loads. The use of liquid cooling for batteries or power electrical components is an important aspect of maintaining the safety and efficiency of the vehicle. Regular inspection and maintenance of the cooling system prevents its breakdown or contamination.

Using high-quality components, it is important to use components made of materials that can withstand high temperatures, provide reliable insulation and effective heat dissipation. This applies to both wiring and batteries, inverters, charging systems.

Temperature Monitoring - Integrated temperature monitoring systems that monitor the status of batteries and other components in real time help prevent overheating. They can automatically shut down the system or enter a safe mode when dangerous temperatures are reached.

Proper energy management, vehicle operating modes must be configured to avoid excessive load on electrical systems. This includes the correct distribution of power between the battery and the engine, as well as intelligent management of energy use during charging.

Regular maintenance, checking electrical systems and components for damage, corrosion, wear or other defects helps prevent overheating and keep the vehicle in good condition.

Problems with the charging system are caused by the fact that the charging system is one of the critical components in ensuring the normal operation of electric and hybrid vehicles. It includes components responsible for transferring energy from the charger to the battery, as well as controlling the charging process. Charging system malfunctions can lead to various problems, including overheating, battery damage, fire, and even power system failure. Therefore, it is important to carefully monitor the condition of the charging system. Main charging system problems: non-compliance with charger standards, or the use of uncertified chargers is one of the main causes of charging system malfunctions. Non-compliance with standards can lead to overheating or short circuits in the vehicle's electrical system or the charger itself. Such problems can also cause damage to the battery or other electrical components.

Overcharging of the battery can occur if the charger does not stop the charging process after reaching a full charge. This leads to overheating of the battery, which can shorten its service life, cause an explosion or fire. To prevent this, modern charging systems are equipped with intelligent algorithms that automatically stop charging when the battery reaches its maximum capacity.

Incorrect temperature during charging can affect the charging efficiency of the battery. If the charging temperature is too high or low, it can damage the battery or reduce its efficiency. Charging systems that are unable to control the temperature or do not have adequate cooling can lead to overheating or incomplete charging.

Problems with cables and connections - Damage or wear to the cables and connections of the charging system can lead to poor contact or overheating. This can cause a short circuit or even a fire. Damaged or poor-quality connections can increase electrical resistance, which will lead to excessive heat generation during the charging process.

Problems with the electronic components of the charging system, damage to electronic components such as inverters or charge controllers, can lead to unpredictable consequences,

including incorrectly configured charging parameters, overheating or even failure of the entire charging system. Faults in these components can also lead to uneven or incomplete charging of the battery.

Charging in rain, humidity or extreme temperatures can cause water or moisture to enter the charging system, which can cause a short circuit, corrosion of electrical contacts or even system failure. A leaky charging system is an important factor that can increase safety risks.

Charge control system failure, inadequate charging management can be caused by a malfunction in charge control systems, such as charge controllers, which are responsible for determining the required power and charging mode. If the system is unable to accurately regulate these parameters, this can lead to incorrect charging or even damage to the battery.

Reduced charging efficiency can occur if the charging system is unable to provide sufficient power or optimal voltage to the battery. This can lead to a very slow charging process or even a stoppage. To maintain the optimal condition of the charging system, it is important to regularly check its components.

Consequences of charging system problems - battery damage, charging system problems can lead to serious damage to the battery, such as reduced capacity, short circuit or even explosion. This significantly reduces the battery life and reduces the efficiency of the vehicle; overheating and fires; charging system faults can lead to overheating, which is one of the main causes of fires or explosions in electric vehicles. Overheating of the battery or charger can lead to thermal decomposition, the release of toxic gases and even fire.

Power system failure, charging system problems can cause the car's power system to fail completely. This can result in the car not being able to start or not having enough power for normal operation.

Measures to prevent charging system problems: use certified chargers. To prevent charging system problems, it is important to use only certified chargers that meet the safety requirements and standards recommended by the vehicle manufacturer; regular maintenance; Regular checks of the charging system, including inspecting cables, connections, chargers and controllers, can help identify and fix potential problems before they become serious.

Using intelligent charging management systems that monitor the process, temperature, voltage and power helps prevent overcharging and provides proper protection for the battery.

Using overheat protection: Many chargers are equipped with overheat protection or temperature control systems that automatically stop charging if the temperature reaches dangerous levels. Charging in safe conditions, to avoid problems with the charging system, it is important to charge the vehicle in dry and moisture-free areas to avoid short circuits and other problems with electrical components. Following these measures will help minimize the risks associated with the charging system and ensure safety when operating electric and hybrid vehicles.

**Battery damage and exposure to external factors (e.g. fire in a traffic accident)**

Battery damage in electric and hybrid vehicles is a serious problem that can lead to various consequences, including short circuits, explosions, fires or significant mechanical damage. Given the large capacities stored in batteries, as well as the high requirements for their safety, it is important to consider not only internal problems (such as component defects or charging errors), but also external factors that can lead to battery damage. One of the greatest risks is battery damage due to accidents or other emergencies, such as fire. Causes of battery damage - mechanical damage to batteries as a result of accidents. Mechanical damage to a battery is one of the main reasons for its failure after an accident. Batteries, especially large batteries in electric vehicles, can be damaged during a strong impact, which leads to the destruction of the case or disruption of the integrity of internal elements. Such damage can cause electrolyte leakage, short circuits or even explosions. Batteries containing lithium are particularly vulnerable, as they are prone to thermal decomposition in the event of damage.

Fires resulting from accidents or other external factors can significantly increase the risk of a battery catching fire. If a battery is damaged or exposed to heat (such as in a fire resulting

from an accident), lithium-ion batteries can undergo thermal decomposition. This is accompanied by the release of flammable gases and toxic materials, which can cause further fire or explosion.

Short circuits due to mechanical damage to the battery can cause short circuits in electrical circuits. This can occur due to damage to the insulation of the wires or internal components of the battery, allowing current to flow through unwanted paths, generating excessive heat and causing a fire or explosion.

Water or other liquids entering the battery due to an accident can lead to water or other liquids entering the battery. This can cause corrosion of the contacts and insulation, which in turn increases the risk of a short circuit or other electrical failure. Exposure to water or other liquids can also negatively affect the chemical properties of the battery and cause thermal or chemical reactions.

Batteries can be exposed to significant thermal stress during an accident. For example, during a severe impact or as a result of a car fire, the battery can overheat, causing thermal decomposition. High temperatures can lead to the release of large amounts of gases and chemical compounds, which increases the risk of explosion or fire.

Fires that occur during an accident can not only damage the body of the car, but also cause thermal stress on the battery, which, without proper cooling, can ignite. Fires are especially dangerous in high-speed accidents, when the temperature rises significantly due to friction or rupture of fuel pipes. Combined with damage to the battery, this can lead to an explosion or fire in the battery system.

Lithium-ion batteries have a tendency to thermal decomposition when exposed to high temperatures or mechanical damage. This breakdown can release flammable gases, causing severe explosions or fires. These explosions can be so intense that even the primary fire extinguishing equipment in the vehicle may not be able to cope with them.

When lithium-ion batteries overheat or thermally decompose, toxic gases such as hydrogen fluoride and other harmful chemicals are released. These can not only increase the risk of fire, but also negatively affect the health of people near the vehicle, especially in conditions of delayed evacuation during an accident.

Once a battery catches fire, there is a possibility of it catching fire again. Batteries that have survived the first stage of the fire may continue to burn or explode, even if firefighting efforts have been focused on extinguishing other parts of the vehicle. This may be caused by increased temperature or prolonged oxidation of battery materials.

Measures to reduce the risk of battery damage during an accident: improving battery design; making stronger battery cases that can withstand shock and mechanical damage is one way to reduce the risk of battery damage during an accident; Using more protective materials for battery containers can reduce the chance of moisture or foreign matter entering the battery, which can damage the battery. Thermal protection systems: Modern batteries are equipped with active cooling systems or temperature control systems that help prevent overheating. This can include liquid cooling systems or air cooling that automatically activate when the temperature rises.

Fire suppression in case of battery damage. Modern safety systems include fire extinguishers and other methods of fighting battery fires that are automatically activated when the threat of overheating or ignition is detected. They can prevent the spread of flames and ensure the safety of passengers.

Engineering solutions for explosion prevention: Built-in safety valves or special shells in batteries can help prevent explosions. For example, using materials that can withstand high temperatures without structural failure reduces the risk of explosion in a fire or accident; improved infrastructure for emergency response; The creation of appropriate infrastructure measures, such as specially trained rescue services, training personnel to handle electric vehicles in emergency situations, and the use of special tools to safely remove burnt batteries from the vehicle, can significantly increase safety in accidents involving electric vehicles. These

measures help reduce the risks associated with battery damage and their impact on the safety of drivers and passengers in the event of accidents [36].

**Analysis of statistics and fire incidents based on research**

Incidents involving batteries in electric and hybrid vehicles that catch fire or explode have drawn attention to the safety issues that arise from the use of new technologies, particularly lithium-ion batteries. Since such incidents often have serious consequences for human health and the environment, they have highlighted the importance of developing safe and reliable systems for electric vehicles.

Some of the most famous incidents that have occurred with electric and hybrid vehicles are: Tesla Model S (2013) - fire after a road accident, date of incident: 2013. One of the first major incidents occurred with a Tesla Model S after an accident, when the car hit metal debris on the road, which damaged its battery. As a result, a fire broke out. However, it is important to note that the Tesla Model S was equipped with a system that disconnected power to the battery after damage, and firefighters were able to quickly extinguish the fire. The aftermath of the incident has drawn much attention to the safety of batteries and battery systems in electric vehicles, but Tesla has continued to improve the safety of its models. The company has since conducted extensive testing and upgrades to its safety features to reduce the risk of battery fires.

Nissan Leaf (2018) — charging station fire, incident date: 2018. A fire broke out at a charging station in Japan where a Nissan Leaf was being charged. The fire was caused by a short circuit in the charging cable that was transmitting power to the vehicle. The incident posed a risk of fire, but the rapid response of staff prevented a major incident. Implications: The incident highlighted the need for regular maintenance of charging stations and the development of more effective protection systems to prevent short circuits and overheating.

BMW i3 (2019) — car showroom fire, incident date: 2019. A fire broke out at a BMW showroom in Germany, where several electric cars were stored. The fire started in one of the cars, causing a large-scale fire that spread to other cars. The cause of the fire was a malfunction in the battery of one of the cars. Consequences: BMW has taken measures to improve battery safety and cooling systems, and has also drawn attention to the importance of storing cars with batteries in special fire-resistant rooms.

Chevrolet Bolt EV (2020) - fire due to a battery defect, date of incident: 2020. In 2020, General Motors (GM) announced a recall of more than 68,000 Chevrolet Bolt EVs due to a battery defect that can lead to a short circuit and fire. The problem was related to a defect in one of the battery cells, which caused several cases of cars catching fire while charging. The fallout: GM conducted a major overhaul of its vehicles, changed battery suppliers, and updated Bolt models with new, more rigorously tested batteries. It also raised questions about the reliability of battery packs in mass production.

Tesla Model X (2017) — fire due to short circuit in the battery, incident date: 2017. During one of the incidents with the Tesla Model X, a fire broke out due to a defect in the battery, which led to a short circuit. The fire spread quickly, but thanks to the efforts of rescuers and the thoughtful design of the car, the further spread of the fire was stopped. This incident contributed to improving the safety system at Tesla, including improved thermal protection and changes in the design of the batteries, and also highlighted the need to improve the temperature control and intrinsic safety of the batteries. Hyundai Kona Electric (2020) — fire due to defects in the batteries, incident date: 2020. In 2020, several cases of fires were recorded in the Hyundai Kona Electric due to defects in the batteries, which led to overheating of the battery and fire. In one incident, the fire spread after a parked car, causing significant damage. Hyundai immediately announced a recall of some batches of the cars to replace defective batteries and conducted additional safety tests.

Tesla Model S (2021) - fire due to overloading the charging system, incident date: 2021. In 2021, a Tesla Model S caught fire as a result of an overload in the electric charging system, which caused a short circuit in the battery. The fire started during charging, but thanks to the

car's protective systems, it did not spread to other components. Tesla has continued to improve its charging systems and has taken measures to reduce the likelihood of similar incidents in the future.

Such incidents show the importance of rigorous safety tests in the development stages of battery systems for electric and hybrid vehicles. Battery safety advances: Car manufacturers, including Tesla and GM, continue to improve their batteries, working on thermal protection, cooling systems, and battery stability. Increased focus on infrastructure: Launching new charging stations and improving charging infrastructure for electric vehicles is also an important step in reducing the risk of fires. The need for recalls and corrections: Recalling vehicles and their batteries when defects are found is an important measure to reduce the risk of major incidents. These incidents highlight the importance of safety in electric and hybrid vehicles and how they can affect the future development of the industry.

**Fire statistics compared to traditional cars**

Comparing fires in electric, hybrid and conventional vehicles is an important part of the safety risk analysis in the automotive industry. On the one hand, electric vehicles (EVs) are considered safer in the context of some types of accidents, but they have other specific risks related to batteries, electrical systems and charging devices. On the other hand, traditional gasoline or diesel vehicles have their own characteristics, such as the risk of fire due to fuel leakage or damage to the fuel system.

Fires in electric vehicles usually occur for several main reasons, including battery damage, overheating of electrical components, short circuits or defects in charging systems. Lithium-ion batteries have a high energy density and their damage or overheating can lead to fire or even explosion. However, such incidents are less common than fires in conventional vehicles.

Statistics: According to studies and reports, such incidents are generally fewer compared to conventional vehicles. For example, there are fewer than 25 fires per million electric vehicles, while the rate for conventional vehicles can be much higher, at more than 1,500 per million vehicles per year. Most fires in electric vehicles are battery-related, and while these incidents can be more intense and dramatic due to the nature of the explosions, they are less common than fires in internal combustion engines (ICEs).

Conventional gasoline or diesel vehicles are more likely to catch fire due to fuel leaks, overheating, or failures in the fuel system, electrical wiring, or braking systems. Technically, internal combustion, especially in older models, can cause fires when fuel leaks or components overheat.

Statistics: According to national fire safety and incident statistics in the United States, conventional vehicles cause about 170,000 fires per year, which is 30-50 times more than for electric vehicles. Fires in such cars often occur due to problems in the fuel system, burnt electrical wires, or short circuits in the engines.

Fires in electric vehicles, although rarer, can be more dramatic due to the high risk of battery explosions and the difficulty of extinguishing a fire due to the large amount of energy contained in the battery. However, due to the limited number of such incidents and the rapid pace of technological improvement, the risk to drivers and passengers is decreasing.

Traditional vehicles: Fires caused by fuel leaks or other malfunctions can spread quickly due to the high flammability of fuel and fuel components, which increases the frequency of fires in traditional vehicles. This includes the risks of ignition due to failures in the fuel system, engine or exhaust systems.

Technical features that reduce the risk of fires in electric vehicles: Modern electric vehicles are equipped with special safety systems that minimize the risks of short circuits and overheating, including automatic overload cut-offs and built-in thermal protection systems for batteries. In addition, metal battery cases and protective mechanisms to prevent battery damage also help reduce the likelihood of fires after accidents or other emergencies.

Safety trends: Given that electric vehicles are a new type of transport, the frequency of their fires is decreasing every year due to continuous technological improvements. Investments

in the safety of batteries, charging systems and other electrical components contribute to reducing risks.

Traditional cars are also gradually becoming safer through improved designs of engines, fuel systems and other critical components, as well as the use of safer materials in production.

Current trends: One important trend is the development of global safety standards for electric and hybrid vehicles, such as ISO 26262, which specifies requirements for the safety of electronic systems. This reduces the likelihood of fires and other serious incidents. The development of charging infrastructure is also becoming increasingly important, as it should ensure proper safety when charging electric vehicles, minimizing possible risks from overheating or short circuits.

Fires in electric vehicles occur much less frequently than in traditional vehicles, although their nature can be more intense due to battery explosions. Traditional gasoline and diesel vehicles have a higher frequency of fires due to fuel leaks, problems with fuel and electrical systems. Safety technologies are constantly improving, which reduces the risk of fires in both types of vehicles.

The development of charging infrastructure for electric vehicles and improvements in battery and electrical system designs will contribute to a further reduction in the number of incidents.

It is known that in electric and hybrid vehicles the main energy elements are traction batteries (as in conventional cars - a fuel tank). During charging of these batteries, lithium ions move through the electrolyte and are introduced into the crystal lattice of graphite on the anode, forming a lithium graphite compound LiC6. During discharge of a lithium-ion battery, the reverse technological process occurs - lithium ions move from the anode to the cathode (oxidant), electrons move in the external circuit to the cathode. As a result, the process becomes electrically neutral [2]. The scheme of operation of a lithium - ion battery is shown in (fig. 10).

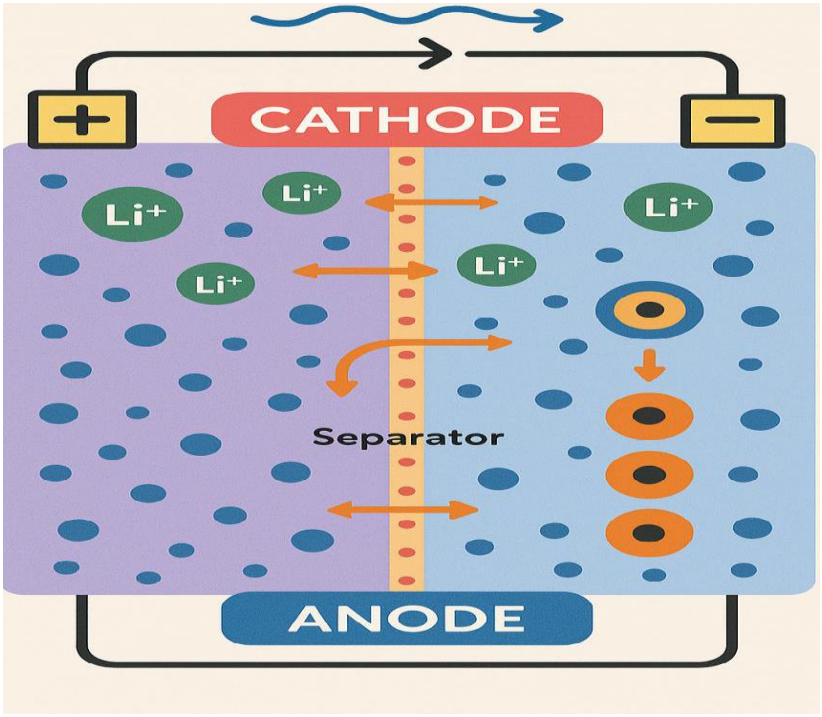



**Fig. 10.** Diagram of the operation of a lithium-ion battery

In Figure 1 we see how on the negative electrode surface of the carbon matrix, as a result of significant overcharging of the battery, metallic lithium (in the form of a finely divided mossy precipitate) is deposited, which has a high reactivity to the electrolyte. On the positive electrode (Fig. 1 and 2) we see the beginning of active oxygen release inside the battery, which caused intense heat release, pressure increase, depressurization of the battery and its ignition (fig. 11).

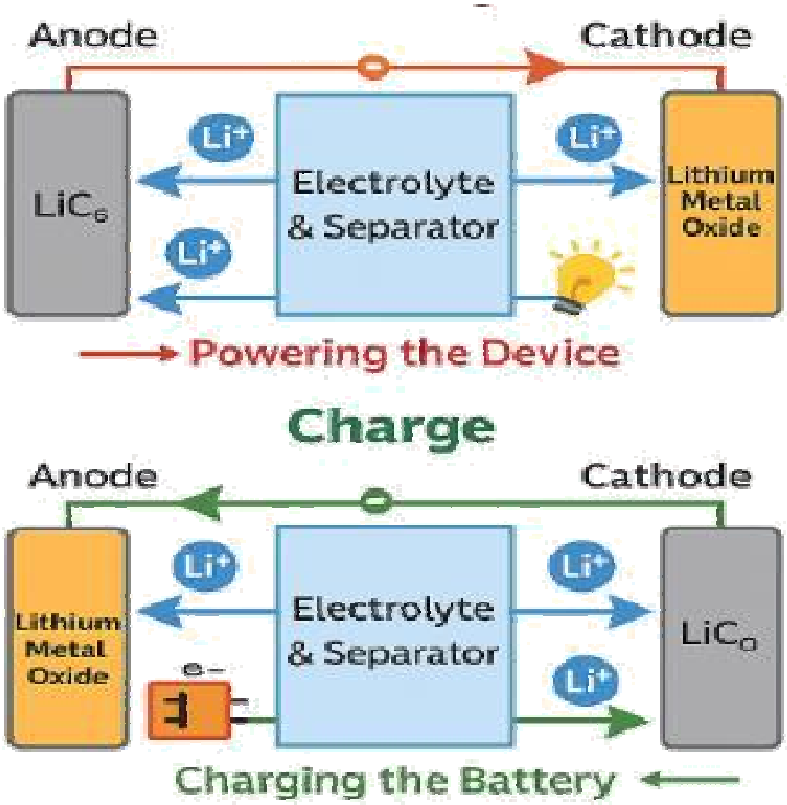



**Fig. 11.** Lithium-ion battery discharge and charge diagram

When a battery supplies power to a device (such as a smartphone or electric car), the following occurs: Anode (left) — usually made of graphite ($LiC_6$) that stores $Li^+$ ions. During discharge: $Li^+$ ions leave the anode, they travel through the electrolyte to the cathode. At the same time, electrons ($e^-$) leave the anode and travel through an external circuit, creating an electric current that powers the device. Cathode (right) — usually made of a metal oxide, such as $LiCoO_2$: accepts $Li^+$ ions and electrons that come in separate ways. The bond is formed: $Li^+ + e^- + CoO_2 \rightarrow LiCoO_2$. Result: Current is supplied to the device. A chemical reaction occurs that gradually reduces the battery's charge.

Charge Process — This is when a battery is charged by an external energy source, such as a charger. What happens: An external source pushes electrons ($e^-$) from the cathode through an external circuit to the anode. At the same time, $Li^+$ ions leave the cathode and pass through the electrolyte to the anode. At the cathode: $LiCoO_2 \rightarrow CoO_2 + Li^+ + e^-$

— that is, a lithium ion and an electron are released. At the anode: $Li^+ + e^- \rightarrow LiC_6$ — the ions and electrons are again stored in the graphite of the anode. Result: the ions and electrons return to the anode. The battery regains its charge and is ready for reuse.

**Tabl. 4**. Key components

| Components | Functions |
|---|---|
| Anode | Gives off lithium ions during discharge, accepts during charge |
| Cathode | Accepts lithium ions during discharge, gives off during charge |
| Electrolyte | Allows movement of $Li^+$ ions between electrodes |
| Separator | Insulates anode and cathode but allows ions to pass |
| Electrons ($e^-$) | Move through external circuit, creating current |

A serious danger is posed by burning metallic lithium (chemical symbol - Ar, chemical element of the 18th group of the third period of the periodic system of L. I. Mendeleev, with atomic number 18, a simple substance, an inert monatomic gas without color, taste and odor, is

the third most common chemical element of the air of the Earth's atmosphere (after nitrogen and oxygen) - 0.93% by volume.

To effectively extinguish lithium, the use of conventional fire extinguishing agents (water, chemical foam, carbon dioxide, halogenated hydrocarbons, etc.) only increases its burning and leads to an explosion. At temperatures above + 950 ° C, lithium quickly destroys glass, quartz, concrete, refractories, reacts with sand.

Lithium burns in an atmosphere of nitrogen and carbon dioxide without oxygen. It is impossible to extinguish a lithium flame with powder fire extinguishers, it is better to use fire extinguishing compositions PS-1 and PS-2, however, in many instructions they are mistakenly recommended for extinguishing alkali metals. Burning lithium can be effectively extinguished by displacing air from the combustion chamber with argon - this is the best way to extinguish the (fire 12).

Considering the pores of the separator of a lithium-ion battery (Fig. 3), we see the formation of an environment in the form of confined space elements, for example, balls, which may contain an inert gas, for example, argon, under atmospheric pressure. The shell of the confined space elements is made of a low-melting material, and the pores of the separator are made larger in size than the dimensions of lithium ions [4].

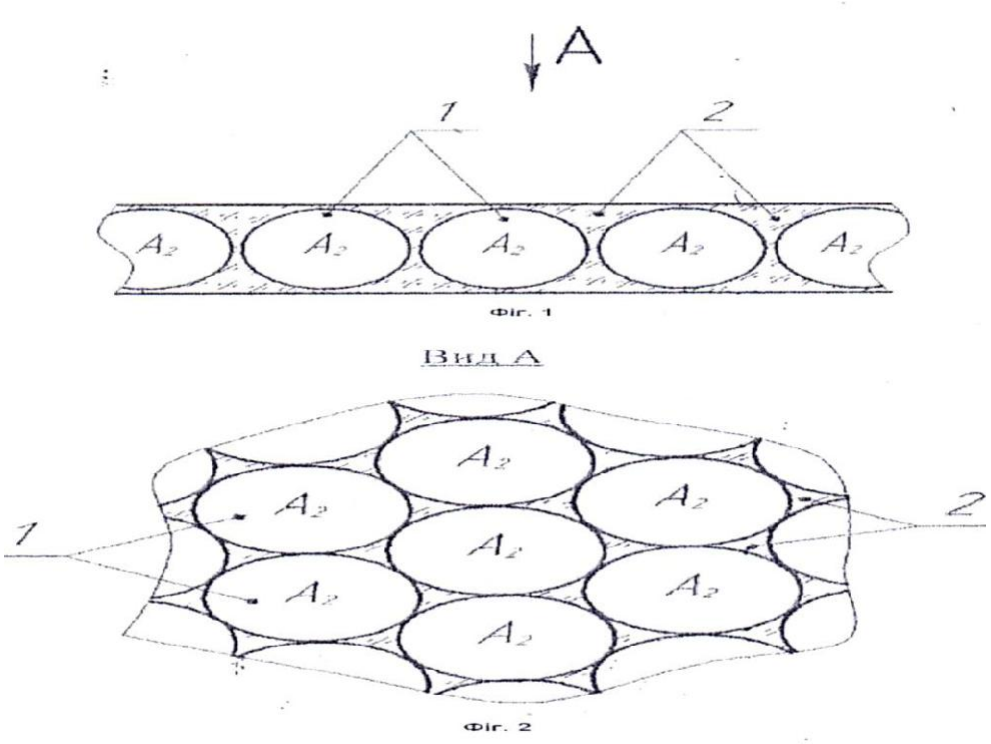



**Fig. 12.** Li-ion battery protection scheme: 1– Ar-argon balls; 2– separator pores

Inside the lithium-ion battery, an exothermic reaction occurs with the release of heat, and when the temperature reaches +180 or +2000C, the cathode material reacts with the release of oxygen, which leads to spontaneous combustion of the flammable mixture. Thus, balls 1 (2 - separator pores) are used for fire extinguishing, due to the destruction of their shell under the influence of high temperature, it collapses and inert gas - argon enters (Fig. 3). Internal short circuit, this is one of the causes of a lithium-ion battery fire. Inside the battery, the temperature rises from +70 to +900C, while the ion-conducting protective layer on the anode begins to decompose and collapse. At the same time, the lithium, which is embedded in the anode, enters into a violent reaction with the release (formation) of carbon-hydrogen compounds consisting of: ethane, methane, ethylene, which represent an explosive mixture, and which has not yet ignited due to the lack of oxygen.

Inside the lithium-ion battery, an exothermic reaction occurs with the release of heat, and when the temperature reaches +180 or +2000C, the cathode material reacts with the release of oxygen, which leads to spontaneous ignition of the flammable mixture. Thus, balls 1, (2 -

separator pores) are used for fire extinguishing, as a result of the destruction of their shell under the influence of high temperature, it collapses and inert gas - argon enters (Fig. 3). This technical solution is protected by the patent of Ukraine for utility model No. 127742 “Lithium-ion battery”.

We have found an even better technical solution for the safety of a lithium-ion battery, which is its increased protection against self-ignition and even from the confined elements of the separator space, i.e. the balls due to the destruction of their shell under the influence of high temperature, which increases in the internal space of the battery, and inert gas, for example argon, which is in the elements of the confined space - into the balls under above atmospheric pressure, enters. As a result, the internal space of the battery is filled with inert gas, argon, even before the appearance of oxygen, i.e. when the temperature already reaches +180 or +2000C and the cathode material embedded in the lithium crystal reacts with the release of oxygen. In this case, the filling of the internal space of the battery with an inert gas - argon occurs before the conditions for self-ignition and explosion of the fire-hazardous mixture of the lithium-ion battery in the form of ethane, methane, ethylene compounds are formed, and, thus, the battery is reliably protected from self-ignition and explosion, i.e., its fire safety is increased [5].

Also, this technical solution is combined with the patent of Ukraine No. 143615 for the utility model “LIIIII-ION BATTERY OF INCREASED PROTECTION”.

In the conclusions, it can be stated that preventing the explosion and fire of a lithium-ion battery is possible only in the presence of the proposed technical solutions of the National Academy of Sciences of Ukraine provided in these theses, as well as when following the instructions for their operation. Lithium-ion batteries, when overcharged and not charged, have a deposition of metallic lithium (in the form of a finely divided mossy sediment), which is dangerous and provokes the occurrence of a short circuit, fire or explosion in it.

In order to avoid these negative factors, the proposed protection of lithium-ion and other types of batteries will be established around the clock at the stage of their manufacture and introduction to consumers.

**Using modern technologies to reduce the risk of fires**

As electric and hybrid vehicles become increasingly popular, the safety of their systems, particularly their batteries, is an important aspect of the industry. Technologies being used to reduce the risk of fires include innovations in battery design, safety systems, and cooling and monitoring technologies. Battery thermal protection and cooling systems. Batteries in electric and hybrid vehicles have a high energy density, which makes them prone to overheating, which in turn can lead to fires. However, there are technologies aimed at maintaining optimal battery temperatures, which significantly reduces the risk of overheating. Cooling systems: The use of liquid or air coolers allows for a stable battery temperature. They help maintain the battery temperature at a safe level, even during intensive use or rapid charging. Some manufacturers use special thermal circuits or channels to distribute heat throughout the battery to avoid overheating individual battery cells. Intelligent thermal management systems: These systems use temperature sensors to monitor and adjust the battery temperature, thereby preventing overheating.

Short circuit and overload protection mechanisms. Short circuits and overloads are one of the main causes of fires in electric vehicle batteries. To combat these threats, technologies have been developed that automatically disconnect the battery or power supply system when potentially dangerous situations arise. The use of relays and circuit breakers allows you to quickly disconnect power from the battery in the event of a short circuit or other malfunction. This minimizes the likelihood of fire or explosion. The use of insulating materials that prevent the spread of short circuits is an important part of the design of batteries. This reduces the likelihood of overheating and fire. The battery management system (BMS) is the heart of battery safety in electric vehicles. It constantly monitors the condition of the battery, including temperature, voltage and capacity, to prevent possible dangerous situations. The BMS system monitors the condition of each battery cell, detecting potentially dangerous situations such as overvoltage or

temperature. It can automatically reduce power or disconnect the battery if necessary. If problems are detected, the BMS can disconnect the battery from the rest of the vehicle's systems to prevent further damage or fire.

Protection technologies against mechanical damage In the event of an accident or other mechanical damage, batteries can be seriously damaged, which can cause a fire. To reduce the risks, special protective technologies have been developed that protect battery packs from physical damage. Armored battery cases: Batteries are often placed in armored cases that can withstand impacts and protect against the penetration of foreign objects. In the event of an accident, vehicles can be equipped with systems that automatically disconnect the battery from the rest of the electrical system to minimize possible risks.

The use of new materials for the production of batteries helps reduce the risks associated with fire or explosions. Given the high risk of fire due to malfunctions in lithium-ion batteries, some companies are introducing new chemical formulas or protective electrolytes that reduce the likelihood of overheating or explosion. Switching to solid-state batteries, which do not contain liquid electrolytes, can significantly reduce the risk of fire, as these batteries are more stable and less prone to overheating.

Fire and explosion protection: Additional technologies related to fire suppression include new materials used to fight fire, as well as automatic extinguishing systems. Installing systems that automatically detect and extinguish fires in batteries or electrical systems can significantly reduce the potential for damage from fire. The use of fire-resistant materials in the construction of a vehicle and in its battery systems helps minimize the spread of fire, if one does occur.

To reduce the risk of fire when charging electric vehicles, special standards have been developed for charging stations. Charger safety: The use of protection systems against overvoltage, temperature drops and overheating in charging stations is an important element of ensuring safety when charging electric vehicles. If charging problems are detected, the system automatically stops the energy supply to prevent the risk of fire.

Conclusions: Modern technologies to reduce the risk of fire in electric and hybrid vehicles focus on the development of new battery systems, improved safety systems, cooling and protection mechanisms against short circuits and overheating. The use of such innovative solutions helps not only reduce the likelihood of fires, but also contributes to increasing the reliability and durability of electric vehicles.

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За контакти:
[1] Bazhinov Olexey, Prof., doct. texn. nauk, Kharkiv National Automobile and Highway University, Ukraine, phone 80983379445, e-mail: alexey.bazhinov@gmail.com

# ВЛИЯНИЕТО НА СМЕСЕНИ БЕНЗИНИ ВЪРХУ ЕМИСИИТЕ НА ВРЕДНИ ВЕЩЕСТВА В ОТРАБОТЕНИ ГАЗОВЕ НА ПРЕВОЗНИТЕ СРЕДСТВА

# THE EFFECT OF BLENDED GASOLINES ON EMISSIONS OF HARMFUL SUBSTANCES IN VEHICLE EXHAUST GASES

**Volodymyr Bezridnyi**

**Abstract.** The use of mixed gasolines is a topical issue at the moment. This makes it possible to reduce the costs of producing such gasoline and improve the environmental performance of cars. To produce ethanol, which is used for mixing with gasoline, any products that undergo fermentation can be used. These are agricultural waste, various household food waste. Traditionally, ethyl alcohol in industrial conditions is obtained from grain, sugar beet molasses (waste from sugar production), sugar beets and potatoes. Ethyl alcohol is divided into food ethyl alcohol and technical ethyl alcohol.
**Keywords**: car, emissions of harmful substances, toxicity of exhaust gases, gasoline, ecology

## 1. Introduction:

The global fuel crisis, which caused the prices of gasoline and diesel to jump, is once again making us think about other energy sources for vehicles. A good alternative to traditional fuel is alcohol. Alcohol has a number of advantages compared to petroleum fuel, and only its high cost, low heat dissipation, high hygroscopicity and high aldehyde content prevent its widespread use as a fuel for internal combustion engines. The advantages of alcohol include the following:

- high anti-knock properties (octane number - over 100). The introduction of ethanol into gasoline provides an increase in the octane number. Every 3% of ethanol in a mixture with gasoline provides an increase in the octane number of fuel by an average of 1 unit. That is, alcohol can be used as a high-octane additive to fuel. It also increases the detonation resistance of fuel, since the autoignition temperature of pure gasoline is 290 ° C, and its mixture with ethanol - 425 ° C;
- the evaporation process begins in the intake manifold and ends in the cylinder during the compression stroke, ensuring cooling of engine parts - pistons and valves - and more complete filling of the cylinders with a fresh charge (compressor effect with a 5 percent increase in power);
- reliable ignition from an electric spark with significant changes in the composition of the combustible mixture (the flammability range by the excess air coefficient for alcohol is approximately 0.4 ... 1.7);
- the efficiency of an engine running on pure alcohol is higher than when using gasoline;
- lower toxicity of exhaust gases;
- low fire hazard.

There are two ways to use alcohol as fuel for automobile engines - with partial (up to 30%) and complete replacement of gasoline and diesel fuel. High anti-knock qualities determine the preferential use of alcohol in internal combustion engines with forced (spark) ignition. A standard engine does not need to be modified to run on a gasoline-alcohol mixture.

According to the results of bench tests, the use of A-95E gasoline with a 5 percent alcohol content does not lead to a deterioration in the vehicle's performance and does not require changes to the engine's initial settings.

But to run on pure alcohol, it is necessary to increase the fuel tank capacity and compression ratio to 12 - 14 units (to fully use the fuel's detonation resistance) and reprogram the injection engine ECU. The combustible mixture must be enriched: 9 kg of air is required for the combustion of 1 kg of alcohol, and 14.93 kg for the combustion of 1 kg of gasoline.

**2. Description:**

The idea of using alcohol as fuel is not new. Brazil has the richest experience in its use in internal combustion engines. After the world oil crisis of 1973 - 75, this country adopted the "Ethanol-based fuel" program in the early 80s. As a result, by the end of the last century, ethanol was replacing up to 250,000 barrels of imported oil every day. In the 1990s, ethanol fueled more than 7 million cars in Brazil, and its blend with gasoline (gasohol) fueled another 9 million. Ethanol in this country is made from sugar cane and sold through a network of 25,000 filling stations. [1] The second world leader in the use of ethanol in motor vehicles is the United States. It also has a program to replace gasoline with alcohol, which is obtained by processing surplus corn and other grain crops. Pure ethanol in this country is used as fuel in 21 states, and the benzoethanol blend accounts for 10% of the US fuel market.

Previously, interest in using more expensive ethanol ($ 60 per barrel) as a motor fuel abroad was due to tax breaks. In the USA, they compensate sellers for losses if they sell ethanol at the price of gasoline. Now, after the jump in oil prices ($ 75 - 80 per barrel), taking into account the processing of raw materials to obtain gasoline, the cost of these fuels has almost equaled. Therefore, the use of alcohol has turned out to be even more appropriate. [2]

The use of alcohol as a fuel has also received support in some European countries - in particular, France and Sweden. On November 7, 2001, two EU commissions adopted the so-called bio-directives on the use of biofuels in the European Union countries. They provide for the mandatory use of this fuel as an additive to gasoline in the future.

In Ukraine, government programs have also been developed for the use of alcohol as an additive to gasoline.

At the end of June 2000, the Government Committee on Reforming the Agrarian Complex and Environmental Problems approved the draft state program "Ethanol: 2000 - 2010", as well as the "Program of State Support for the Development of Non-Traditional and Renewable Energy Sources and Small Hydro- and Thermal Power Generation", developed in accordance with the Decree of the President of Ukraine No. 285 of April 2, 1997. The Cabinet of Ministers of Ukraine approved the "Ethanol" program by Resolution No. 1044 of July 4, 2000. The document provides for the accelerated conversion of approximately a third of the vehicle fleet to gasohol and ethanol. [2]

Resources for ethanol production in our country are practically inexhaustible: from agricultural waste, mainly beet growing, and the processing of imported raw cane sugar, more than 5.5 million decalitres of ethanol and 300 - 310 thousand decalitres of technical alcohols are produced annually. The capacities of Ukrainian enterprises allow producing 66 million decaliters of such alcohols per year. In mid-June 2004, Ukraine agreed with Cuba to increase barter (in exchange for industrial products) supplies of raw cane. According to Cuban experts, about 25% of this raw material can be used exclusively for the production of alcohol and alcohol-oil fuel. The Ethanol program provides, in particular, for the re-profiling of more than a third of the capacities of Ukrainian alcohol and related (sugar raw material processing) plants for the production of high-octane oxygen-containing additives to gasoline and technical alcohol - mainly from agricultural raw materials. Experts assess this as the most promising and economically profitable solution.

In the 70s of the 20th century, attempts began to reduce the harmful impact of road transport on the environment. It was then that the first regulations regulating the toxicity standards of exhaust gases came into force. Over the past 15 years, a significant reduction in harmful emissions has been achieved. This was facilitated by the introduction of new technologies, the progress of electronics and computer technology. The Euro toxicity standard determines the maximum content of all harmful substances in exhaust gases in grams per kilometer for internal combustion engines, in particular, for self-ignition engines installed in passenger cars. [3]

Today, the Euro 5 toxicity standard is used in Ukraine. This standard is even stricter in terms of the maximum content of harmful substances in exhaust gases.

To compare the toxicity of automobile exhaust gases when using A-92e TURBO gasoline, obtained from petroleum raw materials, and gasoline containing 50% bioethanol, special laboratory studies were performed.

To perform the experimental part, a Skoda Octavia 2003 model, a mobile station for diagnosing the technical condition of passenger cars PDS-1, and a BOSCH FSA-760 motor tester were used.

The motor tester is modern equipment. It allows for comprehensive diagnostics of engine operation. It also has a gas analyzer.

The research was conducted in the testing laboratory of the Department of Technical Operation and Service of Automobiles of the Kharkiv National Automobile and Road University.

The content of toxic substances in engine exhaust gases primarily depends on the condition and adjustment of the power supply and ignition system devices, as well as on the general technical condition of the vehicle and the operating modes of the internal combustion engine. Engine load also affects the toxicity of exhaust gases.

The research was conducted as follows. According to DSTU 4277:2004, the measurement of exhaust gas toxicity was carried out at idle speed, crankshaft rotation of about 800-850 min-1. And then, also according to DSTU at increased crankshaft speed, 0.8 max, 3500-4000 min-1.

Next, the measurement of exhaust gases was carried out by increasing the crankshaft speed by 1000 min-1. The last measurement was carried out at crankshaft rotations at 5000 min-1. This crankshaft rotation is the maximum for this car, according to factory recommendations.

After each measurement, the exhaust gas sampling hose was removed and blown from the compressor to reduce measurement errors.

During the research, the engine temperature was checked, because during the tests the car was not moving and the engine could overheat.

After checking the toxicity of the exhaust gases on petroleum gasoline, the gasoline was drained from the tank. Then biofuel was poured, the engine ran on biofuel for several minutes to adapt it to the second fuel. Only then did the following research begin.

When performing work under the same conditions, measurements were taken of the content of CO and hydrocarbons in the exhaust gases of a car running on petroleum gasoline and a mixture of petroleum gasoline with ethanol, which was obtained from plants in a ratio of 1:1.

The results of the research are given in Tables 1, 2.

**Table 1.** Change in CO and CnHm concentration at idle

| Bench test modes | | A-92 | | A-92e TURBO | |
|---|---|---|---|---|---|
| | | CO, % | CnHm , $mln^{-1}$ | CO, % | CnHm , $mln^{-1}$ |
| Idle speed, $min^{-1}$ | 850 | 0,07 | 25 | 0,02 | 18 |
| | 1000 | 0,06 | 12 | 0,02 | 10 |
| | 2000 | 0,05 | 7 | 0,02 | 6 |
| | 3000 | 0,04 | 4 | 0,01 | 4 |
| | 4000 | 0,03 | 1 | 0,01 | 0 |
| | 5000 | 0,01 | 1 | 0,01 | 0 |

**Table 2.** Change in CO and CnHm concentration at idle

| Test modes | Limit values according to DSTU 4277: 2004 (for vehicles equipped with catalytic converters) | | A-92 | | A-92e TURBO | |
|---|---|---|---|---|---|---|
| | CO, % | CnHm, $mln^{-1}$ | CO, % | CnHm , $mln^{-1}$ | CO, % | CnH,m $ln^{-1}$ |
| $n_{min}$ 800±50 $min^{-1}$ | 1,0 | 600 | 0,07 | 25 | 0,02 | 18 |
| $n_{max}$ 3500-4000 $min^{-1}$ | 0,6 | 300 | 0,03 | 1 | 0,01 | 0 |

## 3. Conclusions:

The production of gasoline with ethanol is an important moment in the economy of Ukraine and the world as a whole. This leads to saving world oil reserves and improving the environmental situation. Since when using such gasoline, emissions of harmful substances in exhaust gases are significantly reduced. In Ukraine, from May 1, 2025, a mandatory ethanol content of at least 5% in gasoline is introduced..

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Contacts: Bezridnyi Volodymyr, Assistant, Senior Lecturer. Kharkov National Automobile and Highway University, Department “Technical operation and service vehicles”, Yaroslava Mudroho str. 25, Kharkov, Ukraine, Tel.: +380577073768. E-mail: rostik405220@gmail.com

# ГРЕШКИ ПРИ ДИАГНОСТИКА НА АВТОМОБИЛНИ АМОРТИСЬОРИ

# ERRORS IN DIAGNOSING CAR SHOCK ABSORBERS

**Alexander Dityatiev**

**Abstract.** Safety is one of the most important operational properties of a car, which is realized through stability, controllability, and reliable contact of the tire with the road. During operation with wear and tear, the parameters of the suspension, including the shock absorber, deteriorate, and both safety and comfort are reduced. This leads to the need to periodically monitor the condition of the shock absorbers using diagnostics. Diagnostics by definition involves testing without disassembling. However, when testing the assembled suspension, the shock absorber test report contains an error due to the influence of other suspension components, for example, sprung and unsprung masses, rigidity (internal pressure) in the tire. If the error is significant, it can provoke a diagnostic error. A diagnostic error of the first kind can contribute to recognizing a serviceable shock absorber as faulty, and as a result of the presence of an error of the second kind - to recognize a faulty shock absorber fit for operation. Different methods of diagnosing shock absorbers show different levels of errors. In this article, the error values from the influence of other factors, mainly from the tire rigidity, are determined using calculation methods when diagnosing shock absorbers using various methods.
**Key words**: shock absorber diagnostics, methods, accuracy, third-party factors, modeling, analysis.

## 1. Introduction:

The car suspension performs two most important functions - comfort and safety of movement. Comfort is ensured by the correct characteristic "speed - force" during the stroke of the rod during compression and recoil, and safety - by the stability of the tire contact with the road. The contact of the tire with the road is determined by the frequency characteristics of the suspension, in the formation of which an important role belongs to the shock absorber, its technical condition. During operation, the technical condition deteriorates, so it should be periodically checked by diagnostic methods. The diagnostic parameters are subject to requirements of accuracy, sufficient sensitivity, smoothness of change (without breaks), unambiguity, accessible implementation of the measurement process. The following are used as diagnostic parameters: "EuSAMA coefficient (ES coefficient [1]", unsprung mass oscillation amplitude at resonance (resonance method) [2], phase angle [3] and others. The task of determining the technical condition of the shock absorber without removing it from the vehicle ultimately comes down to the correct determination of the diagnostic parameter and formulation of the diagnosis.

A large set of diagnostic parameters and corresponding methods indicates the absence of a method that meets all the requirements, especially the requirement of accuracy [4-6]. The lack of accuracy is due to the influence of external factors that are not related to the technical condition of the shock absorber.

In a significantly simplified form, the amplitude of forced oscillations of the sprung mass A is equal to:

$$A = \frac{F_0}{m} \frac{1}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\xi\omega)^2}}, \quad (1)$$

where: F0,ω - is the amplitude and frequency of the force that changes;

m – masa;

ξ - suspension damping coefficient;

ω₀ - frequency of wild, non-extinguishing sounds.

$$\text{In turn,} \quad \omega_0 = \sqrt{(c/m)}; \quad \xi = 2r/m; \quad (2)$$

where: c – suspension stiffness;

r – support coefficient.

With the sprung mass in one oscillatory system there is an unsprung mass, the movement of which also depends on the parameters of the system and this movement is the initial value for most methods.

Taking into account formulas 1, 2, as well as the composition of the mass and stiffness of the suspension (stiffness of the tire and elastic device), we can conclude that the change in the mass of the sprung and unsprung parts and the change in the stiffness of the tire (internal pressure) are the main sources of errors in diagnosing the shock absorber. Thus, we are dealing with the error of the method - "the method of diagnosing the shock absorber in an oscillatory system (without disassembling)". However, different diagnostic technologies demonstrate different error values.

## 2. Presentation:

In this article, diagnostic errors are determined by calculation for some diagnostic methods using mathematical models based on systems of differential equations compiled on the basis of the d'Alembert - Lagrange principle. Modeling was performed in the MATLAB SIMULINK environment. Simulation modeling as a method in numerous studies has shown adequacy and efficiency [7].

### Diagnostic method – EuSAMA.

Determination of the error from the change in tire rigidity in the structure of the diagnostic parameter [8]. The diagnostic parameter is the ES coefficient, equal to the ratio of the vertical dynamic force to the static load on the wheel at high-frequency resonance.

The figure shows the dependence of the "ES coefficient" on the frequency of the excited vibrations for different tire rigidity 195/55 R15 86 T of the ŠKODA FABIA 1.6 car.

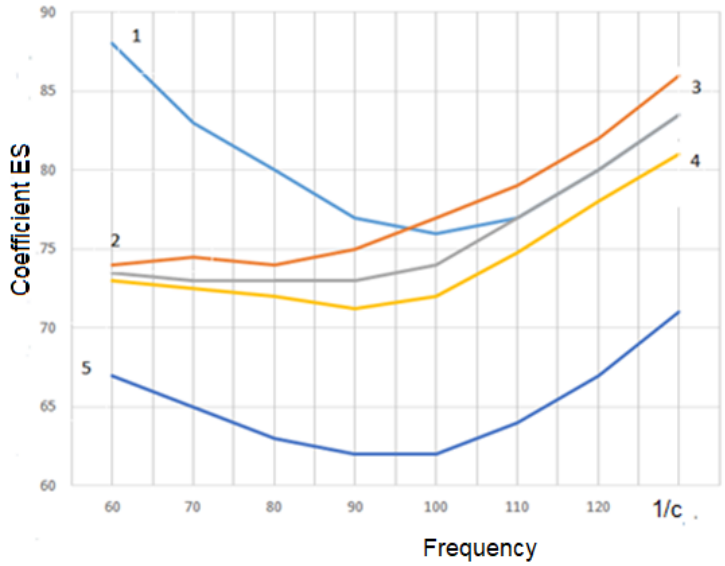



Fig. 1. Dependence of the "ES coefficient" on the frequency of forced oscillations for different calculated tire stiffness): 1 - experimental characteristic of the "ES coefficient", taken from the stand at with pressure in the tire рш = 210 kPa. Calculated characteristics: 2 - at $2c_2$ = 338 kN/m; 3 - at $2c_2$ = 353 kN/m; 4 - at $2c_2$= 373 kN/m; 5 - at $2c_2$= 448 kN/m (see table 1), [8].

**Table 1.** Correspondence of air pressure in a tire to its calculated stiffness

| Tire air pressure рш, kPa | Tire stiffness 2c2, kN/m |
|---|---|
| 200 | 338 |
| 210 | 353 |
| 220 | 373 |
| 280 | 448 |

Analysis of the obtained dependencies allows us to draw the following conclusions.

A decrease in tire pressure by 10 kPa (from 210 to 200 kPa - by 4.8%) leads to an increase in the "ES coefficient" by 5%. The error that appears corresponds to the same value. An increase in tire pressure relative to the recommended one by 10 kPa causes a decrease in the "ES coefficient" by 2.2%, which is comparable to the error of the calculation model. Finally, if the tire pressure is 280 kPa (an increase of 33.3%), this will lead to a decrease in the "ES coefficient" by 15.6% and, in addition, an increase in the error of the test result. The data were obtained at a high resonant frequency of 107 1/s.

**Resonance method in comparison with the EuSAMA method.**

Determination of relative errors [10].

The fundamental difference between the resonance method and the EuSAMA method is that the mass of the support platform and the elastic device of the platform are additionally introduced into the power structure of the stand that implements the method. This means that we have a three-mass dynamic system in which the vibration energy is distributed differently than in the two-mass EuSAMA, which contributes to obtaining qualitatively different results.

Due to the additional mass of the support platform and the elastic device of the platform, resonance in the system occurs in the region of 10 Hz and the amplitude of the platform vibrations increases to values determined by the properties that dampen the system, i.e. the absorbing properties of the shock absorber and the tire. The maximum amplitude of the platform vibrations is recorded by the stand and is further interpreted as a diagnostic parameter of the shock absorber state.

To determine the error from different values of air pressure in the tire, data from the SDL 260 BOSCH (EuSAMA) [9] and MSD 3000 MAXA (EUROSYSTEM) test stands were used. Data for the SDL 260 BOSCH test stand were obtained by calculation on two-mass models. Calculations were carried out for the resonant mode (at a high-frequency resonance frequency of ~ 100 1/s).

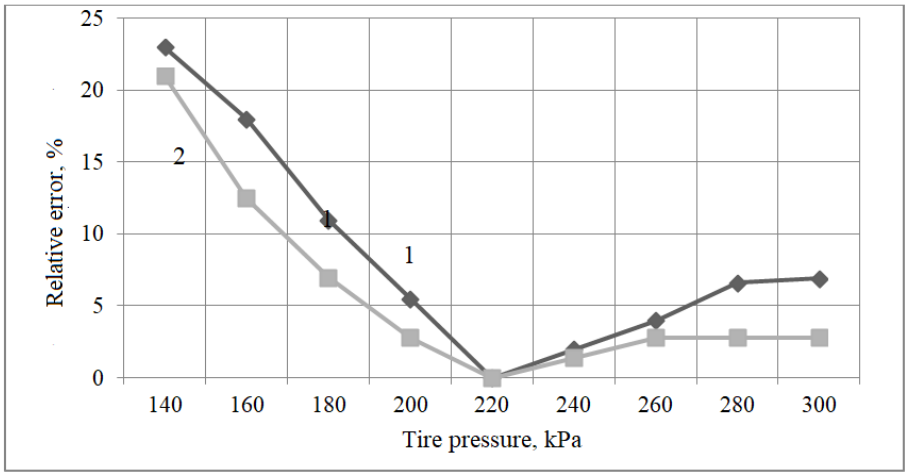



**Fig. 2.** Comparative characteristics of the relative errors of the stands at different tire pressures: 1 – MSD 3000 MAXA stand; 2 – SDL 260 BOSCH stand [10].

Figure 2 presents the curves of changes in the error of the stands when changing the tire pressure. The standard value is 220 kPa. When the pressure decreases (the left part of the diagram), the absolute values of the errors are negative in tests on the EUROSYSTEM stand and positive on the EuSAMA stand. When the tire pressure increases (the right part of the diagram), the opposite picture is observed. The average value of the relative error of this test on the EUROSYSTEM stand is 8.6%, for the EuSAMA stand 6.2%.

As follows from the figure, the “resonant” stand and the corresponding method are significantly inferior to the EuSAMA stand and method in the value of the error of the result when changing the tire pressure.

**EuSAMA method. Determination of error taking into account the mating wheel [11].**

Usually, EuSAMA diagnostics are performed by sequentially checking the suspensions of the left and right wheels. This means that when, say, the left wheel is loaded with harmonic oscillations, the right wheel is stationary. But the left and right wheels, connected by the anti-roll bar, are elements of the same oscillatory system and for this reason their oscillations are not independent. It is known from practice that the parameters of the suspension on the left and right are rarely the same, in other words, the influence of the untested wheel is generally unknown.

This article examines the influence of a stationary (non-tested) wheel on the diagnostic result of the suspension of the tested wheel of the same axle.

The parameters of the ŠKODA FABIA 1.6 with a front axle weight of 740 kg were used for modeling. The values of the range boundaries for the damping coefficient of the shock absorbers for a known load on the wheel (370 kg) were found by modeling with excitation of one side and in the absence of the anti-roll bar (Cst=0). Therefore, the known dependence of the suspension capacity assessment (ES coefficient) on the axle load [12] for a front axle weighing 740 kg has the following form (Table 2):

Table 2. Correspondence of ES coefficients and shock absorber damping coefficients with an axle load of 740 kg, [11]:

| Rating: upper end of the range: | EuSAMA coefficient, % | Shock absorber damping coefficient, N*s/m |
|---|---|---|
| "good" (Zone A) | 70+ | 1460+ |
| "sufficient" (Zone B) | 50 | 700 |
| "insufficient" (Zone C) | 30 | 430 |
| "bad" (Zone D) | 20 | 20 |
| "bad" (Zone E) | 0- | 0 |

For the given values of the ES coefficients of the tested or active wheel (in this calculation, the left one), the characteristics were taken at various values of the shock absorber resistance coefficient from 1460 to 110 N*m/s in the suspension of the passive (for certainty, the right one) wheel. Then the values of the ES coefficient were compared at the edges of each of the ranges (good, sufficient, etc.) and conclusions were made about the influence of the damping of the passive wheel on the diagnostic result of the tested one.

**Table 3.** ES coefficient values for different damping of the passive wheel, [11]:

| Damping coefficient on the passive wheel ψp | EuSAMA coefficient on the tested wheel at different damping coefficients ψa | | | | |
|---|---|---|---|---|---|
| | ψa = 1460 | ψa = 700 | ψa = 430 | ψa = 350 | ψa = 0 |
| 1460 | 72,5 | 49,6 | 29,41 | 19,78 | -82,8 |
| 1310 | 72,6 | 49,95 | 29,49 | 20,11 | -82,3 |
| 1160 | 72,6 | 50,02 | 29,62 | 20,32 | -81,5 |
| 1010 | 72,7 | 50,14 | 29,73 | 20,32 | -80,7 |
| 860 | 72,7 | 50,24 | 29,89 | 20,47 | -79,6 |
| 710 | 72,6 | 50,32 | 30,11 | 20,73 | -78,3 |
| 560 | 72,4 | 50,43 | 30,35 | 21,00 | -79,7 |
| 410 | 72,2 | 50,51 | 30,59 | 21,27 | -75,5 |
| 260 | 72,2 | 50,62 | 30,62 | 21,62 | -73,4 |
| 110 | 72,2 | 50,84 | 31,19 | 22,00 | -71,0 |
| Change in EuSAMA coefficient on the tested wheel, % | 0,97 | 2,50 | 6,05 | 11,22 | 14,25 |

Note: ψa – resistance coefficient of the shock absorber of the tested wheel;
ψп – resistance coefficient of the shock absorber of the passive wheel.

The following conclusions can be drawn from the results of the study.

As a component of the vibration system, the damping of the passive wheel during suspension diagnostics affects the result of testing the active wheel, thereby provoking the appearance of a corresponding error.

A decrease in damping on a passive wheel leads to an overestimation of the EUSAMA coefficient on the tested wheel. The exception is the case (column No. 2), when the suspension of the tested wheel (shock absorber) is in good technical condition, i.e. has good damping characteristics. In this case, a change in the damping coefficient over a wide range has an insignificant (up to 0.97%) effect on the result of the tested wheel. This change is essentially equal to the relative measurement error of the EUSAMA coefficient. The data in the table also indicate that with a decrease in the level of evaluation zones from A to D, the degree of influence of the passive wheel damping increases from 0.97 to 11.22% (the last column with the damping coefficient ψa=0 is not considered as a low-probability case in operation). This also means that the amount of loss increases with changes in the EuSAMA coefficient in the suspension of the wheel being tested, and with a EuSAMA coefficient that is higher than 22 (at rating “insufficient”), and also with a low damping coefficient of the passive wheel, it can become more than 11%.

**The phase angle method in comparison with the EuSAMA method [13].**

From the theory of dynamics of mechanical systems it is known that the phase of oscillations of the mass of the system is uniquely related to the damping coefficient, i.e. it can be a diagnostic parameter [5]. Calculation on the simulation model showed that the maximum sensitivity of the diagnostic parameter – the phase angle – for the suspension of the wheel of the ŠKODA FABIA 1.6 car is achieved in the frequency range of 10 … 13 Hz. Figure 00 shows the dependence of the phase angle on the tire rigidity.

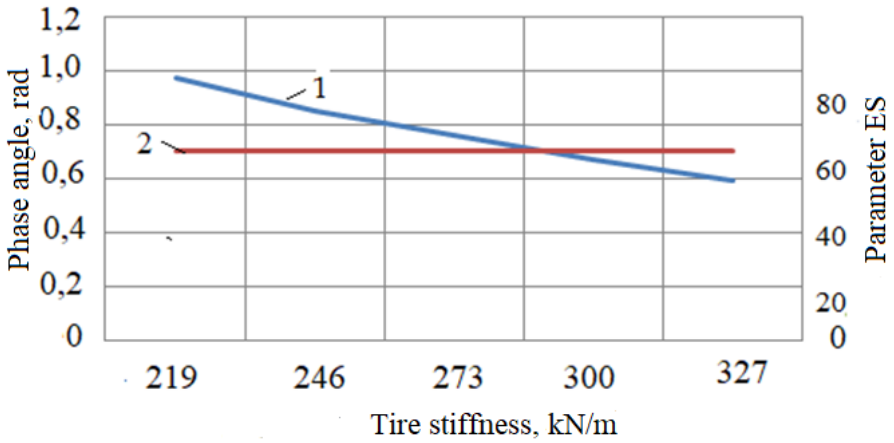



**Fig. 3.** Effect of tire stiffness on phase angle at an excitation frequency of 10 Hz.
1 – phase angle, 2 – parameter ES [13].

The effect of sprung mass on the magnitude of the phase angle is presented in Figure 8.

As follows from the figure, for changing the bus hardness by 10%, the phase speed changes by 11.4%. The diagnostic error increases by the same amount. The ES parameter at this frequency contributes insignificantly to the error.

The influx of the compressed mass on the value of the phase cut and the ES parameter shows different trends: with an increase in the unsprung mass, the phase cut increases, while the ES parameter changes with less fluidity. The rows are close to linear.

The expansion of the inflow by the value of the phase cut of the stiffness of the spring element of the suspension and the damping of the tire showed the absence of inflow.

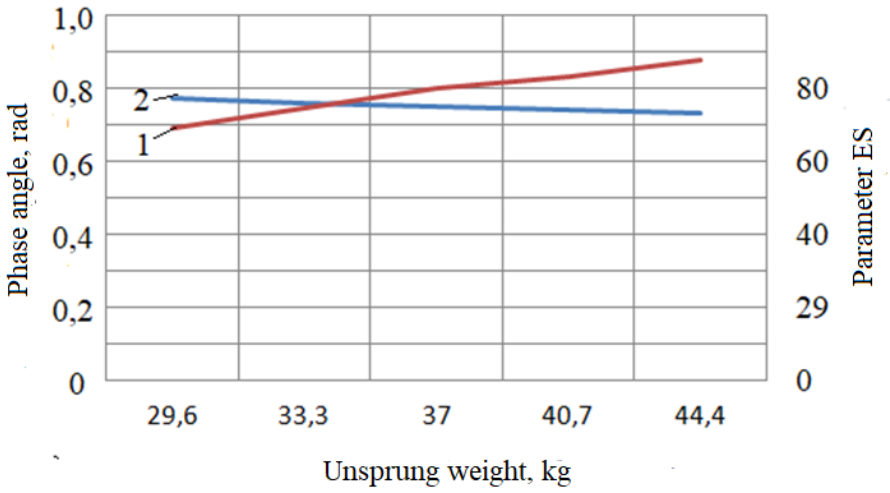



**Fig. 4.** Effect of the unsprung mass on the phase angle at an excitation frequency of 10 Hz:
1 – phase angle, 2 – ES parameter [13]

The amplitude of the input harmonic excitation of the wheel, the stiffness of the spring element of the suspension and the damping of the tire do not influence this diagnostic parameter and do not affect the errors of the diagnostic parameter.

## 3. Conclusion:

Despite the fact that the nature of the errors in shock absorber diagnostics is the same and consists of the action of the same factors, the errors in diagnostics by different methods differ significantly in absolute value. Here, the frequency ranges of suspension excitation during diagnostics play an important role - they are different for different methods. In case of significant deviations from the nominal values of secondary factors of influence, in particular, the internal pressure in the tire, it is necessary to make a correction to the test result.

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Contact: Alexander Dityatiev Ph. D. (Ing.), Senior Research Fellow, Associate Professor of the Department of Technical operacion and service of cars, Kharkiv National Automobile and Highway University. Yaroslava Mudryho str., 25, Kharkiv, Ukraine, (+38) 068-608-20-95, alex-dit@ukr.net

# АНАЛИЗ НА АВАРИЙНИТЕ ОТКАЗИ ПРИ ТРАМВАЙНИТЕ МОТРИСИ В ГРАД СОФИЯ

# ANALYSIS OF EMERGENCY FAILURES IN TRAMS IN SOFIA CITY

**Emil M. Mihaylov[1)], Petya Stoyanova[2)]**

**Abstract.** The material concerns the emergency failures of trams in Sofia's tramway system during 2023 and 2024. Based on the Emergency Bulletin from the Emergency Service, an analysis was conducted on the emergency failures of tram rolling stock according to various criteria. The analyses were performed using the following criteria: failures by types of trams, by tram lines, by types of damage, and by duration of traffic hold-ups. Dependencies among the failures across different criteria have been identified. The leading factor in the analyses is the impact of emergency failures on the transportation process.
**Keywords:** tram, emergency failures.

## 1. Въведение:

Анализите направени тук са въз основа на официалните данни за 2023 и 2024 година на „Аварийна служба” [1], звено за спешна техническа помощ на „Столичен електротранспорт” ЕАД – транспортния оператор на София с електрически возила. Данните са за авариите по трамвайния подвижен състав (ТрПС), на които са се отзовали дежурните аварийни екипи. Това са около 97 % от случаите на аварийни откази по трамвайните мотриси (ТМ).

Характерно за трамвайния транспорт е, че аварирала трамвайна мотриса спира движението на следващите след нея. Така аварийният отказ на една мотриса влияе на останалите движещи се в същия участък като ги извежда от разписанието. А при по-дълго времетраене на аварията се налага и отклоняване на колите по линиите преминаващи през участъка. Това води до неудобства за пътниците.

## 2. Общи сведения:

За разглежданият период линиите на трамвайния транспорт в София са обслужвали около 300 трамвайни мотриси. Броят на ТМ по междурелсие, типове и дял от общия им брой са нанесени в Таблица 1.

Таблица 1.

| междурелсие | | 1009 *mm* | | | | | | | | 1435 *mm* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Година | Типове ТМ | T6M 700 | T8M 700 M | T8M 503 | T8M 700 IT | T6A2-BG | T6A2-Sf | PESA 122NaSF | Be4/6S | T6A5 | T6B5 | Duewag | Общо |
| 2023 | Брой ТМ | 18 | 6 | 9 | 18 | 40 | 17 | 67 | 28 | 55 | 37 | 6 | 301 |
| | Дял от всички | 6,0 | 2,0 | 3,0 | 6,0 | 13,3 | 5,6 | 22,3 | 9,3 | 18,3 | 12,3 | 2,0 | |
| 2024 | Брой ТМ | 2 | 5 | 9 | 18 | 40 | 17 | 67 | 28 | 55 | 37 | 6 | 284 |
| | Дял от всички | 0,7 | 1,8 | 3,2 | 6,3 | 14,1 | 6,0 | 23,6 | 9,9 | 19,4 | 13,0 | 2,1 | |

През цялата 2023 година поетапно са извеждани от експлоатация трамвайни мотриси типове T6M 700 и T8M 700 M, произвеждани в Завода за трамваи - София през 80-те години на XX век. При всички останали типове няма промяна на броя им в този период.

Аварийните откази за периода по типове ТМ са показани в Таблица 2.

Таблица 2.

| междурелсие | | 1009 *mm* | | | | | | | | 1435 *mm* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Година | Типове ТМ | T6M 700 | T8M 700 M | T8M 503 | T8M 700 IT | T6A2-BG | T6A2-Sf | PESA 122NaSF | Be4/6S | T6A5 | T6B5 | Duewag | Общо |
| 2023 | Брой аварии | 12 | 15 | 28 | 53 | 145 | 66 | 170 | 94 | 57 | 61 | 5 | 706 |
| | Дял от всички | 1,7 | 2,1 | 4,0 | 7,5 | 20,5 | 9,3 | 24,1 | 13,3 | 8,1 | 8,6 | 0,7 | |
| 2024 | Брой аварии | 1 | 22 | 45 | 55 | 198 | 91 | 166 | 97 | 73 | 64 | 5 | 817 |
| | Дял от всички | 0,1 | 2,7 | 5,5 | 6,7 | 24,2 | 11,1 | 20,3 | 11,9 | 8,9 | 7,8 | 0,6 | |

Аварийните откази разпределени по линии (маршрути) са показани в Таблица 3. В таблицата са показани типовете трамвайни мотриси, които обслужват съответните линии.

Таблица 3.

| Линия | 2023 година | | 2024 година | | Типове ТМ, обслужващи линиите: |
|---|---|---|---|---|---|
| | Брой аварии | Дял от всички | Брой аварии | Дял от всички | |
| 1 | 12 | 1,7 | 25 | 3,1 | T6A2-Sf, PESA 122NaSF |
| 3 | 66 | 9,3 | 71 | 8,7 | T6A2-Sf |
| 4 | 22 | 3,1 | 15 | 1,8 | PESA 122NaSF |
| 5 | 13 | 1,8 | 11 | 1,3 | PESA 122NaSF |
| 6 | 55 | 7,7 | 49 | 6,0 | PESA 122NaSF, T8M 700 IT |
| 7 | 66 | 9,3 | 43 | 5,3 | PESA 122NaSF |
| 8 | 37 | 5,2 | 69 | 8,4 | Be4/6S |
| 10 | 92 | 12,9 | 103 | 12,6 | T6A2-BG |
| 11 | 110 | 15,4 | 105 | 12,9 | T6A2-BG, T8M 503, T8M 700 M, Be4/6S |
| 12 | 43 | 6,0 | 49 | 6,0 | Be4/6S, T8M 700 IT |
| 15 | | | 50 | 6,1 | T6A2-BG |
| 18 | 22 | 3,1 | 20 | 2,4 | PESA 122NaSF |
| 20 | 61 | 8,6 | 54 | 6,6 | T6B5 |
| 21 | | | 20 | 2,4 | T6B5, T6A5 |
| 22 | 58 | 8,1 | 64 | 7,8 | T6A5 |
| 23 | 4 | 0,6 | 5 | 0,6 | Duewag |
| 27 | 46 | 6,5 | 55 | 6,7 | PESA 122NaSF |
| 22a | | | 2 | 0,2 | Be4/6S |
| други | 6 | 0,8 | 7 | 0,9 | Служебни, учебни, изпитания и други |
| Общо: | 713 | | 817 | | |

Линии 15, 21 и временната 22а са пуснати през 2024.

По линии 11, 20 и 22 четириосните ТМ се движат в състав по две. Отказите в тези случаи са на едната от тях, в редки случаи на двете.

Времето за отстраняване на авариите е показано в Таблица 4. Задържано движение до 10 минути не влияе на изпълнението на графика, тъй като такова закъснение може да се навакса бързо. Спряно движение от 11 до 20 минути изисква по-дълго време за

влизане на колите в график. Над 20 минути се налага определени коли от линията да се отклоняват по други маршрути или към маневрени обръщателни колела. Спряно движение над 40 минути се счита за сериозно отклонение от графика.

Таблица 4.

| Задържано движение, *min* | 2023 година | | | | 2024 година | | | |
|---|---|---|---|---|---|---|---|---|
| | брой | дял | Обща продължителност, *min* | дял | брой | дял | Обща продължителност, *min* | дял |
| до 10 | 122 | 25,8 | 953 | 11,2 | 137 | 26,0 | 1012 | 10,4 |
| от 11 до 20 | 202 | 42,8 | 3136 | 36,7 | 226 | 43,0 | 3509 | 36,1 |
| от 21 до 30 | 109 | 23,1 | 2716 | 31,8 | 116 | 22,1 | 2939 | 30,2 |
| от 31 до 40 | 20 | 4,2 | 684 | 8,0 | 30 | 5,7 | 1049 | 10,8 |
| от 41 до 50 | 7 | 1,5 | 312 | 3,7 | 6 | 1,1 | 277 | 2,8 |
| от 51 до 60 | 5 | 1,1 | 227 | 2,7 | 3 | 0,6 | 204 | 2,1 |
| над 60 | 7 | 1,5 | 510 | 6,0 | 8 | 1,5 | 736 | 7,6 |
| Общо: | 472 | | 8538 | | 526 | | 9726 | |

Най-голям брой са авариите и съответно загубеното време, при които е задържано движението от 21 до 30 минути. Най-дългата задръжка на движението през 2024 година е 126, а през 2023 година - 99 минути. Практиката показва, че най-голям дял от времетраенето на задържаното движение при авариите със задръжки до 30 минути е времето за пътуване на аварийния екип към авариралата мотриса. Най-дългите задръжки са при дерайлиране и/или повреди по ходовата част когато се налага частично повдигане на ТМ и поставяне на аварийни колички.

**3. Видове откази.**

Авариите по същество представляват извънредни ситуации поради своята непредвидимост и неясни последици. При голяма част от тях трудно, а понякога е невъзможно еднозначно да се определи причината за отказа, особено когато повредата е в тяговото оборудване и управлението на тягата.

Отказите предизвикали аварийно спиране на трамвайното движение са групирани по сходни признаци и са показани в Таблица 5.

Таблица 5.

| № | Аварийни откази: | 2023 година | | 2024 година | |
|---|---|---|---|---|---|
| | | Брой аварии | Дял от всички | Брой аварии | Дял от всички |
| 1 | Дерайлиране, ТМ в два коловоза. | 25 | 3,46 | 21 | 2,60 |
| 2 | Механични повреди по ходовата част и силовото предаване. | 52 | 7,20 | 54 | 6,59 |
| 3 | Откази по тяговото оборудване и управление на тягата. | 127 | 17,59 | 194 | 23,69 |
| 4 | Откази на статични преобразуватели. | 100 | 13,85 | 98 | 11,97 |
| 5 | Повреди по помощните агрегати. | 15 | 2,10 | 15 | 1,80 |
| 6 | Повреди по вратите. | 14 | 1,90 | 6 | 0,70 |
| 7 | Повреди по токоснемането. | 74 | 10,20 | 61 | 7,40 |
| 8 | Откази, при които има забрана за движение. | 34 | 4,70 | 48 | 5,90 |
| 9 | Повреди по спирачните системи и приводи. | 122 | 16,90 | 144 | 17,60 |
| 10 | Няма ход - причини неустановени на място. | 131 | 18,10 | 146 | 17,80 |
| 11 | ТМ спряла на изолиран участък. | 18 | 2,50 | 26 | 3,20 |
| 12 | Субективни причини. | 10 | 1,39 | 6 | 0,70 |

Попадане на ТМ в два коловоза се случва на стрелка когато една от талигите се отклонява по коловоз различен от коловоза, в който са другите талиги. Причините за това са сходни с причините за дерайлиране в зоната на стрелките.

Повредите по ходовата част и силовото предаване са поставени в една група по конструктивни причини. При двигателните талиги силовото предаване е част от ходовата част. Механичните повреди, непосредствена причина за аварията, могат да се окажат с непредвидими последствия за околните механизми и части на машините. Тези допълнителни повреди могат да бъдат видими при началния оглед на машината, но могат и да се видят или възникнат по време аварийно-възстановителните работи.

Отказите по тяговото оборудване и управлението на тягата са в обща група поради общите им признаци. Освен повреди на тяговите електродвигатели (ТЕД) в групата са включени откази на всички елементи от електрическите вериги, които управляват и/или контролират работата на двигателите.

Броят на отказите на статичните преобразуватели е отделен в самостоятелна група откази. Това се налага от спецификата на тези уреди и съизмеримия брой откази с тези откази от най-големите групи.

Повредите по токоснемането включват различни механични повреди по токоприемниците, повреди по задвижването им и други свързани непосредствено с тях.

Има една категория аварии, при които на място аварийния екип не може да установи причината. Обикновено това е поради липса на време или (в по-редки случаи) когато има повече от една причина. Тогава авариралата мотриса са бута или тегли до съоръжение (маневрен коловоз, обръщателно колело или близко депо), в което може да преседи за установяване на причината или отстраняване на повредата.

При новите ТМ тип PESA 122NaSF, чиято работа изцяло се контролира от компютър, може да има забрана за придвижване на собствен ход в различна степен в зависимост от степента на повредата. Има два аварийни режима, при които се допуска придвижване до депо със съответните ограничения на хода. При отказ от най-висок клас ТМ не може да се придвижва на собствен ход.

Повредите по спирачните системи и спирачните приводи са отделна категория откази. При мотрисите, управлявани от компютър това са откази от висок клас. Тъй като спирачките на ТМ са от постоянно затворен тип се налага тяхното разхлабване и придвижване до депо в авариен режим или с боксиране от друга мотриса.

Спирането на съоръжение без захранване - секторен изолатор или ТМ/ТБ кръстовка е предимно за предотвратяване на ПТП.

**4. Анализ на аварийните откази.**

Определяне на влиянието на описаните по-горе групи откази върху общата картина на проблема е направено по метода на Парето [2].

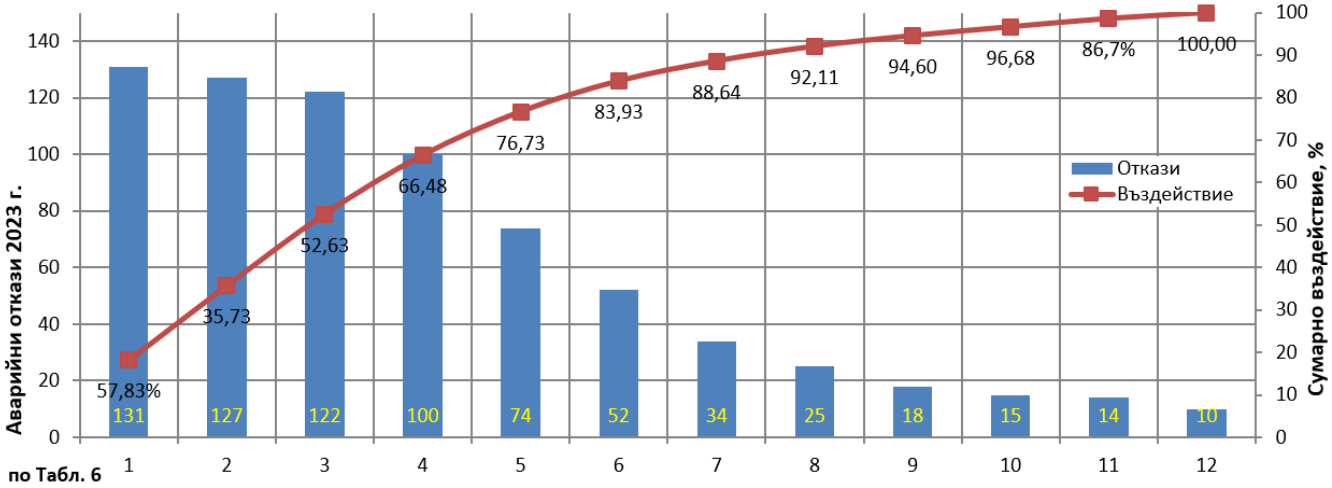
В Таблица 6. са показани отказите за 2023 година и въздействието им.

Таблица 6.

| | № | Аварийни откази: | Брой: | Въздействие: |
|---|---|---|---|---|
| 2023 година | 1 | **Няма ход - причини неустановени на място.** | 131 | 18,10 |
| | 2 | **Откази по тяговото оборудване и управление на тягата.** | 127 | 17,59 |
| | 3 | **Повреди по спирачните системи и приводи.** | 122 | 16,90 |
| | 4 | **Откази на статични преобразуватели.** | 100 | 13,85 |
| | 5 | **Повреди по токоснемането.** | 74 | 10,20 |
| | 6 | Механични повреди по ходовата част и силовото предаване. | 52 | 7,20 |
| | 7 | Откази, при които има забрана за движение. | 34 | 4,70 |
| | 8 | Дерайлиране, ТМ в два коловоза. | 25 | 3,46 |
| | 9 | ТМ спряла на изолиран участък. | 18 | 2,50 |

| | | | | |
|---|---|---|---|---|
| | 10 | Повреди по помощните агрегати. | 15 | 2,10 |
| | 11 | Повреди по вратите. | 14 | 1,90 |
| | 12 | Субективни причини. | 10 | 1,39 |

Парето-диаграмата за отказите през 2023 година е показана на фигура1.



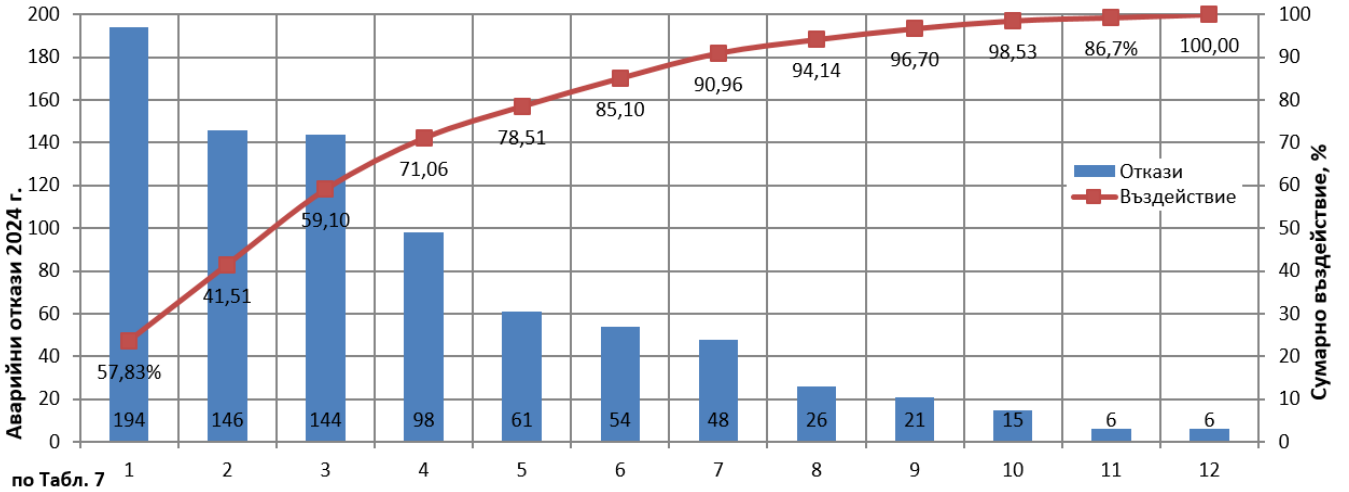

**Фиг. 1.** Парето диаграма на отказите през 2023 година.

В Таблица 7. са показани отказите за 2024 година и въздействието им.

Таблица 7.

| | № | Аварийни откази: | Брой: | Въздействие: |
|---|---|---|---|---|
| 2024 година | 1 | **Откази по тяговото оборудване и управление на тягата.** | 194 | 23,7 |
| | 2 | **Няма ход - причини неустановени на място.** | 146 | 17,8 |
| | 3 | **Повреди по спирачните системи и приводи.** | 144 | 17,6 |
| | 4 | **Откази на статични преобразуватели.** | 98 | 12,0 |
| | 5 | **Повреди по токоснемането.** | 61 | 7,4 |
| | 6 | Механични повреди по ходовата част и силовото предаване. | 54 | 6,6 |
| | 7 | Откази, при които има забрана за движение. | 48 | 5,9 |
| | 8 | ТМ спряла на изолиран участък. | 26 | 3,2 |
| | 9 | Дерайлиране, ТМ в два коловоза. | 21 | 2,6 |
| | 10 | Повреди по помощните агрегати. | 15 | 1,8 |
| | 11 | Повреди по вратите. | 6 | 0,7 |
| | 12 | Субективни причини. | 6 | 0,7 |

Парето-диаграмата за отказите през 2023 година е показана на фигура 2.




**Фиг. 2.** Парето диаграма на отказите през 2024 година.

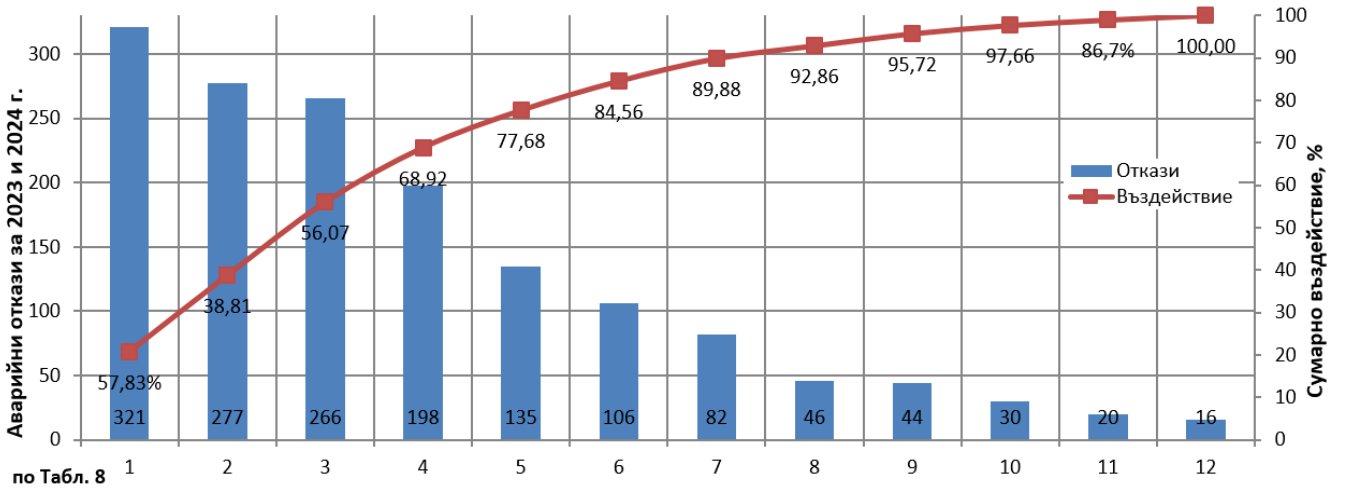
Резултатите от анализа за двете изследвани години по отделно показва сходни резултати с минимални разлики, които не влияят на общата картина. Разместване на позициите има при категориите „*Откази по тяговото оборудване и управление на тягата*“ и „*Няма ход - причини неустановени на място*“, както и при „*ТМ спряла на изолиран участък*“ и „*Дерайлиране, ТМ в два коловоза*“.

Минималните разлики в дяловете на отказите по групи за двете изследвани години дава основание за обединяването им в един общ период. Тогава обобщените данни придобиват вида показан в Таблица 8.

Таблица 8.

| | № | Аварийни откази: | Брой: | Въздействие: |
|---|---|---|---|---|
| 2023 и 2024 години | 1 | **Откази по тяговото оборудване и управление на тягата.** | 321 | 20,8 |
| | 2 | **Няма ход - причини неустановени на място.** | 277 | 18,0 |
| | 3 | **Повреди по спирачните системи и приводи.** | 266 | 17,3 |
| | 4 | **Откази на статични преобразуватели.** | 198 | 12,8 |
| | 5 | **Повреди по токоснемането.** | 135 | 8,8 |
| | 6 | Механични повреди по ходовата част и силовото предаване. | 106 | 6,9 |
| | 7 | Откази, при които има забрана за движение. | 82 | 5,3 |
| | 8 | Дерайлиране, ТМ в два коловоза. | 46 | 3,0 |
| | 9 | ТМ спряла на изолиран участък. | 44 | 2,9 |
| | 10 | Повреди по помощните агрегати. | 30 | 1,9 |
| | 11 | Повреди по вратите. | 20 | 1,3 |
| | 12 | Субективни причини. | 16 | 1,0 |

Парето-диаграмата за отказите през 2023 и 2024 години е показана на фигура 3.




**Фиг. 3.** Парето диаграма на отказите през 2023 и 2024 години.

Анализът по метода на Парето показва, че основно въздействие оказват аварийните откази в категориите „*Откази по тяговото оборудване и управление на тягата*“, „*Няма ход - причини неустановени на място*“, „*Повреди по спирачните системи и приводи*“, „*Откази на статични преобразуватели*“ и „*Повреди по токоснемането*“. В таблиците тези позиции са показани с по-дебел шрифт.

Макар, че данните за аварийните откази са във висока степен точни няма достатъчна прецизност при някои категории откази за причините. За допълнително прецизиране на информацията са необходими данни от ремонтните звена на депата за установените причини за отказите, извършените ремонти и вложените резервни части.

## 5. Заключение

Направените анализи показват, че тенденциите при аварийните откази се запазват през годините. Резултатите са сходни с аналогични изследвания за минали периоди [3]. Минималните разлики през различните години не влияят на общата картина. Този анализ може да се използва при определяне на приоритетите за профилактика на възлите и агрегатите при техническото обслужване на трамвайния подвижен състав.

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За контакти:
[1] Emil M. Mihaylov, Ph.D., M.Eng., c.a., „Todor Kableshkov“ University of Transport, Department of Material Handling and Construction Machines Sofia, Bulgaria, emil.mihaylov@vtu.bg & Sofia Public Electrical Transport Company JSC, Sofia, Bulgaria, *emm_1968@abv.bg*.
[2] Petya Stoyanova, Ph.D., Eng., c.a., „Todor Kableshkov“ University of Transport, Department of Technology, Organization and Management of Transport, Sofia, Bulgaria, pstoyanova@vtu.bg

# МЕТОДОЛОГИЯ ЗА ОЦЕНКА НА ТЕХНИЧЕСКОТО СЪСТОЯНИЕ НА АВТОМОБИЛ ПО РАЗХОД НА ГОРИВО И ЕФЕКТИВНОСТ

# METHODOLOGY FOR ASSESSING THE TECHNICAL CONDITION OF A PASSENGER CAR BY FUEL CONSUMPTION AND EFFICIENCY

**Yurij Gorbik**

**Abstract.** The paper proposes a model of energy diagnostics on fuel consumption, allows to evaluate the overall condition of the car and its separate units of analysis and measurement of specific and general efficiency of the unit.
**Keywords:** car, efficiency, fuel consumption, losses.

## 1. Introduction:

Fuel consumption is an integral indicator that reflects the efficiency of vehicle operation, the degree of energy optimization in its design, the level of technical condition, as well as the influence of operating conditions. During diagnostic procedures aimed at evaluating a vehicle's fuel efficiency, it is necessary to compare empirically measured fuel consumption values with standard reference parameters. However, existing reference sources do not provide regulated fuel consumption values (in liters per 100 km) specific to vehicle makes. Moreover, manufacturers often either omit operational fuel consumption standards from technical documentation or report inflated values of fuel efficiency.

The deterioration of the technical condition of individual vehicle components and systems leads to increased energy losses, which in turn result in higher fuel consumption and reduced specific engine power. By monitoring energy losses across separate units, it becomes possible not only to assess the overall technical condition of the vehicle based on fuel consumption but also to localize malfunctions within specific functional modules. A comprehensive evaluation of a vehicle's technical condition can be based on experimental and calculated fuel consumption data, whereas the individual assessment of components can be effectively performed using partial efficiency coefficients and indicator-based fuel consumption metrics.

## 2. Presentation:

The fundamental principles for assessing fuel efficiency and standardizing fuel consumption are laid out in [1], where, from the standpoint of systems engineering and energy-based approaches, the design and operational parameters influencing vehicle performance are examined.

In [2], a methodology is presented for evaluating the technical condition of a vehicle based on changes in its overall efficiency and the efficiency of its major components (engine, transmission, suspension, and wheels). The publication provides formulas for calculating the efficiency of both the entire vehicle and its individual aggregates under real-world driving conditions and during bench testing on roller dynamometers.

Reference [3] introduces a novel method for calculating fuel consumption based on the determination of four efficiency coefficients: the engine's indicated and mechanical efficiency, the transmission efficiency, and the efficiency of the wheel mechanism (including wheels and suspension).

In [4], a new approach is proposed for fuel consumption calculation during diagnostic testing on a roller dynamometer. Additionally, [5] presents a method for diagnosing technical condition based on the indicated fuel consumption of individual vehicle components.

The objective of this study is to further improve the methodology and develop an algorithm for diagnosing the technical condition of a vehicle based on changes in indicated fuel consumption and overall vehicle efficiency.

To achieve this goal, mathematical relationships and a calculation algorithm were proposed for determining the indicated fuel consumption and efficiency coefficients of the vehicle by

individual aggregates (indicated and mechanical efficiency of the engine, transmission, and suspension system).

Knowing the weight of the car, road and transport conditions, consumption and density of the fuel used, it is possible to determine the overall efficiency of the car using the formula:

$$\eta_a = \frac{100 \cdot M_a \cdot K_d}{H_n \cdot \rho_t \cdot Q}, \quad (1)$$

where $M_a$ – is the mass of the car, kg;
$K_d$ – coefficient of road conditions of operation;
$H_n$ – lower heat of combustion of fuel, kJ/kg;
$\rho_t$ – fuel density, g/cm$^3$;
$Q$ – fuel consumption, l/100 km.

When diagnosing a car in general, it is expedient to determine two efficiencies: effective engine efficiency ($\eta_i \cdot \eta_m$) and vehicle chassis efficiency (product of transmission and suspension efficiency – $\eta_t \cdot \eta_p$).

Dependence (1) is proposed to be used to evaluate the performance of the car on the road.

Initial data:

The following data belong to the calculated initial data: mass of the VAZ-21104 car
$M_a$ = 1515 kg,
engine cylinder volume $V_h$ = 1,596 *l*,
piston stroke $S_n$ = 0,0756 m,
gear ratio of the main gear $i_0$ = 3,937,
wheel radius $r_k$ =0,310 m,
flow factor $kF$ = 0,026· $V_a^2$ N·s$^2$·m$^{-2}$,
and engine power $N_a$ = 65,5 kW at 5000 min$^{-1}$.

Calculation formulas:

Values of forces $P_k$ applied to the wheels:

$$P_k = \frac{0{,}8 \cdot G_a}{V_a} + 0.029 \cdot V_a^2, \text{ N.} \quad (2)$$

where $G_a$ – car weight, N.

Average effective pressure

$$P_e = 12{,}56 \frac{r_k}{V_h \cdot i_0 \cdot i_k \cdot \eta_т} \cdot P_k \text{ kPa.} \quad (3)$$

where $V_h$ – is the working volume of the engine, *l*;
$i_0$ – gear ratio of the main transmission;
$\eta_m$ – transmission efficiency;
$i_k$ – is the average weighted gear ratio of the gearbox.

If we take for the VAZ-21104 [1, 5] $a_n$ = 43 kPa, $b_n$ = 13 kPa·sm$^{-1}$, the stroke of the piston $S_n$ = 0,0756 м, and $n$ = 2500 min$^{-1}$, then the mechanical losses in the engine are determined by the formula

$$P_m = (a_n + b_n \cdot 2S_n \cdot n/60) = (a_n + 0{,}033 \cdot b_n \cdot S_n \cdot n) \text{ kPa,} \quad (4)$$

where $a_n$ and $b_n$ – are constant coefficients for this engine;
$n$ – is the frequency revolutions of the crankshaft of the engine, min$^{-1}$;
$S_n$ – stroke of the piston, m.

$$P_m = (43 + 0{,}033 \cdot 13 \cdot 0{,}0756 \cdot 2500) = (43 + 81{,}1) = 124{,}1 \text{ kPa}.$$

At higher crankshaft rotation frequencies и $i_k$ =0,941.

$$P_m = (43 + 0{,}033 \cdot 13 \cdot 0{,}0756 \cdot \frac{2{,}65 \cdot V_a \cdot 3{,}937 \cdot 0{,}941}{0{,}31}) = 43 + 1{,}03 \cdot V_a. \quad (5)$$

Average indicator pressure $P_i$, kPa

$$P_i = P_e + P_m. \quad (6)$$

Correction factor

$$K_P = \frac{7{,}95 \cdot V_h \cdot i_0 \cdot i_k}{H_n \cdot \rho_t \cdot r_k} = 0{,}00496 \cdot i_k, \; l^2/N \cdot m^2. \quad (7)$$

Car transmission efficiency

$$\eta_t = \frac{P_k}{1{,}3 \cdot V_a + 1.025 \cdot P_k}, \quad (8)$$

Gear ratio of the gearbox

$$i_k = \frac{107}{V_a}. \quad (9)$$

Indicator efficiency

$$\eta_i \approx 0{,}35\alpha.. \quad (10)$$

$$\alpha = a_1 + b_1 \cdot N_1, \quad (11)$$

where $N_1$ – is the percentage of capacity utilization, %.

For gasoline injector internal combustion engines

$$\eta_i = 0{,}35(0{,}85 + 0{,}00337N_1) = 0{,}298 + 0{,}00118N_1. \quad (12)$$

The percentage of capacity utilization is determined by the formula

$$N_1 = \frac{100(G_a \cdot \Psi \cdot V_a + 0{,}077 \cdot kF \cdot V_a^3)}{3{,}6 \cdot 10^3 \cdot N_{Te_{max}}}, \quad (13)$$

where $N_{e\,max}$ – is the maximum engine power, kW.

Mechanical efficiency

$$\eta_m = \frac{\eta_e}{\eta_i}. \quad (14)$$

Efficiency is effective

$$\eta_e = \eta_i \cdot \eta_m. \quad (15)$$

Suspension efficiency

$$\eta_p = \frac{100 \cdot M_a \cdot K_d}{H_н \cdot \rho_t \cdot \eta_i \cdot \eta_m \cdot \eta_t \cdot Q}. \quad (16)$$

General efficiency of the car

$$\eta_a = \eta_i \cdot \eta_m \cdot \eta_t \cdot \eta_p. \quad (17)$$

In the table 1 shows calculated values of losses, fuel consumption and efficiency of the car and units.

**Table 1.** Calculated data of changes in the private and general efficiency of the car with increasing speeds in the range of 25-150 km/h

| $V_a$, km/h | $P_k$, N | $P_e$, kPa | $P_m$, kPa | $P_i$, kPa | $Q$, l/100 km | $\eta_i$ | $\eta_m$ | $\eta_e$ | $\eta_t$ | $\eta_p$ | $\eta_a$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **25** | 493.7 | 77.75 | 124.1 | 201.85 | **13.83** | 0.310 | 0.384 | 0.119 | 0.917 | 0.401 | 0.044 |
| **35** | 375.2 | 87.00 | 124.1 | 211.10 | **10.17** | 0.315 | 0.413 | 0.130 | 0.872 | 0.524 | 0.059 |
| **60** | 302.6 | 134.61 | 124.1 | 258.71 | **6.99** | 0.320 | 0.531 | 0.170 | 0.779 | 0.654 | 0.087 |
| **90** | 367.0 | 256.45 | 135.7 | 392.15 | **7.15** | 0.331 | 0.637 | 0.211 | 0.744 | 0.539 | 0.085 |
| **120** | 516.7 | 475.00 | 166.6 | 641.60 | **8.13** | 0.349 | 0.739 | 0.258 | 0.754 | 0.383 | 0.074 |
| **150** | 731.8 | 819.19 | 197.5 | 1016.69 | **9.52** | 0.378 | 0, 8 07 | 0.305 | 0.774 | 0.269 | 0.064 |

On fig. 1 shows graphs of changes in the private and general efficiency of the car and aggregates depending on the average technical speed.

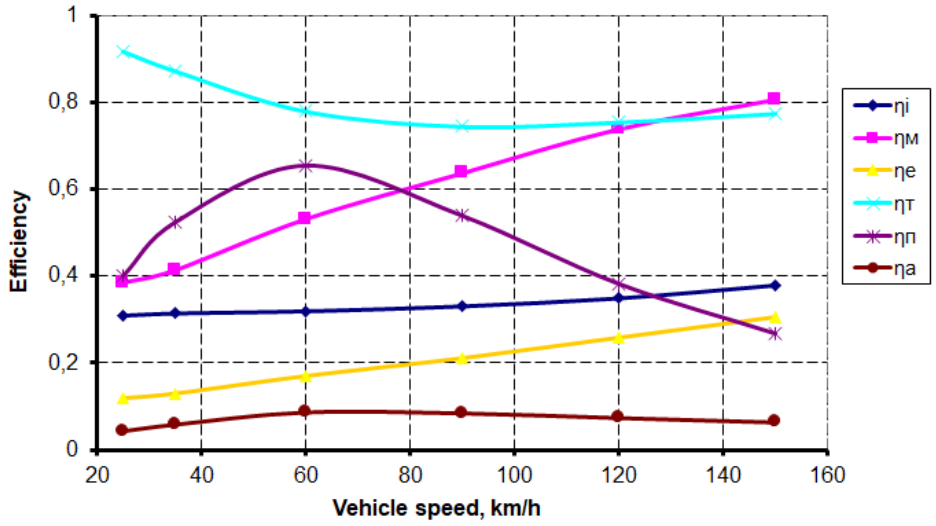



**Fig. 1.** Dependence of the private and general efficiency of the car and aggregates

To calculate the fuel consumption of the VAZ-21104 car, we have obtained a calculation formula

$$Q = \frac{100 \cdot M_a \cdot K_d}{H_н \cdot \rho_t \cdot \eta_a} = \frac{0{,}605}{\eta_a}. \quad (18)$$

**3. Conclusions:**

A general assessment of the vehicle's technical condition can be performed based on experimental and calculated fuel consumption data. The individual assessment of the technical condition of the aggregates should be assessed based on specific efficiency and indicative fuel consumption.

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За контакти: Gorbik Yurij Vasiliyvich, Ass Prof. PhD., Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(057)7073687, yuragorbik@gmail.com.

# АНАЛИЗ НА ВРЕДНИТЕ ЕМИСИИ ОТ ПРЕВОЗНИ СРЕДСТВА С ГАЗОВИ ДВИГАТЕЛИ В АВТОМОБИЛНИЯ ТРАНСПОРТ

# ANALYSIS OF HARMFUL EMISSIONS FROM VEHICLES WITH GAS ENGINES IN MOTOR TRANSPORT

**Sergy Krivoshapov**[1], **Alexander Nazarov**[2], **Denis Leontiev**[3]

**Abstract.** The main sources of pollution in road transport are considered. The impact of pollution on humans is analyzed. Regulatory acts on limiting pollution in transport are analyzed. The types of harmful substances that are controlled in cars are indicated. The mathematical model for determining fuel consumption for cars equipped with a gas fuel system is finalized. The influence of the physicochemical properties of fuel on consumption is studied. Graphical dependences of fuel consumption for the VAZ-1118 car, which runs on gasoline and liquefied gas, are obtained. The mathematical model for determining emissions of harmful substances for cars running on gas fuel is expanded. Recommendations and suggestions for further research are given.
**Keywords**: Ecology, motor vehicle, car toxicity, emissions of harmful substances, fuel consumption, efficiency.

## 1. Introduction:

The number of cars is constantly growing and, as a consequence, environmental pollution will increase. The situation can only be corrected through qualitative measures aimed at reducing emissions from each car. Environmental pollution can be reduced by switching to alternative fuels. Namely: biofuels, compressed or liquefied gases, methyl and ethyl alcohols, hydrogen, electric energy and others. However, a certain concentration of these fuels is also harmful to humans.

In the work, considerable attention will be paid to the use of liquefied petroleum gas in cars as an alternative source of energy. The advantages of using a propane-butane mixture over gasoline are as follows: the gas emits much less harmful combustion products; the best protection against quality falsification; less prone to detonation in any engine operating mode; has a higher calorific value per unit mass; cheaper. The disadvantages are: the need for additional equipment that suspends the curb weight of the car; increased gas volatility and ability to accumulate rapidly, increasing the risk of explosion; reduced engine power due to low specific heat of combustion; increased cost and time of vehicle maintenance.

The transition from gasoline to LPG will affect fuel consumption and the concentration of harmful substances in vehicle exhaust gases. These changes must be taken into account in the methodology for calculating and regulating fuel consumption for motor vehicles. Also, the corresponding changes must be taken into account in regulatory acts that limit emissions of harmful substances in exhaust gases from transport, so that the environmental characteristics of the vehicle comply with the standards [1, 2].

The purpose of the work: to increase the level of environmental safety of the car through constant monitoring of a possible source of pollution.

The aim of the work: to increase the level of environmental safety of a vehicle through mathematical modeling and monitoring of the level of fuel consumption and the content of harmful substances in the exhaust gases of a vehicle.

## 2. Description:

The amount of harmful emissions is significantly affected by fuel consumption. The method of Prof. Govorushchenko M.Ya. [3] involves calculating fuel consumption for cars with carburetor and diesel fuel systems.

For cars with a gas fuel system, it is recommended to increase fuel consumption to 25% [4], but this is a very rough assumption. We adapt the method [3] for calculating fuel consumption for cars using gas fuel.

The basic formula for calculating fuel consumption [3] in l/100 km:

$$Q = \frac{1}{\eta_i} \cdot \left[ A \cdot i_k + B \cdot i_k^2 \cdot V_a + C \cdot \left( G_a \cdot \psi + 0.077 \cdot kF \cdot V_a^2 \right) \right] , \quad (1)$$

where:
$V_a$ - car speed, km/h.;
$A$, $B$, $C$ - constant coefficients;
$\eta_i$ - indicator efficiency;
$i_k$ - weighted average gear ratio of the gearbox;
$\psi$ - coefficient of total road resistance of a vehicle;
$k$ - streamline factor, N·s$^2$/m$^2$;
$G_a$ - vehicle weight, N.

Between the engine's indicated efficiency $\eta_i$ and excess air coefficient $\alpha$ there is a close relationship [5]. Given the better homogenization of the fuel-air mixture and the best distribution over the engine cylinder, we accept the indicator efficiency of gas fuel to be slightly higher than that of gasoline.

We will use the following dependency [6]:

$$\eta_i \approx 0.35 \cdot \alpha \, . \quad (2)$$

Excess air ratio $\alpha$ depends on the engine load mode.

Fig. 1 shows the graphical dependence of the change in the excess air coefficient $\alpha$ from the degree of engine load $N_1$. Fuel enrichment occurs at minimum and maximum loads and engine crankshaft speeds. At medium speeds, the engine management system maintains a stoichiometric fuel-air mixture when $\alpha$ close to unity

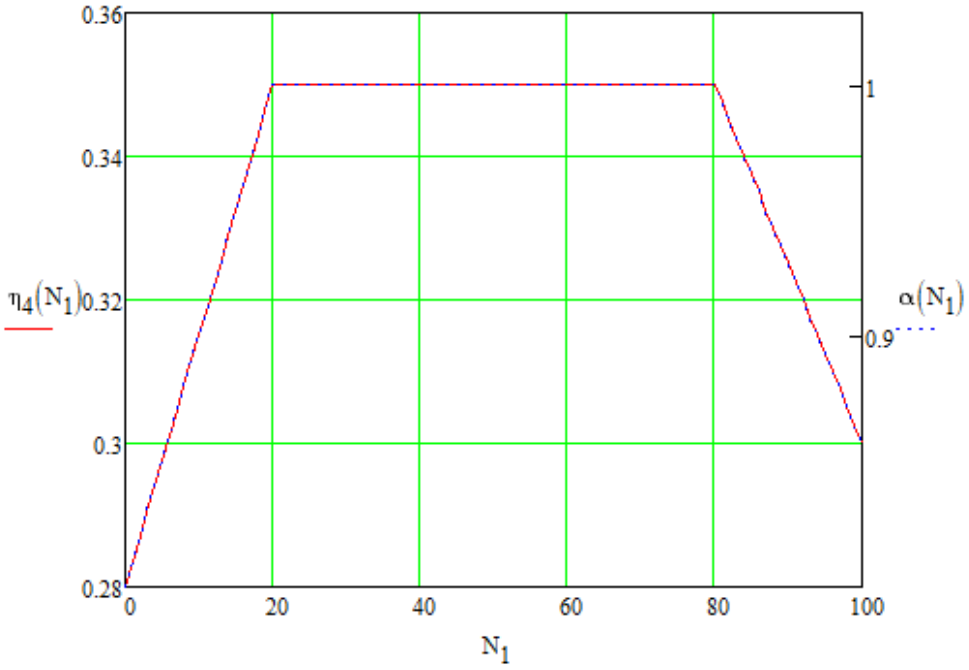



**Fig. 1.** Dependence of the indicator efficiency coefficient and the fuel excess coefficient $\alpha$ from the percentage of engine power $N_1$

Fig. 1 shows the result of a piecewise linear regression model of the form:

$$\alpha = a_1 + b_1 \cdot N_1 \, . \quad (3)$$

We assume the following coefficient values $a_1$ and $b_1$ for gas engine:

- for the range $N_1 < 20$: $a_1 = 0.8$ i $b_1 = 0.1$;
- for the range $20 < N_1 < 80$: $a_1 = 0$ i $b_1 = 1$;
- for the range $N_1 > 80$: $a_1 = -0.007$ i $b_1 = 1{,}57$.

The percentage of power is determined by the formula:

$$N_1 = \frac{100 \cdot \left(G_a \cdot \psi \cdot V_a + 0.077 \cdot kF \cdot V_a^3\right)}{3{,}6 \cdot 10^3 \cdot N_{e\max} \cdot \eta_{mp}} \quad \%, \tag{4}$$

where:
$N_{emax}$ - maximum vehicle engine power, kW;
$\eta_{тр}$ - transmission efficiency.

The fuel consumption formula (1) includes coefficients A, B, C, which depend on the quality of the fuel used [3]:

$$A = \frac{7.95 \cdot a_m \cdot V_h \cdot i_0}{H_н \cdot \rho_T \cdot r_k}; \tag{5}$$

$$B = \frac{0.69 \cdot b_m \cdot V_h \cdot S_n \cdot i_0^2}{H_н \cdot \rho_T \cdot r_k^2}; \tag{6}$$

$$C = \frac{100}{H_н \cdot \rho_T \cdot \eta_{mp}}, \tag{7}$$

where:
$V_h$ - working engine capacity, l;
$i_0$ - final drive ratio;
$r_k$ - dynamic wheel radius, m;
$S_n$ - piston stroke, m.

In formulas (5) – (7), fuel quality is determined by two indicators:: $H_н$ - lower calorific value (kJ/kg) and $\rho_T$ - fuel density (kg/m$^3$).

Table 1 shows the main properties of different types of fuel [7].

**Table 1.** Physicochemical properties of different types of fuel

| Parameters | Fuel type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Gasoline | Diesel fuel | Methane | Ethan | Propane | Butane | Hydrogen | Alcohol |
| Chemical formula | | | $CH_4$ | $C_2H_6$ | $C_3H_8$ | $C_4H_{10}$ | H | $C_2H_5OH$ |
| Molecular weight | 110 | 220 | 16 | 30 | 44 | 58 | 2 | 46 |
| Heat of combustion, MJ/kg | 44 | 43 | 49,7 | 47 | 45 | 55 | 120 | 29,7 |
| Volumetric heat of combustion, MJ/m$^3$ | 213 | | 33,8 | 60 | 85,6 | 111,6 | | |
| Theoretically, the amount of air required for burning fuel, kg/kg | 14,9 | | 17,2 | 16,8 | 15,7 | 15,5 | 34,5 | 8,85 |
| Heat of combustion of stoichiometric mixture, MJ/m$^3$ | 3,5 | | 3,2 | 3,4 | 3,5 | 3,5 | - | 3,5 |

| Parameters | Fuel type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Gasoline | Diesel fuel | Methane | Ethan | Propane | Butane | Hydrogen | Alcohol |
| Ignition temperature of fuel in air, ºC | 470-530 | 800-900 | 680-750 | 508-605 | 507-577 | 475-547 | 547-637 | 426 |
| Температура кипіння при тиску 100 кПа, ºС | 33-188 | 170-380 | -161 | -89 | -42,1 | -0,5 | -252,7 | 78,3 |
| Density of the liquid phase at boiling point at a pressure of 100 kPa, kg/m$^3$ | 735 | 845 | 416 | 549 | 584 | 600 | | |
| Density of the gas phase under normal conditions, kg/m$^3$ | 5,18 | | 0,71 | 1,36 | 2,02 | 2,7 | | |
| Volumetric flammability limits, % | 1,5-6 | | 5,3-14 | 3-12 | 2,4-9,5 | 1,9-8,5 | | |
| Octane number | 80-90 | | 110 | 106 | 105 | 94 | | 94 |

The chemical composition of propane [8]: carbon content - 0.817, hydrogen content - 0.182. Lower calorific value of propane - $H_н$ = 46,47 МДж/кг, liquid phase fuel density – 0,542 kg/m$^3$. Chemical composition of butane: carbon fraction - 0.545, hydrogen fraction - 0.455.

Natural gas consists of methane ($CH_4$) – 95 % and ethane ($C_2H_6$) – 5 %. The lower calorific value will be $H_н$ = 49,74 MJ/kg.

According to the methodology [5] in formulas (1) and (4) is used as a weighted average value, which depends on the speed of the vehicle.

$$\mathrm{i_k} = \frac{\mathrm{K_C \cdot V_{max} \cdot i_{кп}}}{\mathrm{V_a}} \ . \tag{8}$$

$$\psi = \frac{0.01 \cdot \mathrm{V_{max}}}{\mathrm{V_a}} . \tag{9}$$

where:
$K_c$ - speed ratio;
$V_{max}$ - maximum vehicle speed, km/h;
$i_{кп}$ - the gear ratio of the gearbox corresponding to the highest gear.

Fig. 2 shows the result of calculating fuel consumption for a VAZ-1118 car, which is equipped with gas cylinder equipment that uses liquefied petroleum gas. For this car, we assume the following initial data [9]: engine displacement $V_h$=1,596 cm$^3$; piston stroke $S_n$=0,0756 m; final drive ratio $i_0$=3,937; tire sizes 175/65 R14 or 185/60 R14; wheel radius $r_k$=0,285 m; transmission efficiency $\eta_{TP}$=0,93; streamline factor $kF$=0,641 N·s$^2$/m$^2$; curb weight of the vehicle with $G_a$=10594 N; total weight of the vehicle with $G_a$=15254 N; maximum speed - $V_{max}$=160 km/h.; speed ratio - $K_c$=0,76; gear ratio of the high-level gear of the gearbox - $i_{кп}$=0,784; maximum engine power - $N_{emax}$=66,2 kW; lower calorific value $H_u$=46470 kJ/kg; fuel density for the liquid phase $\rho_T$=0.542 g/cm$^3$.

According to the calculation, the minimum fuel consumption for liquefied gas is 10.56 l/100 km, and for gasoline - 8.46 l/100 km at an average speed of 80 km/h. Switching the VAZ-1118 from gasoline to liquefied gas will increase fuel consumption by 24.8%.

The basic formula for calculating emissions of harmful substances [5] in g/km is:

$$Q' = 0.0548 \cdot M_{вв} \cdot \rho_m \cdot (A_2 + B_2 \cdot N_1 + C_2 \cdot N_1^2) \cdot Q \cdot \alpha \ , \tag{10}$$

where:

$M_{вв}$ - is the molecular weight of the harmful substance, g/mol;

$\rho_m$ - is the fuel density, g/cm$^3$;

$A_2$, $B_2$, $C_2$ - are constant coefficients that depend on the type of engine installed on the car and the type of harmful substance;

$N_1$ - is the percentage of power use, %;

Q - is the fuel consumption, l/100 km;

$\alpha$ - excess air coefficient.

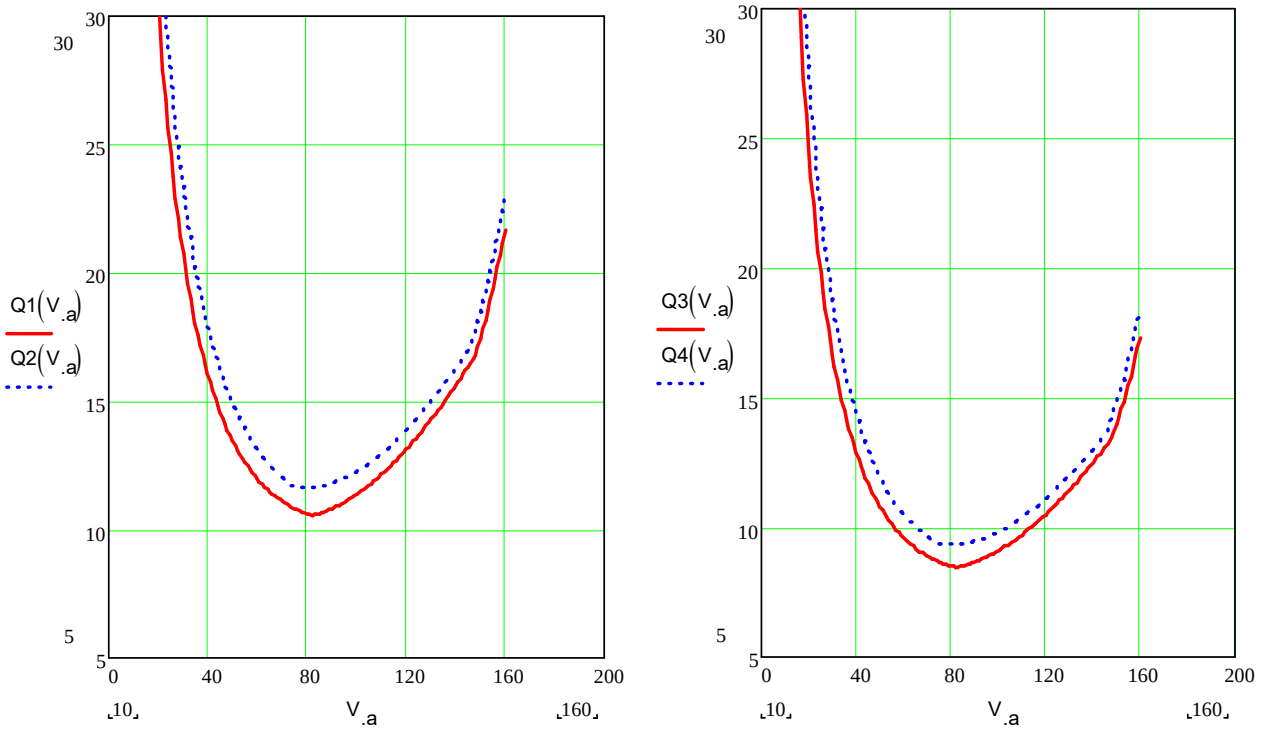



**Fig. 2** – Graphical dependence of the consumption of liquefied gas (a) and gasoline (b) for a VAZ-1118 car on the speed of movement

Table 2 shows the values of the coefficients $A_2$ , $B_2$ , $C_2$ for cars that use gasoline and gas as fuel. The coefficients were obtained after processing the experimental results and references [3, 5, 8, 10]. The experimental results were processed by the least squares method, and the coefficients of the second-degree polynomial regression model were obtained.

**Table 2**. Values of molecular weight and coefficients $A_2$, $B_2$, $C_2$ for various types of harmful substances

| Engine type | Harmful substance | Coefficient values | | | |
|---|---|---|---|---|---|
| | | $M_X$ | $A_2$ | $B_2$ | $C_2$ |
| gasoline | CO | 28 | 4.02 | -0.122 | $0.935 \cdot 10^{-3}$ |
| | $NO_x$ | 30 | 0.181 | $7.02 \cdot 10^{-3}$ | $-0.68 \cdot 10^{-4}$ |
| | $C_nH_m$ | 86 | 0.077 | $-1.83 \cdot 10^{-3}$ | $0.137 \cdot 10^{-4}$ |
| gas | CO | 28 | 2.88 | -0.0697 | $0.438 \cdot 10^{-3}$ |
| | $NO_x$ | 30 | $6.52 \cdot 10^{-3}$ | $2.38 \cdot 10^{-3}$ | $-1.7 \cdot 10^{-6}$ |
| | $C_nH_m$ | 86 | 0.046 | $-0.46 \cdot 10^{-3}$ | $2.79 \cdot 10^{-6}$ |

## 3. Conclusions:

The car pollutes the atmosphere heavily with such nasty substances as: carbon oxide, rare gas-like carbohydrates, nitrogen oxides, sour gas, soot, soot, aldehydes and benz(a)pyrene. The

rapid influx of this and other speech into humans can be assessed through the values of the maximum permissible concentration. The fuel calculation method of Prof. M.Ya. Govorushchenko was carefully improved for vehicles running on compressed or liquefied gas [9]. The power reduction of gas car is due to the low heat of combustion and the intensity of burning. A new characteristic for the indicator coefficient of engine combustion for gas-like combustion has been removed. The method for identifying waste products in manufactured gases for cars with gas cylinder equipment has been thoroughly developed. Level of toxicity of petrol and gas car VAZ-1118 at a speed limit of 75 km/year. set decrease: emissions carbon oxide was changed by 11 %, carbohydrate – by 21 %, nitric oxide – by 80 %. A method has been identified for reducing the concentration of waste fluids in an engine placed during operation.

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За контакти:
[1] Ass Prof. PhD. Krivoshapov Sergy Ivanovich, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(057)-707-37-68, keat@khadi.kharkov.ua.
[2] Ass Prof. PhD. Nazarov Alexander Ivanovich, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(099)-704-41-23, hefer64@ukr.net.
[3] Graduate student Leontiev Denis Vadimovich, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(099)-051-18-21, samodelkin.renault@gmail.com.

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# ХАРАКТЕРИСТИКИ НА ДИАГНОСТИКАТА НА СВОЙСТВАТА НА ТЕГЛОТО НА ПЪТНИЧЕСКИ АВТОМОБИЛИ НА РОЛКОВИ СТОЙКИ

# FEATURES OF DIAGNOSING TRACTION PROPERTIES OF PASSENGER VEHICLES ON ROLLER STANDS

**Ihor Marmut[1], Volodymyr Zuiev[2]**

**Abstract.** As you know, the main output parameters characterizing the state of the power unit are the power and torque values. These parameters determine the dynamic qualities of the car, and can also affect fuel consumption and the level of harmful emissions. The above parameters are checked using traction roller stands. Such stands allow you to reproduce real speed and load modes. Usually, the traction force on the drive wheels is measured on the stands. It is then easy to calculate the power at a given test speed. Therefore, a refined method of building the external speed characteristic using the example of the SKODA FABIA car is proposed using additional equations that specify the values of the empirical coefficients A, B, C. Standards for diagnostic parameters of the power unit in acceleration mode under partial load are also defined. The proposed method of registering engine diagnostic parameters to determine their normative values provides an individual approach to diagnosing the technical condition of cars.

**Keywords:** power unit, roller stand, traction force, loading mode, external speed characteristics of the engine.

## 1. Introduction:

To check the performance of the car's power unit on the stand, it is necessary to measure the value of the greatest traction force, fuel consumption and the content of toxic substances in real speed and loading modes. We specify these requirements, translating them into stand indicators.

To check the power unit, it is necessary to implement clutch forces that are noticeably smaller than when braking, but in a long-term stable mode, as well as to have smooth adjustment of the load and high accuracy of its measurement. In general, the requirements here are much softer than when checking the brakes.

In order to find a way to fulfill these requirements, it is necessary to consider the laws that connect the rotation of the rollers of the stand and the wheel that rests on them. The movement of the "wheel-roller" system is steady and unsteady. There are break-in and loading stable modes [1].

Run-in mode is the uniform movement of the stand's rollers and the wheels resting on them, driven by the stand's engine. On diagnostic stands, run-in modes are used, for example, to check the ease of rotation of the wheels. On the running-in stands of factories, such modes are used for cold running-in of a new or repaired car, which is performed for preliminary running-in of connected parts.

The loading mode is the uniform movement of rollers and wheels driven by the car engine. On diagnostic stands, loading modes are used to check traction properties and fuel consumption, on run-in machines - for hot running of the car with the engine running and various external loads.

The fulfillment of the requirements for the accuracy and quality of testing the traction properties of cars is ensured by the metrological characteristics of the stand: the type of measuring system, as well as the established method of registering diagnostic parameters and determining their standards [2-11].

Let's consider the processes of interaction of the car with the diagnostic stand in the loading mode.

The purpose of the study. To improve the method of determining the standards of traction properties during bench diagnostics using the example of the SKODA FABIA car.

## 2. Presentation:

*1. Determination of the traction force on the drive wheels.*

In the loading mode, the engine of the car installed on the stand overcomes the resistance in the transmission, "permanent" supports and additional resistance created by the loading device

of the stand ("load"). The power balance for the loading mode will be written as follows:

$$F_т = F_{трс} + F_к + F_п + F_н, \quad (1)$$

where $F_т$ – traction force on the driving wheels; $F_{трс}$ – force of friction in the stand; $F_к$ – force of rolling resistance of the wheel on the rollers; $F_п$ – the force of air resistance during the rotation of car wheels and rollers; $F_н$ – the load force is created by the loading device of the stand.

The diagnostic parameter in this case is the load force created by the loading device of the stand:

$$F_н = F_т - F_{трс} - F_к - F_п, \quad (2)$$

As you know, the traction force on the driving wheels is calculated according to the formula

$$F_т = \frac{M_e \cdot i_в \cdot i_o}{r_к} \cdot \eta_{тр}, \quad (3)$$

where $M_e$ – effective torque on the crankshaft of the engine, N·m, is determined by the external speed characteristic of the engine; $i_в$ – gear ratio of the gearbox in the highest gear; $i_o$ – gear ratio of the main gear; $\eta_{тр}$ – transmission efficiency; $r_к$ – rolling radius of the wheel, m.

We accept the following parameter values for the car under study: $i_в$ = 1; $i_o$ = 4,22; $\eta_{тр}$ = 0,91; $r_к$ = 0,265 м. If we substitute all accepted values into formula (3), we get the following transition from torque to traction force: $F_т = \frac{M_e \cdot 1 \cdot 4,22}{0,265} \cdot 0,91 = 14,49 \cdot M_e$.

*2. Improvement of the method of determining the external speed characteristic of the engine.*

When there is no reliable, experimentally obtained external speed characteristic of an internal combustion engine, for its approximate construction it is usually used Leiderman's formula [6], which calculates the effective power $N_e$ in kW at different crankshaft rotation frequency $n$, knowing the maximum effective power $N_{emax}$ and its corresponding frequency $n$ in min$^{-1}$:

$$N_e = N_{emax} \cdot \left[A \cdot \left(\frac{n}{n_N}\right) + B \cdot \left(\frac{n}{n_N}\right)^2 - C \cdot \left(\frac{n}{n_N}\right)^3\right], \quad (4)$$

where $A$, $B$, $C$ – empirical coefficients depending on the type of engine and combustion chamber.

The torque curve $M_e$ is built by calculating the value of the moment in N·m under the condition:

$$N_e = M_e \cdot \omega = M_e \frac{2\pi \cdot n}{60 \cdot 1000} = M_e \frac{n}{9549,3}; \qquad M_e = 9549,3 \frac{N_e}{n}. \quad (5)$$

Of course, they are accepted for gasoline engines $A = B = C = 1$.

This technique gives a satisfactory approximation of the dependence of power on revolutions. However, the moment curve is noticeably different from the experimental one. Even the values of the maximum moment, and sometimes the frequency corresponding to it, do not coincide with those indicated in the characteristics of the car. Yes, for SKODA FABIA engine $N_{emax}$ = 55 kW at 5800 min$^{-1}$, $M_{emax}$ = 107 N·m at 3800 min$^{-1}$.

This technique is clearly imperfect due to the fact that it uses only one experimental point – the maximum power and the corresponding revolutions. Therefore, it gives the same shape of curves $N_e(n)$) and $M_e(n)$ for all engines. However, the technique can be refined by using different

values of the coefficients $A$, $B$ and $C$. To obtain them, two more equations are needed in addition to (5).

The second equation can be obtained based on the values of the maximum torque $M_{emax}$ and the corresponding revolutions $n_M$. The third equation is derived from the condition that the torque curve has an extremum, namely a maximum. At this point, the first derivative of the torque with respect to the rotation frequency must be zero.

The first equation is given by formula (4) when $N_e = N_{emax}$. It is convenient to convert it – take out the fraction $^{n}/_{n_N}$ in square brackets and substitute $n = n_N$:

$$N_e = N_{emax} \cdot \frac{n}{n_N} \cdot \left[A + B \cdot \left(\frac{n}{n_N}\right) - C \cdot \left(\frac{n}{n_N}\right)^2\right], \quad (6)$$

$$1 = A + B - C. \quad (7)$$

The second equation is obtained from (5) by entering into it the nominal value of the maximum torque $M_{emax}$ and the corresponding revolutions $n_M$ according to the technical characteristics of the engine or car:

$$M_e = 9549{,}3\frac{N_e n}{n \cdot n_N}\left[A + B \cdot \left(\frac{n}{n_N}\right) - C \cdot \left(\frac{n}{n_N}\right)^2\right]; \quad (8)$$

$$\frac{M_{emax} \cdot n_N}{9549{,}3 \cdot N_{max}} = A + B \cdot \left(\frac{n_M}{n_N}\right) - C \cdot \left(\frac{n_M}{n_N}\right)^2. \quad (9)$$

The expression on the left side of equation (9) represents the ratio of the maximum effective torque to the torque at maximum power $M_{eN}$, which is commonly called the engine adaptability coefficient for the torque $k_M$:

$$k_M = \frac{M_{emax}}{M_{eN}} = \frac{M_{emax} \cdot n_N}{9549{,}3 \cdot N_{emax}}. \quad (10)$$

The ratio of the crankshaft rotation frequency at maximum power $n_N$ to the rotation frequency at maximum torque $n_M$ is called the engine adaptability factor by frequency $k_\omega$:

$$k_\omega = \frac{n_N}{n_M}. \quad (11)$$

For gasoline engines, of course $k_M = 1{,}1 \ldots 1{,}35$, $k_\omega = 1{,}5 \ldots 2{,}5$.

Taking into account these notations, expression (9) takes the form:

$$k_M = A + \frac{B}{k_\omega} - \frac{C}{k_\omega^2}. \quad (12)$$

The third equation:

$$\frac{dM_e}{dn} = 9549{,}3 \cdot \frac{N_{max}}{n_N} \cdot \left[\frac{B}{n_N} - \frac{2C \cdot n_M}{n_N^2}\right] = 0. \quad (13)$$

Obviously, the derivative will be zero if the expression in parentheses is zero. Then:

$$B = \frac{2C \cdot n_M}{n_N^2} = \frac{2C}{k_\omega}, \text{ або} C = \frac{B \cdot k_\omega}{2}. \quad (14)$$

Further solution is not difficult.

General view of a system of three equations with three unknowns:

$$\begin{cases} 1 = A + B - C, & (7) \\ k_M = A + \frac{B}{k_\omega} - \frac{C}{k_\omega^2}, & (12) \\ B = \frac{2C}{k_\omega}. & (14) \end{cases}$$

Substituting (14) into (4) and (12), we get:

$$1 = A + \frac{2C}{k_\omega} - C = A + C \cdot \frac{2-k_\omega}{k_\omega}, \quad (15)$$

$$k_M = A + \frac{2C}{k_\omega^2} - \frac{C}{k_\omega^2} = A + \frac{C}{k_\omega^2}. \quad (16)$$

Subtracting equation (15) from (16), we obtain:

$$k_M - 1 = C \cdot \left(\frac{1}{k_\omega^2} - \frac{2-k_\omega}{k_\omega}\right) = C \cdot \frac{1-k_\omega \cdot (2-k_\omega)}{k_\omega^2}. \quad (17)$$

From here:

$$C = \frac{(k_M-1) \cdot k_\omega^2}{1-k_\omega \cdot (2-k_\omega)}. \quad (18)$$

Then:

$$B = \frac{2 \cdot (k_M-1) \cdot k_\omega}{1-k_\omega \cdot (2-k_\omega)} = \frac{2 \cdot (k_M-1)}{\frac{1}{k_\omega} - 2 + k_\omega}; \quad (19)$$

$$A = 1 - B + C = 1 + \frac{k_\omega^2 \cdot (k_M-1) - 2k_\omega \cdot (k_M-1)}{1-k_\omega \cdot (2-k_\omega)} = \frac{1 - 2k_\omega + k_\omega^2 + k_M \cdot k_\omega^2 - k_\omega^2 - 2k_M \cdot k_\omega + 2k_\omega}{1-k_\omega \cdot (2-k_\omega)}; \quad (20)$$

$$A = \frac{1-k_M \cdot k_\omega \cdot (2-k_\omega)}{1-k_\omega \cdot (2-k_\omega)}. \quad (21)$$

In practical calculations, it is most convenient to find $B$ using the rather simple formula (19), and then to find $C$ and $A$ using the following formulas:

$$C = \frac{B \cdot k_\omega}{2}, \quad (22)$$

$$A = 1 - B + C. \quad (7)$$

*3. Construction of external speed characteristics for the SKODA FABIA car engine.*

Calculation of the engine adaptability factor by torque $k_M$ and the engine adaptability factor by frequency $k_\omega$:

$$k_M = \frac{M_{emax} \cdot n_N}{9549{,}3 \cdot N_{emax}} = \frac{107 \cdot 5800}{9549{,}3 \cdot 55} = 1{,}187; \; k_\omega = \frac{n_N}{n_M} = \frac{5800}{3800} = 1{,}526.$$

Calculation of empirical coefficients $A$, $B$, $C$:

$$B = \frac{2 \cdot (k_M-1) \cdot k_\omega}{1-k_\omega \cdot (2-k_\omega)} = \frac{2 \cdot (1{,}187-1) \cdot 1{,}526}{1-1{,}526 \cdot (2-1{,}526)} = 2{,}06; \; C = \frac{B \cdot k_\omega}{2} = \frac{2{,}06 \cdot 1{,}526}{2} = 1{,}57;$$

$$A = 1 - B + C = 1 - 2{,}06 + 1{,}57 = 0{,}51.$$

Thus, the calculated formula for the dependence of torque on crankshaft revolutions has the following form:

$$M_e = 9549{,}3\frac{55}{5800}\left[0{,}51 + 2{,}06 \cdot \left(\frac{n}{5800}\right) - 1{,}57\left(\frac{n}{5800}\right)^2\right], \quad (23)$$

or, after opening the parentheses:

$$M_e = 46{,}35 + 0{,}032 \cdot n - 4{,}24 \cdot 10^{-6} \cdot n^2. \quad (24)$$

Figure 1 shows the external speed characteristic calculated by the refined (solid line) and simplified (dashed line) methods. As you can see from the graphs, the power curves are not very different, but the torque curve, which is important for our calculation, according to the simplified method, does not even pass through the maximum point specified in the car characteristics – neither by the torque value, nor by the corresponding revolutions. Therefore, we will continue to use exclusively the specified method.

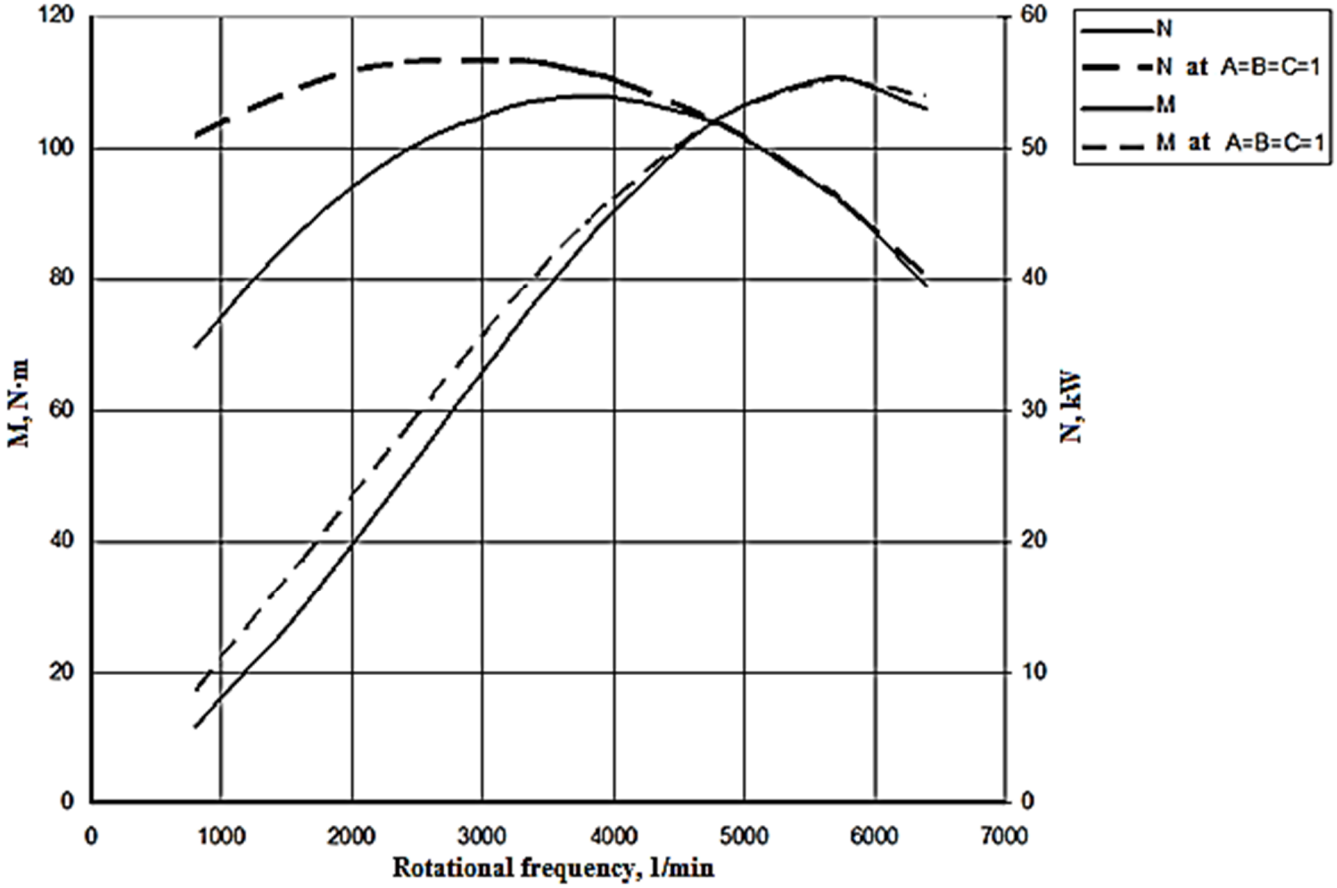



**Fig. 1.** External speed characteristics of the SKODA FABIA engine

*4. Construction of the dependence of traction force on speed.*

Above, the dependence of the torque on the revolutions of the crankshaft was deduced. To analyze the traction balance, it is more convenient to have the dependence of the traction force on the speed of the car. As calculated above, for the vehicle under study:

$$F_T = 14{,}49 \cdot M_e. \quad (25)$$

Substituting the above expression for the effective torque (formula (24)) into formula (25), we obtain:

$$F_T = 671{,}6 + 0{,}4636 \cdot n - 0{,}000061 \cdot n^2. \quad (26)$$

Let's move from revolutions to speed. The relationship between car speed and engine revolutions is known:

$$V = 0{,}377\frac{n \cdot r_к}{i_в \cdot i_o}. \quad (27)$$

For the vehicle under investigation: $V = 0{,}377\frac{n \cdot 0{,}265}{1 \cdot 4{,}22} = 0{,}02367 \cdot n$, or $n = 42{,}24 \cdot V$.

Substitute the last equation into formula (26) and get the empirical dependence of the traction force on the speed:

$$F_т = 671{,}6 + 19{,}58 \cdot V - 0{,}109 \cdot V^2. \quad (28)$$

In operation, engine power and torque may decrease when the technical condition changes. Let's assume that the revolutions that correspond to the maximum moment do not change, but only the value of the maximum moment decreases - by 5, 10, etc. percent Calculation formulas for cases of different moment values are summarized in Table 1.

The calculated values of the traction force for these cases are summarized in Table 2 and illustrated in Figure 2.

**Table 1.** Formulas for calculating the traction force on the driving wheels of the SKODA FABIA car in direct gear

| Technical condition of the engine and transmission (torque, %) | The formula for calculating the traction force on the driving wheels, N |
|---|---|
| 100 | $671{,}6 + 19{,}58 \cdot V - 0{,}109 \cdot V^2$ |
| 95 | $638{,}02 + 18{,}6 \cdot V - 0{,}1036 \cdot V^2$ |
| 90 | $604{,}4 + 17{,}6 \cdot V - 0{,}0981 \cdot V^2$ |
| 85 | $570{,}86 + 16{,}64 \cdot V - 0{,}093 \cdot V^2$ |
| 80 | $537{,}28 + 15{,}66 \cdot V - 0{,}087 \cdot V^2$ |

**Table 2.** Estimated values of traction force for cases of nominal and reduced engine torque

| $F_т$, % | $V$, km/h | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 40 | 60 | 80 | 100 | 120 | 130 | 140 | 150 | 160 |
| 100 | 968 | 1359 | 1453 | 1473 | 1419 | 1364 | 1291 | 1199 | 1090 |
| 95 | 909 | 1291 | 1380 | 1399 | 1348 | 1296 | 1226 | 1140 | 1035 |
| 90 | 849 | 1223 | 1307 | 1325 | 1277 | 1228 | 1162 | 1080 | 981 |
| 85 | 790 | 1155 | 1235 | 1252 | 1206 | 1159 | 1097 | 1020 | 926 |
| 80 | 730 | 1087 | 1162 | 1178 | 1135 | 1091 | 1033 | 960 | 872 |

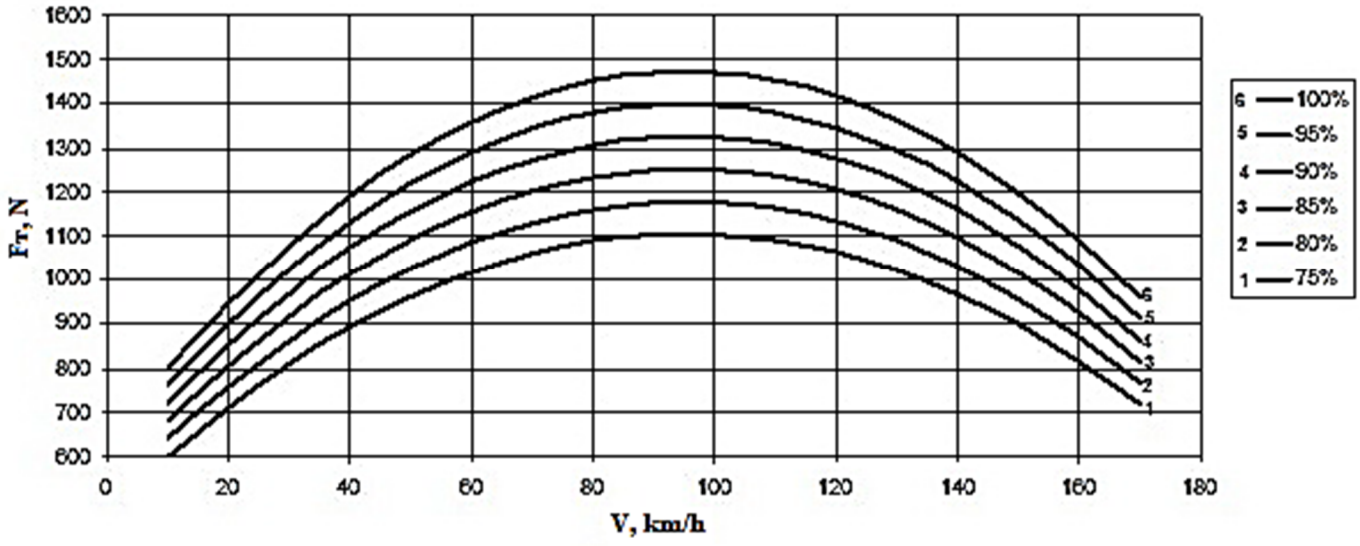



**Fig. 2.** Calculated traction force curves for cases of different torque (%%)

*5. Determination of standards of diagnostic parameters of the power unit in acceleration mode under partial load.*

On a stand with a loading device (LD), checking the power unit in acceleration mode has its advantages, for example, it allows you to track the inclusion of certain automatic systems of the engine or transmission according to the acceleration diagram.

The partial load acceleration mode can be used in various cases. Yes, sometimes it is necessary to stretch the acceleration in time in order to track transient processes in more detail or to reduce the requirements for the accuracy and speed of the measuring system. Then turn on the LD of the stand, creating a known load that is insufficient to stabilize the mode and accelerate the wheels of the car from one set speed ($V_1$) to another ($V_2$). In this case, the acceleration will be much less than during free acceleration. Points of interest in the process can be recorded even if the measurement system does not allow it (eg, a manual stopwatch). Sometimes the use of such a regime is a forced measure. Some stands have limited power LD, which is not enough for newer models of cars with higher pulling power (or when traction tests need to be done in reduced gears). Then, involuntarily, you have to use the partial load mode.

Acceleration is the diagnostic parameter of the power unit in this mode – $a_{\text{р}}$, m/sec$^2$, (or acceleration time depending on it – $t_{\text{р}}$, sec):

$$a_{\text{р}} = \frac{F_{\text{н}} - F_{\text{нд}}}{m_{\text{ст}} + 2m_{\text{к}}} = \frac{V_2 - V_1}{t_{\text{р}}}, \tag{29}$$

where $F_{\text{н}}$ – required load force, N; $F_{\text{нд}}$ – actual load force in case of partial load, N; $m_{\text{ст}}$ – given inertial mass of the stand, kg; $m_{\text{к}}$ – the mass of the driving wheels and the rotating parts of the car connected to them is given, kg; $V_2$ – final speed, m/sec; $V_1$ – initial speed, m/sec.

For the car under study, we will calculate the normative values of $a_{\text{р}}$ and $t_{\text{р}}$ for three acceleration modes: no load, 300 N and 600 N load. The processing results are summarized in the table. 3 and illustrated in fig. 3.

**Table 3.** Calculated values of acceleration indicators of the SKODA FABIA car on a roller stand

| Speed, km/h | 86,75 | 70,45 | 50,06 | 35,13 | 17,22 |
|---|---|---|---|---|---|
| Traction force on the driving wheels $F_{\text{т}}$, N | 1549,879 | 1510,022 | 1378,62 | 1224,927 | 976,446 |
| ***Total resistance in the stand $F_{\text{с}}$, N*** | ***227,7658*** | ***203,7165*** | ***184,9203*** | ***170,3097*** | ***157,037*** |
| $F_{\text{н}}$, N (no load) | 1322,113 | 1306,305 | 1193,7 | 1054,617 | 819,409 |
| $a_{\text{р}}$, m/sec$^2$ | 5,045077 | 4,984757 | 4,555064 | 4,024334 | 3,126799 |
| Time, sec | 0,897465 | 1,136242 | 0,910464 | 1,236229 | 1,529786 |
| ***Total time (without load)*** | ***5,710186*** | ***4,812721*** | ***3,676479*** | ***2,766015*** | ***1,529786*** |
| ***The stand was created 300 N*** | ***1022,113*** | ***1006,305*** | ***893,7001*** | ***754,6169*** | ***519,409*** |
| $a_{\text{р}}$, m/sec$^2$ | 3,900301 | 3,839981 | 3,410288 | 2,879558 | 1,982023 |
| Time, sec | 1,160879 | 1,474978 | 1,216091 | 1,727696 | 2,413359 |
| ***Total time (300 N), sec*** | ***7,993004*** | ***6,832125*** | ***5,357146*** | ***4,141055*** | ***2,413359*** |
| ***The stand was created 600 N*** | ***722,1128*** | ***706,3054*** | ***593,7001*** | ***454,6169*** | ***219,409*** |
| $a_{\text{р}}$, m/sec$^2$ | 2,755525 | 2,695205 | 2,265512 | 1,734782 | 0,837247 |
| Time, sec | 1,643163 | 2,101469 | 1,830589 | 2,867796 | 5,713168 |
| ***Total time (600 N), sec*** | ***14,15619*** | ***12,51302*** | ***10,41155*** | ***8,580964*** | ***5,713168*** |

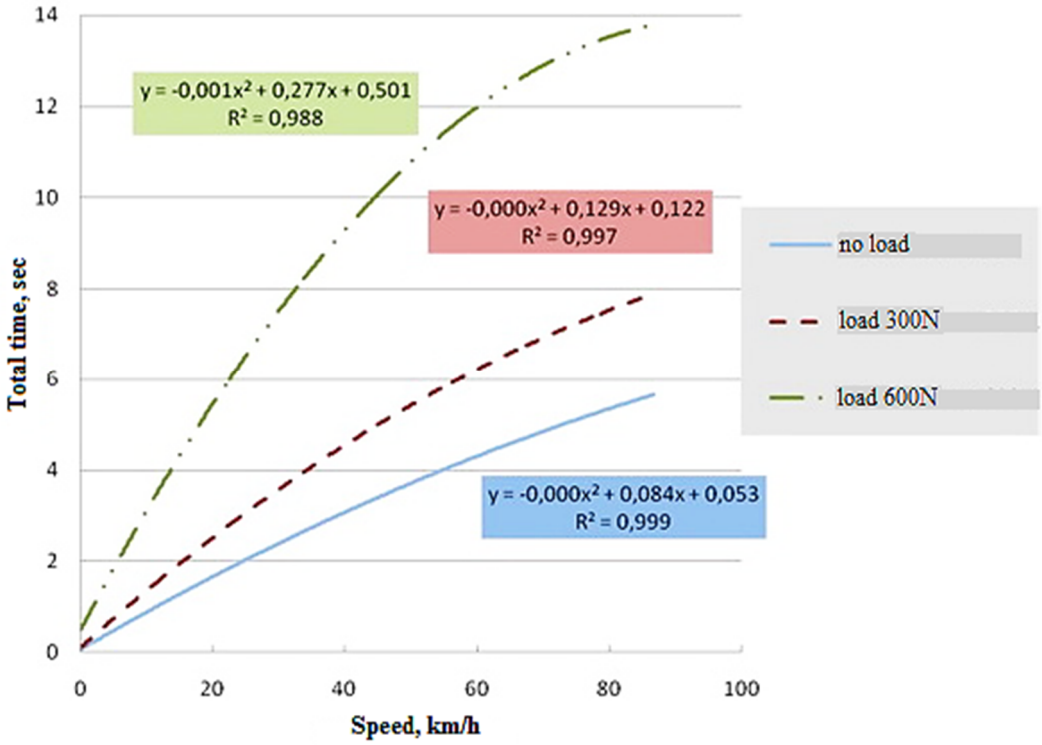



**Fig. 3.** Graphs of the dependence of the total acceleration time $t_p$ on the speed

## 3. Conclusions:

1. The application for diagnosing traction properties of the car during bench diagnostics of parameters that provide a general assessment of the state of the power unit (external speed characteristics of the engine, traction force on the wheels, acceleration and acceleration time on the bench) is justified.

2. The proposed method of registering engine diagnostic parameters to determine their normative values provides an individual approach to diagnosing the technical condition of cars.

3. The preliminary evaluation showed that the proposed method of determining the standards of traction properties during bench diagnostics on the example of the SKODA FABIA car can be used for practical application.

4. The proposed method gives results that do not exceed the values obtained by more accurate methods and can be recommended for building the external speed characteristic of a car engine in the absence of reliable data.

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За контакти:
[1] Ihor Marmut, Associate Professor (Assoc. Prof.), Candidate of Science in Engineering (Ph. D. (Eng.)), Kharkiv National Automobile and Highway University (KhNAHU), St. Yaroslav Mudriy, 25, Kharkiv, 61002, Ukraine, e-mail: mia2005.62@ukr.net, tel.: +38-057-707-36-87.
[2] Volodymir Zuiev, Chairman of the Cycle Committee, Teacher of Special Disciplines, e-mail: vlal.zuyev@gmail.com. Vyacheslav Chornovol Halych Vocational College, Ternopil.

# ПРОМЕНИ В ЕЛЕКТРИЧЕСКАТА ПРОВОДИМОСТ НА ОХЛАЖДАЩИТЕ ТЕЧНОСТИ НА ПРЕВОЗНИТЕ СРЕДСТВА ПОРАДИ ВРЕМЕТО НА РАБОТА

# CHANGES IN THE ELECTRICAL CONDUCTIVITY OF VEHICLE COOLANTS DUE TO OPERATING TIME

**Mikhail Nahliuk**

**Abstract.** The article presents the results of changes in the electrical conductivity of antifreeze and coolant fluids with operating time, as well as their graphical dependencies. It is established that with the same operating time of cars, the change in the electrical conductivity of their antifreeze occurs in different ways.

**Key words:** antifreeze, cooling liquid, electrical conductivity, operating time.

## 1. Introduction:

The development of road transport is associated with the production of modern cars, and improving their quality, reliability and durability requires the use of modern high-quality performance materials. In addition, automobiles are subject to increasingly stringent and growing requirements, which are caused by the improvement of various systems and components of transport vehicles to improve safety, efficiency and environmental friendliness. One of the ways to improve the efficiency and environmental friendliness of a car is to improve the engine cooling system by using antifreeze for all-season operation in liquid cooling systems, as well as optimizing the timing of coolant changes.

Antifreeze is a fluid used to cool the vehicle engine and other mechanical systems to prevent them from overheating and freezing at low temperatures. It is an important element of the cooling system that serves to keep the engine running at an optimal temperature. Modern antifreeze is a mixture of water with organic or inorganic additives such as ethylene glycol or propylene glycol. Ethylene glycol and propylene glycol play a key role in lowering the freezing point of the fluid and raising the boiling point, as well as affecting the corrosion resistance of the cooling system. Antifreeze may contain different chemicals depending on the manufacturer and type of antifreeze (e.g. organic acids, silicate compounds, etc.). These components can influence the conductivity of the fluid, which is important for evaluating the safety and functionality of the antifreeze under different conditions.

The conductivity of antifreeze depends on its chemical composition. Water, unlike pure organic compounds, has a certain conductivity due to dissolved minerals and salts. Additives in antifreeze, such as various chemicals (e.g. corrosion inhibitors), can alter its conductivity. Antifreeze generally does not conduct electric current as well as water, but it still has some conductivity. This is due to the fact that it may contain ions that allow the movement of electrical charge. This is especially true when mineral salts or other additives are used in antifreeze that increase its electrical conductivity.

For vehicles equipped with advanced electronic systems, the high electrical conductivity of antifreeze can be a source of potential problems. If antifreeze escapes from the cooling system and gets on electrical components, it can cause short circuits or corrosion, which can damage the vehicle's electrical system. Therefore, it is important to monitor the condition of the cooling system and avoid antifreeze leaks in the area where electrical components are located.

Antifreeze manufacturers conduct conductivity tests on their products to make sure they are safe for use in vehicles and will not damage engine management systems or other electronic components. Typically, antifreeze has a fairly low conductivity, but if it contains salts or other conductive additives, the conductivity can be higher. Interestingly, the conductivity of the antifreeze itself does not significantly affect its cooling capacity. The cooling capacity of an antifreeze is determined by its thermal characteristics, such as boiling and freezing point, as well as the efficiency of its heat dissipation properties. However, it is important that the antifreeze is properly balanced, as additives that increase conductivity can also change the

viscosity or other physical properties of the fluid, which in turn will affect the efficiency of the cooling system.

**2. Description:**

Nowadays, for each car there are service books that regulate the frequency of antifreeze replacement, taking into account the mileage of the car or the service life of the coolant in time. The replacement is carried out on a first-come, first-served basis. This is not entirely rational, as this approach does not take into account such factors as vehicle operating conditions, technical condition, load and speed conditions, and the actual condition of the antifreeze at the time of replacement. This approach leads to the fact that the fluid being drained may not have reached the end of its service life yet, or vice versa, it may have already begun to cause damage to the cooling system due to the production of additives.

All-season coolant is one of the main functional elements of the engine, which largely determines the reliability and efficiency of its systems. And, accordingly, like any functional element, it needs periodic diagnostics and quality control.

One of the indicators of coolant quality is the electrical conductivity of antifreeze. Issues related to the electrical conductivity of liquids have been considered by the scientific community for a long time. The results of measurements of the electrical conductivity of standard solutions at different temperatures, given in reference [1], show that with increasing liquid temperature, the conductivity also increases. Paper [2] describes studies and presents the results of changes in the electrical conductivity of clean and used samples of various oils. The authors of [3,4] studied the electrical conductivity of various hydrocarbon liquids.

To determine the actual condition of the coolant and its replacement, it is necessary to perform periodic monitoring. As a rule, the period is a value measured in kilometers or time (month, year). However, this does not take into account the fact that when the car is idle with the engine running (warming up, driving uphill, idling at a traffic light, etc.), the coolant continues to work and produce its service life.

To investigate the change in the electrical conductivity of antifreeze with operating time, samples were taken from passenger cars with different brands and types of fluids, both domestic and foreign. All of them are operated in the same road and climate conditions. Sampling was carried out after a certain period of operation. At the same time, other antifreeze quality indicators were analyzed: alkalinity, corrosivity of basic metals, density, crystallization temperature and ph.

Based on the results obtained, graphs of changes in the electrical conductivity of antifreeze with operating time were constructed (Fig. 1).

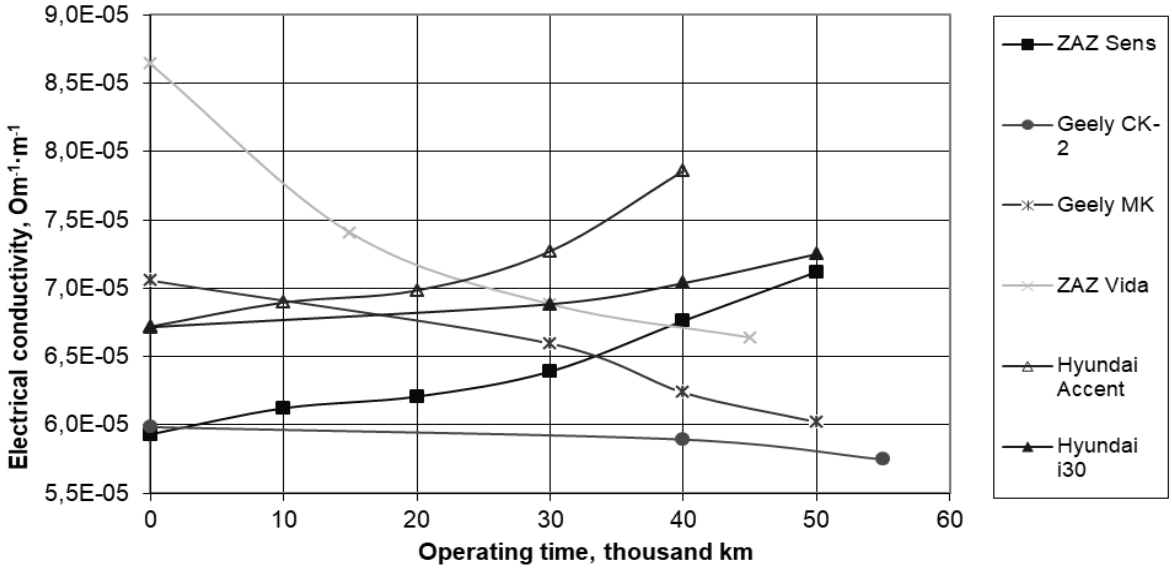



**Fig. 1.** Graph of changes in the electrical conductivity of antifreeze with operating time

The graphs show that the electrical conductivity of pure antifreeze varies from $5,8 \cdot 10^{-5}$ (car ZAZ Sens) to $8,6 \cdot 10^{-5}$ $Om^{-1} \cdot m^{-1}$ (car ZAZ Vida). And as the operating time increases, the electrical conductivity behaves differently. In ZAZ Sens, Hyundai Accent and Hyundai i30, there is an increase in electrical conductivity. In ZAZ Vida and Geely MK, there is a decrease in the electrical conductivity of antifreeze, and closer to the end of the service life, it becomes quite significant. Only in the Geely CK-2 the electrical conductivity has changed slightly over the entire service life. This suggests that antifreeze replacement should be done individually for a particular vehicle, taking into account its design features, the quality of the antifreeze and fuel used, and not just the operating time.

**3. Conclusions:**

Antifreeze conductivity testing can be used to assess the condition of the antifreeze and the degree of corrosion contamination. Elevated conductivity may indicate additive depletion and the need for coolant replacement. In some cases, the use of antifreeze with high conductivity may result in current leakage and equipment damage.

By diagnosing the quality of antifreeze by electrical conductivity, it is possible to state its actual condition with greater certainty than by generally accepted standards based on experience.

When specifying the frequency of coolant diagnostics, it is necessary to set the limit value of electrical conductivity individually for each vehicle, taking into account the technical condition of the engine and its systems, the quality of the antifreeze and fuel used, as well as external operating conditions.

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Contacts: Nahliuk Mykhailo, Associate Professor, PhD. in Technical Science. Kharkov National Automobile and Highway University, Department “Technical operation and service vehicles”, Yaroslava Mudroho str. 25, Kharkov, Ukraine, Tel.: +380577073768. E-mail: golkiper86@ukr.net

# ОСИГУРЯВАНЕ НА ЕНЕРГИЙНИ НАТОРАНИЯ НА СПИРАЧКИТЕ, КОИТО НЕ ПРЕВИШАВАТ ЕНЕРГИЙНИЯ ИМ КАПАЦИТЕТ ПО ВРЕМЕ НА ЦИКЛИЧНО СПИРАНЕ НА АВТОМОБИЛИ

# ENSURING ENERGY LOADS ON BRAKES THAT DO NOT EXCEED THEIR ENERGY CAPACITIES DURING CYCLIC BRAKING OF PASSENGER CARS

**Alexander Nazarov[1], Sergey Krivoshapov[2], Vyacheslav Pavlenko[3], Nikola Sergienko[4], Evgeny Kalashnikov[5]**

**Abstract.** The dynamics of braking of two-axle passenger cars in the mode of emergency and cyclic braking are considered. It is indicated that increasing the efficiency of modern brake systems leads to higher energy load, especially front disc brake mechanisms, which leads to temperature deformations and increased wear of friction surfaces. The paper establishes the relationship between the energy load of brakes and the distribution of braking forces between the axles of the vehicle. The results of the study of braking properties of the Lanos car are presented. The effectiveness of cyclic braking was evaluated and recommendations were given for its improvement using the example of the Lanos car. Conclusions and ways of further research are formulated.
**Keywords**: motor vehicles, braking system, efficiency, testing, power balance, distribution of braking forces..

## 1. Introduction:

The sharp increase in the number of passenger cars on the main roads of Ukraine and the increase in speed necessitates the need to ensure the safety of use, especially during emergency braking under various operating conditions [1].

Most studies [2–5] of the braking dynamics of two-axle vehicles are devoted to single, both service and emergency braking, where the issues of achieving maximum braking intensity due to the fullest possible use of the coupling weight while maintaining directional stability were considered exclusively.

Studies [6, 7] conducted during cyclic braking in mountainous and flat terrain reflect the influence of thermal load on the brakes, especially the front axle, on the braking efficiency of vehicles, without touching on the main reason - different energy load on the brakes at the initial moment of braking.

Thus, the issue of ensuring the safety of use of passenger cars during emergency braking on various sections of the highway is an urgent scientific and technical problem.

## 2. Presentation:

### Publication analysis.

Braking properties are one of the operational properties of passenger cars [3-8].

They are, to one degree or another, related to both the structural and weight parameters of the car, its braking system, the type and design of the brake mechanisms used, the brake drive, and the nature of the interaction of the wheels with the supporting surface in certain operating conditions.

It is known [1, 2] that in the process of braking passenger cars under the control of the brake drive, the piston of the wheel cylinder of the brake mechanism acts on the brake pads, and they, in turn, are pressed against the rotor. The resulting sliding friction force creates a friction moment that slows down the rotation of the wheels and the movement of the car. As a result of friction, heating and wear of the mating parts (pad-rotor) of the brake mechanisms occur [6, 7].

A worn brake pad creates less friction than a new one, and this reduces the efficiency of the brakes [7].

Many engineering developments throughout the history of the automotive industry have been able to significantly increase the efficiency and reliability of the brake system [3].

Drum-type brakes are not functionally stable, since when the pads rub against the rotor, heat is generated, which is sufficient to reduce braking efficiency by reducing the coefficient of sliding friction between friction pairs, especially if cyclic braking occurs [7]. Therefore, a decrease in braking efficiency occurs already at the initial moment of braking, when a certain amount of energy load on the brakes is exceeded, which maintains the heating temperature of the friction bodies.

A significant improvement occurs when using disc brakes. Currently, they are widely used on the front wheels of almost all cars. The disc brake system is equipped with a cast iron or steel disc or one made of a non-metallic material (carbon).

This effect is achieved by changing the rate of increase of the maximum value of the braking force on the front or rear wheels. Moreover, in all cases of regulation, the stability of the vehicle must be ensured. In this regard, in real brake systems of passenger cars, the coefficient of distribution of braking forces is chosen within 0.6-0.75 [3].

Existing methods and laws for regulating braking forces between the axles of passenger cars assume its change in accordance with the dynamic redistribution of the normal load between the axles of the vehicle.

In addition, wear of the mating friction surfaces of the brake mechanisms and their overheating during operation leads to a decrease in not only efficiency, but also safety of use [4].

Based on the above, the coefficient of distribution of braking forces should be chosen so that, in addition to solving the issues of efficiency and stability in the braking process, such an energy load on the front and rear brake mechanisms is ensured that does not exceed their energy intensity.

The same fact is noted in the work [5], which, when considering the influence of operational factors on the braking dynamics of a car equipped with a brake force regulator, indicates that the rationality of choosing the brake force distribution coefficient should be evaluated not only by braking efficiency, but also by maintaining the vehicle's controllability due to the rational energy load on the brake mechanisms. It should be noted that the process of brake force distribution is not constant, and can significantly change in both service and emergency braking modes [6].

Thus, in the works [7] it is indicated that during tests of a passenger car, where a mixed braking system is used, there is a significant delay in the operation of the rear brake drive compared to the front drive. This leads to the fact that cyclic braking is carried out mainly by the front brakes, which significantly exceeds their energy load and worsens the thermal mode of operation of friction parts.

Thus, it was established that:

– when the energy load of the brakes is exceeded, their dynamic characteristics deteriorate, which ultimately leads to a decrease in the braking properties of cars;

– the energy intensity of disc brakes is higher than that of drum brakes, in particular, due to the fact that they are better cooled, as a result of which they should be used on both axles of the car;

– higher braking efficiency leads to an excess of the energy intensity of the brakes, on which in most cases the stability of the braking moments created by the braking mechanisms depends, and, as a result, leads to a decrease in the safety of use;

– exceeding the energy consumption of the brakes causes temperature deformations of the mating parts, which dramatically affects the actual contact area of the friction surfaces of the mating parts and leads to a decrease in braking properties.

**Purpose of the work and research objectives.**

The purpose of the study is to improve the safety of passenger cars by ensuring that the energy load on their brakes does not exceed their energy capacity during cyclic braking during operation.

To achieve this goal, the following tasks should be solved:

– analyze the reasons for exceeding the energy capacity of the brakes, which ultimately leads to a decrease in the braking properties of cars;

– establish the relationship between the energy load on the brakes, on which the stability of braking torques depends, and the coefficient of distribution of braking forces;

– analyze the impact of the energy load on the brakes on the safety of passenger cars using the example of Lanos cars.

**Establishing the relationship between brake energy load and brake force distribution coefficient.**

The ratio of the energy capacities of the front and rear brakes, and therefore the stability of their characteristics, as well as the safety of using passenger cars, is determined by the braking force distribution coefficient [11]

$$\beta = \frac{T_1}{T_1 + T_2}, \tag{1}$$

where: $T_1$ and $T_2$ – braking forces on the front and rear axles.

We will evaluate the energy load and energy intensity of brake mechanisms using the example of disc brakes of a Lanos passenger car when reducing the coefficient of distribution of braking forces between the axles.

The assessment will be carried out under brake preheating modes that correspond to type 1 and type 2 tests [8].

The load conditions of brake mechanisms are determined by the vehicle loading state, braking conditions and the position of the center of mass (Fig. 1).

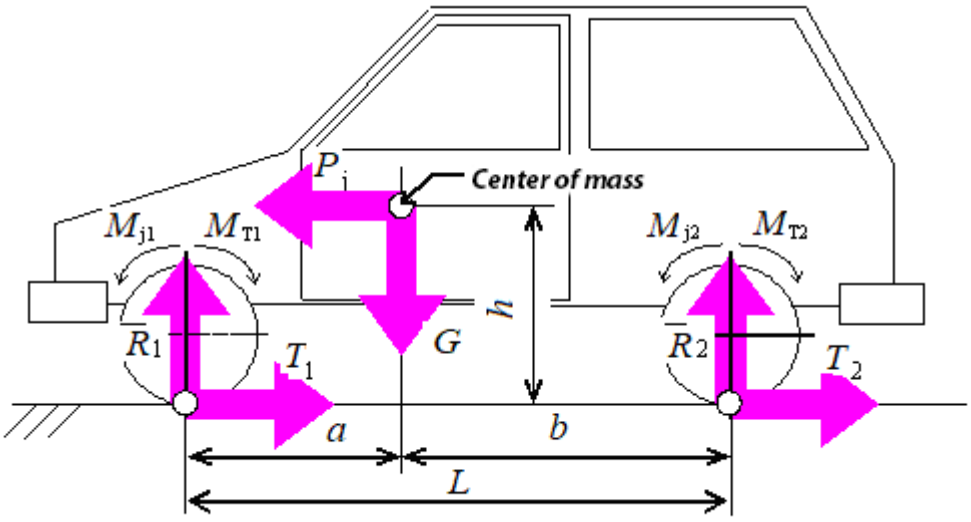



**Fig. 1.** Diagram of forces and moments acting on a car during braking

To create conditions for simultaneous maximum heating of the conjugate friction surfaces of the brakes of the front and rear axles, it is necessary to prevent the wheels from locking until the vehicle comes to a complete stop. This is possible with the corresponding maximum coefficient of specific braking forces of the vehicle, which depends on the coefficient of constant distribution of braking forces between the axles, established by Gredeskul A.B. [3, 4]

$$\beta_o = \frac{b + \varphi_o \cdot h}{L}, \tag{2}$$

where:
*b* - distance from the rear axle to the projection of the center of mass onto the supporting surface;
*h* - height of the center of mass;
*L* - longitudinal wheelbase of the car;
$\varphi_o$ - optimal coefficient of adhesion of wheels to the road.

Gredeskul A.B. proposes to choose for a single passenger car from the condition of equality of the coefficients of use of the coupling weight at the minimum (0.15) and maximum (0.8) values of the coefficient of adhesion of the wheels with the road

$$\varphi_o = \frac{a \cdot \varphi_{\min} + b \cdot \varphi_{\max}}{L}. \tag{3}$$

For the most effective braking of a car, it is necessary to create braking forces on the wheels equal to the maximum clutch forces, and the type and design parameters of the braking mechanisms should be selected so that the energy load does not exceed their energy capacity. These braking forces on the front and rear axles are determined by the formulas [1]

$$T_1 = G \cdot \varphi \cdot \beta_o = G \cdot \varphi \cdot \frac{b + \varphi_o \cdot h}{L}, \tag{4}$$

$$T_2 = G \cdot \varphi \cdot (1 - \beta_o) = G \cdot \varphi \cdot \frac{a - \varphi_o \cdot h}{L}, \tag{5}$$

where: *G* – Lanos car weight condition.

Theoretically possible decelerations of a Lanos passenger car are determined

$$j = \frac{\sum_{i=1}^{2} T_i}{G}. \tag{6}$$

The calculated parameter values, initial weight and layout data of the Lanos car with partial and full load are given in Table 1.

**Table 1.** Design parameters of the Lanos car and its brake system

| Loading the car | Parame-ters | Coefficient of adhesion $\varphi$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,7 | 0,8 |
| Curb weight 1096 kg | *a*, m | 0,959 | | | | | | |
| | *b*, m | 1,561 | | | | | | |
| | *h*, m | 0,561 | | | | | | |
| | *L*, m | 2,520 | | | | | | |
| | *G*, N | 10960 | | | | | | |
| | $\beta_0$ | 0,669 | 0,693 | 0,717 | 0,742 | 0,766 | 0,790 | 0,815 |
| | $T_1$, N | 1169 | 1817 | 2507 | 3241 | 4017 | 4835 | 5690 |
| | $T_2$, N | 579 | 805 | 989 | 1129 | 1227 | 1283 | 1296 |
| | $T_\Sigma$, N | 1748 | 2622 | 3496 | 4370 | 5244 | 6118 | 6992 |
| | *j*, *m*/s$^2$ | | | | | | | |
| Gross weight 1595 kg | *a*, m | 1,185 | | | | | | |
| | *b*, m | 1,335 | | | | | | |
| | *h*, m | 0,471 | | | | | | |
| | *L*, m | 2,540 | | | | | | |

| Loading the car | Parame-ters | Coefficient of adhesion $\varphi$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0,2 | 0,3 | 0,4 | 0,5 | 0,6 | 0,7 | 0,8 |
| | *G*, N | 15950 | | | | | | |
| | $\beta_0$ | 0,582 | 0,607 | 0,631 | 0,656 | 0,681 | 0,705 | 0,730 |
| | $T_1$, N | 1313 | 2052 | 2847 | 3697 | 4602 | 5563 | 6579 |
| | $T_2$, N | 941 | 1329 | 1661 | 1938 | 2160 | 2326 | 2437 |
| | $T_\Sigma$, N | 2254 | 3381 | 4508 | 5635 | 6762 | 7889 | 9016 |
| | *j*, *m*/s$^2$ | | | | | | | |

Analysis of the obtained calculated data of the Lanos passenger car shows that in the case of a curb weight, the ideal coefficient of distribution of braking forces varies within wider limits of 0.669–0.815, while at full load 0.582–0.730. In this case, the constant coefficient of distribution of braking forces is 0.76. The total braking force of 6992 N provides a deceleration of 6.38 m/s$^2$ of the car in a curb condition, and 9016 N - 5.65 m/s$^2$, which is 11.4% less.

If you adjust the change in the coefficient of distribution of braking forces within the specified limits, this will not lead to a decrease in the realized decelerations, and the energy load of the brakes of the front axle and rear axles will not exceed their energy capacity, which will ensure the stability of the braking moments on the vehicle axles and the safety of their use.

**Justification of the results obtained.**

The kinetic energy absorbed by the brakes of a passenger car during one braking operation of the previous stage of type 1 tests [8] is in kJ

$$W_{T1} = 1{,}27 \cdot 10^{-5} \cdot \vartheta_a^2 \cdot \frac{\sum_{i=1}^{2} T_i}{j}, \tag{6}$$

where: $\vartheta_a$ = 31,5 m/s – initial braking speed of a passenger car during tests.

The friction work performed by the brakes during successive braking operations of the previous stage of type 1 tests is determined by

$$A_{TP} = W_{T1} \cdot n, \tag{7}$$

where: *n* – number of consecutive braking operations performed.

The average friction power in the brake mechanisms during successive braking of the previous stage of type 1 tests, kW, is

$$\overline{N}_{TP} = \frac{A_{TP}}{1000\tau}, \tag{8}$$

where: $\tau$ – time of one braking cycle.

The frictional work performed by the vehicle brakes in the preliminary Type 2 test phase is determined in kJ.

$$A_{TP} = \frac{G \cdot S \cdot \sin\alpha}{1000}, \tag{9}$$

where:

*S* – descent length, m [8];

$\alpha$ – road longitudinal slope angle, degrees [8].

The average friction power in the brake mechanisms at this

$$\overline{N}_{\text{TP}} = \frac{A_{\text{TP}} \cdot \vartheta}{S}, \tag{10}$$

where: $\vartheta$ – car speed on the descent [1].

The work and average friction power developed by the front disc brakes is determined by

$$A_{\text{T1}} = \beta \cdot A_{\text{TP}}, \tag{11}$$

$$\overline{N}_{\text{TP1}} = \beta \cdot \overline{N}_{\text{TP}}, \tag{12}$$

where: $\beta$=0,76 – braking force distribution coefficient between Lanos axles.

The preliminary stage of type 1 and type 2 tests of passenger cars is carried out by the method of sequential braking, the mode of which is given in Table 2.

**Table 2.** Type 1 and Type 2 test modes [8]

| Initial braking speed $\vartheta_0$, m/s | Final braking speed, m/s | Duration of one cycle, $\tau$, s | Number of brakings, n | Descent length *S*, m | Descent angle, degrees | Downhill speed, $\vartheta$, m/s |
|---|---|---|---|---|---|---|
| 31,5 | $0{,}5\vartheta_0$ | 45 | 15 | – | – | – |
| | 0 | – | 30 | 6000 | 4 | 8,3 |

The results of parameter calculations for the Lanos car are given in Table 3 for different values of the braking force distribution coefficient between the axles.

**Table 3.** Estimated energy load of the brakes of the front axle of the vehicle

| Parameter | | Trial | |
|---|---|---|---|
| | | type 1 | type 2 |
| $W_{\text{T1}}$, kJ | | 380 | – |
| $A_{\text{TP}}$, kJ | | 5705 | 4010 |
| $\overline{N}_{\text{TP}}$, kW | | 126 | 5,548 |
| $\beta$=0,76 | $A_{\text{TP1}}$, kJ | 4450 | 3128 |
| | $\overline{N}_{\text{TP1}}$, kW | 98 | 4,3 |
| $\beta$=0,5 | $A_{\text{TP1}}$, kJ | 2852 | 2005 |
| | $\overline{N}_{\text{TP1}}$, kW | 63 | 2,7 |

As follows from the analysis of the calculated values (see Table 3), with a decrease in the coefficient of distribution of braking forces between the vehicle axles by 34%, the energy load of the front axle brakes, compared to the rear axle brakes, in tests type 1 and type 2 decreases by almost the same amount.

This indicates that by reducing the coefficient of distribution of braking forces to 34%, the energy load of the rear brakes of Lanos passenger cars can be increased by the same amount, which will create conditions for ensuring, on the one hand, stability of braking by reducing the temperature effect on the friction surface of the front axle brakes, and on the other hand, an increase in the temperature effect on the friction surface of the rear axle brakes. As a result, this will lead to the stability of the efficiency of cyclic braking of the vehicle, since the energy load of the braking mechanisms of the front and rear axles will be provided within their energy capacities.

## 3. Conclusion:

The safety of using Lanos passenger cars that perform cyclic braking can be increased by

increasing the energy load of the rear axle braking mechanisms to 34% by ensuring such a coefficient of distribution of braking forces between the axles that would not lead to exceeding their energy capacities.

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For contacts:
[1] Ass Prof. PhD. Nazarov Alexander Ivanovich, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(099)-704-41-23, hefer64@ukr.net.
[2] Ass Prof. PhD. Krivoshapov Sergy Ivanovich, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(057)-707-37-68, keat@khadi.kharkov.ua.
[3] Ass Prof. PhD. Pavlenko Vyacheslav, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(095)- 876-01-08, vp.khadi@gmail.com.
[4] Ass Prof. PhD. Serhienko Mykola, Kharkov National University "Kharkov Polytechnic Institute", Department “ Automobile and Tractor Engineering”, Kirpichova str. 2, Kharkov, Ukraine, +38(050)-632-72-14, nesergienko@gmail.com.
[5] Ass Prof. PhD. Kalashnikov Evgen, National Aerospace University named after M.E. Zhukovsky "Kharkov Aviation Institute", Department “Intelligent Virtual Systems and Energy Engineering”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, y.kalashnikov@khai.edu.

# ДИГИТАЛНА ТРАНСФОРМАЦИЯ НА ДИАГНОСТИЧНИТЕ ПРОЦЕСИ В ТРАНСПОРТА С ИЗПОЛЗВАНЕ НА ИНТЕЛИГЕНТНИ ИНФОРМАЦИОННИ РЕШЕНИЯ

# DIGITAL TRANSFORMATION OF DIAGNOSTIC PROCESSES IN TRANSPORT USING INTELLIGENT INFORMATION SOLUTIONS

**Vyacheslav Pavlenko[1], Vitaliy Pavlenko[2]**

**Abstract.** The article presents the results of a study on the possibilities of applying intelligent systems in the automotive service industry. Various approaches to the creation and optimization of intelligent systems, their structure and functions are considered. Particular attention is paid to the use of multi-agent systems for solving planning and management tasks under conditions of uncertainty.

**Key words:** intelligent systems, automotive service industry, multi-agent systems, planning, management, optimization, decision-making, diagnostics, maintenance, information technology.

## 1. Introduction:

Reliability is one of the key characteristics of complex technical facilities used in the industrial and technical sector. At all stages of the “life cycle” of such facilities - from design to manufacture and operation, including power, metallurgical, mining, oil and gas installations, machines and systems - reliability is ensured by special methods and means specific to each of these stages. A particularly effective level of operational reliability for renewable systems can be achieved through modern approaches to maintenance based on an assessment of the facility's condition. This includes strategies of functional diagnostics (with control of the reliability level) and technical monitoring (with control of the technical condition), the implementation of which requires appropriate technical diagnostics and monitoring systems.

The information, analytical, and intelligent functions of such systems allow, even outside of real time, to effectively carry out maintenance, as well as to plan and implement repair work, taking into account the actual technical condition of the equipment and the residual life of the system [1]. The requirements for the software of the onboard control system include ensuring reliable and safe operation in three main modes: automatic control, advisor mode, and manual control. The realization of these functions became possible due to the active use of modern information and intellectual technologies, in particular expert systems (ES) based on knowledge and the ability to automatically logically derive new information.

The conceptual basis for the intellectualization of diagnostics, forecasting and management processes is the characteristic features of tasks that belong to the class of poorly structured or poorly formalized problems [2], including:

– limited opportunities for obtaining complete and objective information, which complicates the adoption of informed decisions and necessitates the involvement of informal data sources (subjective, expert or heuristic);

– the presence of uncertainties in the initial data, as well as ambiguity and multivariance in the choice of ways to solve problems;

– the need for quick decision-making in the face of tight time constraints imposed by the dynamics of managed processes;

– the need for constant refinement of decisions and interactive interaction between a person and the system when searching for the best option (human-machine communication).

Taking into account these factors leads to the rejection of traditional algorithmic approaches to management and decision-making, directing development towards the use of intelligent technologies. The intellectualization of on-board automated diagnostic systems requires a comprehensive solution to a number of interdependent tasks related to the structural, functional, information, and organizational architecture of the system. These aspects should be taken into account at the design stage of the on-board diagnostic system software.

From a technical point of view, each vehicle is an object with a limited service life. During operation, its technical condition changes under the influence of external and internal operational factors, which leads to wear and tear of parts and mechanisms, unbalanced settings, loosening of fasteners, breakdowns, and other malfunctions.

In the course of operation of electrical machines and apparatus, their electrical and mechanical characteristics, including the properties of insulating materials, gradually deteriorate. This leads to a decrease in the reliability of individual components, assemblies, and the vehicle as a whole. As a result of the gradual exhaustion of the reliability resource laid down in the design, its level may fall below the critical value, which increases the likelihood of failure during operation. Such a failure can lead to emergencies, disruption of the traffic schedule, fuel or electricity overruns, etc. An important function of technical diagnostics systems is to timely identify the preconditions for such consequences and ensure the safe operation of vehicles.

In practice, real automated control systems have already been implemented and are operating, in particular, in rail transport. For example, locomotive depots successfully use a system for the automatic control of passenger trains. Such systems collect data in real time, including information on the position of controls, pressure in main lines, currents, etc. The auto-driving system also includes a diagnostic subsystem that analyzes a large number of signals from the locomotive's control circuits. However, these systems still do not have a sufficient level of intelligence, as they cannot promptly provide information to the decision maker directly while driving. In addition, to analyze the collected data, it is often necessary to move it to stationary maintenance stations.

When considering automated systems for controlling and monitoring the technical condition of vehicles, it should be borne in mind that their intellectualization is carried out through integration with intelligent transport systems. The latter, in turn, are part of broader intelligent information systems (IIS) and technologies.

**2. Description:**

An intelligent information system (IIS) is one of the forms of automated information systems, sometimes defined as a knowledge-based system [3]. It is an integrated set of software tools, logical and mathematical models, and linguistic tools designed to support user activities and ensure effective information retrieval in the format of an extended dialog.

An information system (IS) is an interconnected combination of hardware, software, methods and personnel used to accumulate, process, store and retrieve information in order to achieve the goals set in a particular area.

The main task of an IMS is to ensure the collection, accumulation, processing, retrieval and presentation of information necessary for making informed decisions within a particular subject area.

Although information systems are generally a type of software, they have a number of significant differences from standard application programs. Depending on the area of application, IS may differ significantly in their functional content, architectural solutions, and implementation principles. At the same time, there are at least two universal features that are common to all information systems.

First, any IS is designed to work with information - to collect, store and process it. Therefore, each system is based on an environment that is responsible for reliable data storage and provides efficient access to it. This environment must meet the requirements of the industry in which the system operates, in particular in terms of security, performance, and scalability.

Secondly, information systems (IS) should be end-user oriented. This means that the system interface should be intuitive, easy to use and easy to learn. At the same time, it should provide the user with all the necessary functionality to perform tasks, but at the same time limit the possibility of unwanted or erroneous actions.

Intelligent information systems (IIS) can be placed on any web resource. If the system has a question-and-answer format, the user formulates a query and receives an answer. In the case

of an expert system, the user gradually finds the necessary information by answering questions from the system itself.

The basis of every PIS is a database (DB), an organized collection of information related to a particular subject area.

Modern information technologies (IT) are created with a focus on the needs of IS and are designed to implement their functionality. Information technology is a process that includes the sequential execution of operations and actions according to clearly defined rules and at different levels of data processing complexity:

- data interpretation. This is one of the classic tasks of expert systems, which is to determine the content of the information provided. The interpretation process should provide consistent and correct results. As a rule, a multivariate approach to data analysis is used.
- diagnosis. It involves assigning an object to a certain category and identifying deviations from the norm, i.e. malfunctions. This approach allows the principles of diagnostics to be universally applied to both technical objects (e.g., equipment) and living organisms or natural phenomena, considering their anomalies from a single theoretical position.
- monitoring. Its main goal is to continuously monitor system parameters in real time with subsequent notification of deviations from the permissible limits. The main challenges are the risk of missing critical situations or, conversely, false alarms.
- design. This is the process of developing specifications for creating objects with specified properties. To achieve efficiency, especially in the context of redesign, it is necessary not only to formulate technical solutions but also to argue the reasons for their adoption. Thus, within an expert system, design combines the process of logical decision-making and explanation.
- forecasting. It is aimed at predicting the possible consequences of events or phenomena based on the analysis of current information. Predictive systems perform logical inference, forming probable scenarios and providing appropriate estimates.
- planning. It involves building sequences of actions aimed at achieving a certain goal by objects capable of performing functions. Such expert systems use models of the behavior of real objects, which allows to logically predict the consequences of planned actions.
- training. Learning systems detect typical user mistakes when studying a certain discipline with the help of a computer, suggesting the right solutions. They accumulate knowledge about the “learner” - his or her behavior, problem areas, and individual learning characteristics.

Intelligent information technologies (IIT) are usually understood as technologies that include the following key characteristics:

- availability of knowledge bases containing the generalized experience of individual specialists, teams, society or humanity as a whole in solving complex, creative tasks in various fields of activity. These tasks are usually poorly formalized and have traditionally been the domain of human intelligence (e.g., design, decision-making, learning, explanation, etc.);
- the use of thinking models based on knowledge rules and logical conclusions, as well as the ability to argue, reason, recognize and classify situations, generalize and interpret information;
- the ability to make informed decisions even when the input data is unclear, incomplete or ill-defined;
- the availability of an explanation mechanism that allows to substantiate the conclusions and decisions;
- the ability to learn and adapt, which ensures the development and improvement of efficiency over time.

Information technologies that support the decision-making process (Decision Support, DS) act as expert system shells or specialized expert systems. They help analysts identify relationships between structured enterprise data and evaluate and predict the consequences of various management decisions.

The concept of a decentralized approach involves the interaction of independent solving systems (agents) in a common environment. In this environment, certain rules or constraints are established, and a common global goal is defined. Each agent acts in accordance with the given constraints, pursuing its own local goal and coordinating its actions with other agents. If a sufficient number of agents are focused on achieving a common goal, this global goal will eventually be achieved.

At the initial stage, only a fraction of the agents respond to the formulation of the global goal. Taking into account the limitations of the environment, this leaves only one agent that is directly involved in achieving this goal. Further refinement of the task in the form of subgoals again activates the interest of several agents [4]. As a result, the global goal is decomposed into a number of subgoals, the optimal composition of agents ensuring its implementation is determined, the structure of interaction between them is formed (relevant only for the period of solving a specific task), and, as a result, the solution of the original task is achieved (Fig. 1).

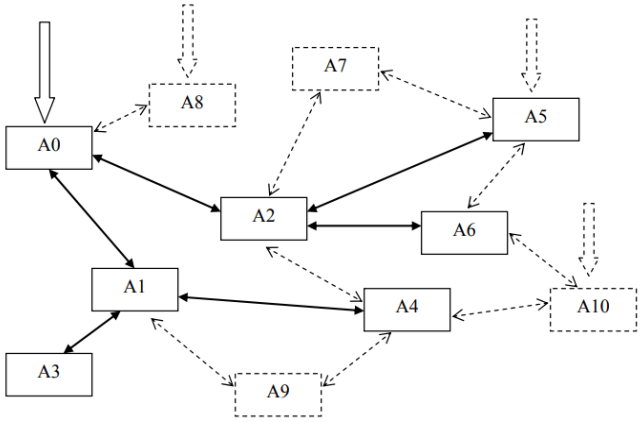



**Fig. 1.** Decentralized multi-agent system

In the context of planning in a decentralized management environment, the development of a plan is carried out by several agents without the participation of a single central coordinator capable of assessing the situation from the perspective of the entire system. This approach inevitably leads to possible conflicts in a multi-agent environment, as an individual agent may set a goal that contradicts the goals of other participants [5]. In this regard, detecting and eliminating undesirable interactions between agents in a decentralized system is a more difficult task than in a centralized way of management.

The essence of the mixed approach is to integrate elements of both centralized and decentralized approaches. The choice in favor of one or the other method is made taking into account the amount and depth of knowledge about the structure of the goal tree available in the system. For example, if the subject area of an intelligent system can be pre-structured, then local goals for each agent, as well as the relationships between them, can be determined in advance. In this case, agent management becomes hierarchical. In the process of achieving the overall goal, this generalized hierarchy is gradually specified to a clear tree structure that implements the solution of a specific task (Fig. 2).

In the opposite case, when the problem condition contains uncertainty about the static structure of the initial model, but the depth of the hierarchical tree is known, it becomes impossible to determine in advance the composition of the team of agents required to solve it, as well as to formulate specific local goals for each of them. However, it is possible to classify all agents in the system by levels of abstraction. This means that horizontal relationships can only be established between agents belonging to the same level of abstraction, while the plans of lower-level agents must be coordinated with the actions of higher-level agents.

Achieving a specific global goal involves the following outcomes:

- detailing it in the form of subgoals;
- determination of the composition of the executive team;

– formation of a structure of relations between agents that is relevant for solving a specific task;
– obtaining the solution to the original task.

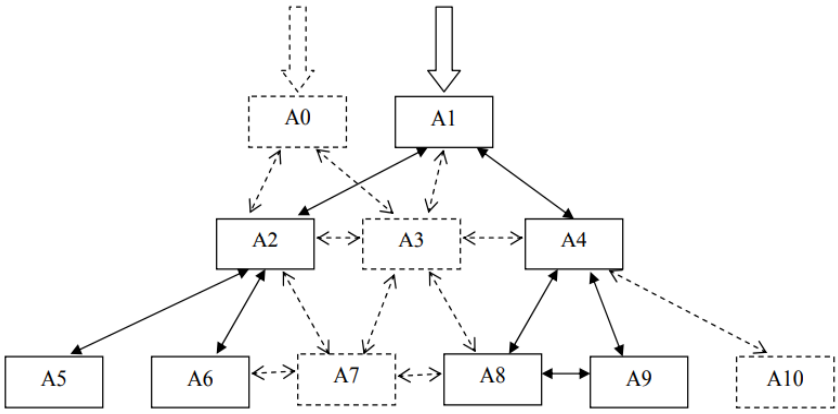



**Fig. 2.** Distributed multi-agent system with a hierarchical structure structure

In a mixed model, agents acting as local coordinators must be able to work under conditions of parametric and functional-structural uncertainty. In this case, the overall task is assigned to a set of such coordinating agents.

## 3. Conclusions:

After conducting a study that showed us a variety of ways to create and optimize intelligent systems, it turned out that their application in the automotive service industry is more than possible. Optimization is performed during the task itself, using real data. The absence of a system control center and the ability to adapt to changes in the network composition allows the system to provide a high degree of survivability.

The main component of a multi-agent system that distinguishes it from other systems is the artificial intelligence of agents. And its creation has not yet been completed and does not have exact ways of implementation. However, thanks to the existing achievements in the field of computer technology, mathematics, technical neuroscience and their interaction, there is only a small step to create a system that will change the perception of car maintenance capabilities and raise the automotive industry to a new level.

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Contacts:
1 Pavlenko Vyacheslav, Associate Professor, PhD. in Technical Science. Kharkov National Automobile and Highway University, Department “Technical operation and service vehicles”. Yaroslava Mudroho str. 25, Kharkiv, Ukraine, 61002 Tel.: +380577073768. E-mail: vp.khadi@gmail.com
2 Pavlenko Vitaliy, Professor, D.Sc. (Eng.), Doctor of Technical Sciences, National aerospace university "Kharkiv aviation institute", Department of Composite structures and aviation materials, Vadym Manko str. 17, Kharkiv, Ukraine, 61070 Tel.: +380577884857 e-mail: v.pavlenko@khai.edu

# ОДИТ НА ПЪТНАТА БЕЗОПАСНОСТ НА УЛИЧНИ УЧАСТЪЦИ СЪС СЪЩЕСТВУВАЩИ СПИРКИ НА ОБЩЕСТВЕНИЯ ТРАНСПОРТ

# ROAD SAFETY AUDIT OF STREET SECTIONS WITH EXISTING PUBLIC TRANSPORT STOPS

**Hennadii Ptytsia**[1], **Liudmyla Abramova**[2]

**Abstract.** This publication presents the results of an assessment of the operational conditions of sections of the urban street and road network, taking into account the impact of public transport stops (specifically for large cities on street sections with historical development). As a result of the study, the specific operational features of the selected site were identified, including an analysis of the operational conditions of a public transport stop within the existing street network. Based on the analysis, it is proposed to use a Road Safety Audit checklist to evaluate the operational conditions of street sections in the vicinity of public transport stops.
**Keywords**: Public Transport Stop, Road Traffic Safety, Traffic Efficiency, Traffic Management.

## 1. Introduction:

The problem of ensuring safety and traffic management on the streets and roads of settlements is attracting increasing attention in all countries due to the significant casualties and material losses in road traffic accidents. To ensure efficient road traffic, new strategies and approaches based on the implementation of a road safety management system are emerging every year. Among the others, the approach that is gaining more and more popularity and distribution is the road safety audit. Based on this approach, existing approaches are being modernised, new progressive approaches to assessing and improving road infrastructure aimed at preventing accidents are being developed and implemented.

To this end, European countries have adopted a new road safety policy: "forgiving infrastructure", which aims to prevent accidents from occurring and, if they do, to mitigate the consequences of accidents. Since people make mistakes, the task of road infrastructure is to minimise the occurrence of these mistakes.

The locations of public transport stops and their types in terms of planning and organisational decisions deserve special attention, as these places create manoeuvring conditions and mainly create conditions for pedestrian movement, which has a significant impact on safety and speed. Safety at stopping points is one of the main priorities of the operation of a facility in the city's street and road network, as these facilities are where contacts between transport and pedestrians occur, with passengers being the most vulnerable road users. In addition, the operation of transport stops should not have a significant negative impact on the capacity of the city's street and road network sections. And the stops must ensure the quality of transport services.

The need to evaluate traffic management measures arises due to its imperfection [1]. The directions of improvement of traffic management can be different and depend on the goal pursued in solving a particular problem [2]. Evaluation of measures can be carried out at local objects (traffic junctions, regulated and unregulated intersections, public transport stops, etc.), as well as on the transport network as a whole. The effectiveness of traffic management measures is assessed by comparing the costs required for their implementation with the traffic conditions and characteristics that will arise after the implementation of these measures [3]. In this case, it is customary to compare the effect obtained before and after the implementation of traffic management measures in terms of social, economic and environmental indicators [2-3].

The object of research in this paper is a typical section of the city's street and road network with a mandatory location of public transport stops. Urban passenger transport is one of the main factors that create an efficient and safe functioning of the city, ensuring social interaction of society, thereby connecting different parts of the city, creating a single system. Public transport stops are a systemic element of the city's planning structure, where passengers can transfer between different types of urban passenger and external transport or between different

lines of the same type of transport, as well as provide passengers with passenger services by social infrastructure facilities.

The specific design of a bus stop needs to be approached in the context of the street type and therefore the connection, in terms of its nature and traffic. Within the bus stop location, attention is focused on the safety of pedestrians arriving at the bus stop and passing public transport vehicles and when using traffic controls.

The object of the study is the traffic process in the area of a public transport stop. Therefore, street sections with the location of a public transport stop in one of the major cities of Ukraine, in particular, on the example of Chernivtsi, were subject to analysis.

## 2. Methodology for stopping point road safety audit:

To inspect the safety of a stopping point for compliance with the requirements of safe and comfortable operation, it is necessary to develop an inspection form [4, 5]. In this work, the form is made in the form of a table and is presented in Figure 1.

Materials required for this audit:

- a stop inspection form - required to record the data obtained;
- a tape measure - for measuring distances (width and length).

The experiment was conducted in several stages. At the first stage, the stop audit form included information about the arrangement:

- presence/absence of a stopping pavilion;
- presence/absence of benches for passengers waiting at the stop;
- presence/absence of garbage cans;
- information on technical means of traffic control;
- presence/absence of a side dividing strip;
- the presence/absence of a stowage pocket;
- presence/absence of lighting at the stopping point;
- presence/absence of pedestrian crossings and pedestrian fences;
- accessibility of the stopping point for people with limited mobility.

At the second stage, the necessary parameters are measured and the results of such indicators as:

- length and width of the stopping area;
- length and width of the landing area, its elevation above the carriageway;
- length and width of the entry pocket (if any);
- length and width of sidewalks and footpaths;
- location of the car pavilion - how far it is from the edge of the landing site;
- pedestrian crossings - the type of pedestrian crossing, how far it is from the stopping point and its width.

The data obtained was entered into the audit form of the stopping point with an analysis of the parameters of compliance with the safety requirements of the installed elements (Figure 1).

In determining the relevant ratios, the requirements of the regulations and the actual conditions at the time of the audit were taken into account. In particular, the following are subject to examination and consideration: $a$ - existing width of the stopping area, m; $a_0$ - width of the carriageway; $b$ - existing length of the stopping area, m; $b_0$ - required length of the stopping area in accordance with the standards, m; $h$ - height of the boarding platform, m; $a_{bp}$ - width of the boarding platform, m; $b_{bp}$ - length of the boarding platform, m; $r$ - existing distance between stopping points of opposite directions, m; $r_0$ - required distance between stopping points of opposite directions, m; $l$ - existing width of the boarding pocket, m; $l_0$ - required width of the boarding pocket, m; $s$ - distance from the stopping point to the ground pedestrian crossing, m; $s_0$ - required distance from the stopping point to the ground pedestrian crossing, m; $a_{sw}$ - existing width of the sidewalk or pedestrian paths near the stopping point, m; $a_{sw0}$ - required width of the sidewalk or pedestrian paths, m.

| Stop point security setting | Evaluation criterion |
|---|---|
| 1. Stopping area:<br>- Length - at least 25 m. with 2 vehicles stopping at the same time;<br>- Width - 3 m. | $k_{\mathrm{L}}^{\mathrm{sa}} = b / b_0$<br>$k_{\mathrm{W}}^{\mathrm{sa}} = a / a_0$ |
| 2. Boarding platform:<br>- Length - equal to the length of the stopping platform;<br>- Width - at least 1.5 m;<br>- Elevation above the IF - 0.2 m; | $k_{\mathrm{L}}^{bp} = b_{bp} / b$<br>$k_{\mathrm{W}}^{bp} = a_{bp} / 1,5$<br>$k_{\mathrm{H}}^{bp} = h / 0,2$ |
| 3. Boarding pocket:<br>- Length 13..60 m;<br>- Width at least 2.5 m.; | $k_{\mathrm{L}}^{\mathrm{p}} = b / b_0$<br>$k_{\mathrm{W}}^{\mathrm{p}} = l / l_0$ |
| 4. Sidewalks and footpaths:<br>- Width - sidewalk: ≥2.25 m;<br>footpath: ≥0.75 m;<br>- Type of pavement - asphalt/cobblestone | $K_{\mathrm{sw}} = a_{\mathrm{sw}} / a_{\mathrm{sw}\,0}$ |
| 5. Car pavilion/canopy:<br>- Pavilion location - ≥3 m;<br>- Equipment - benches, garbage can, information board; | $K_{\mathrm{cp}}$ = 1 in the presence of a closed car pavilion;<br>$K_{\mathrm{cp}}$ = 0,5 in the presence of a closed caravan in the presence of an open caravan;<br>$K_{\mathrm{cp}}$ = 0 in the absence of a car pavilion |
| 6. Pedestrian crossings<br>- Type - underground, above-ground, above-ground;<br>- Distance from the bus stop - ≥5 m;<br>- Width - 4..6 m; | $K_{\mathrm{pc}} = c / 2c_0$ |
| 7. Pedestrian barriers:<br>- Installed at aboveground or underground checkpoints, at least 50 m in both directions | $K_{\mathrm{pb}}$ = 1 – availability of pedestrian fences;<br>$K_{\mathrm{pb}}$ = 0 – lack of pedestrian fences |
| 8. Traffic Control Devices:<br>- Sign 5.45<br>- Markings | $k_{\mathrm{s}}$ = 1 If there are road signs that meet the requirements;<br>$k_{\mathrm{s}}$ = 0 in the absence of road signs that meet the requirements<br>$k_{\mathrm{m}}$ = 1 in the presence of markings that meet the requirements;<br>$k_{\mathrm{m}}$ = 0,5 if the markings do not meet the requirements or the markings are worn out by less than 30%;<br>$k_{\mathrm{m}}$ = 0 in the absence of markings; |
| 9. Accessibility of the bus stop for an inclusive group:<br>- Boarding/disembarking area - 2x2 m;<br>- Tactile tiles; | $K_{\mathrm{incl}}$ = 1 – present;<br>$K_{\mathrm{incl}}$ = 0 – missing |
| 10. Stopping point lighting | $K_{\mathrm{light}}$ = 1 – present;<br>$K_{\mathrm{light}}$ = 0 – missing |
| 11. The distance between stops of opposite directions:<br>- 30-50 m. if the width of the IF is less than 15 m. | $K_{\mathrm{od}} = r / r_0$<br>$K_{\mathrm{od}}$ = 1 with a carriageway width of more than 15 m |

**Fig. 1.** The road safety audit form in the public transport stop area

Thus, in the study of the safety of public transport stops, its compliance with all the criteria set out in the regulatory requirements for the organisation and arrangement of stops is checked. For the numerical evaluation of the results, it is proposed to use the formula [6, 7]:

$$S_{\mathrm{stop}} = K_{\mathrm{SA}} + K_{\mathrm{BP}} + K_{\mathrm{P}} + K_{\mathrm{SW}} + K_{\mathrm{CP}} + K_{\mathrm{PC}} + K_{\mathrm{PB}} + K_{\mathrm{TCD}} + K_{\mathrm{INCL}} + K_{\mathrm{LIGHT}} + K_{\mathrm{OD}} \quad (1)$$

where $K_{\mathrm{SA}}$ is the coefficient of compliance of the stop with the requirements for the stopping area,

$$K_{\mathrm{SA}} = k_{\mathrm{L}}^{\mathrm{sa}} + k_{\mathrm{W}}^{\mathrm{sa}} \quad (2)$$

$K_{\mathrm{BP}}$ is the coefficient of compliance of the stop with the landing site requirements,

$$K_{\mathrm{BP}} = k_{\mathrm{L}}^{\mathrm{bp}} + k_{\mathrm{W}}^{\mathrm{bp}} + k_{\mathrm{H}}^{\mathrm{bp}} \quad (3)$$

$K_{\mathrm{P}}$ is the coefficient of compliance of the stop with the requirements for the arrival pocket,

$$K_{\mathrm{P}} = k_{\mathrm{L}}^{\mathrm{p}} + k_{\mathrm{W}}^{\mathrm{p}} \quad (4)$$

$K_{SW}$ is the coefficient of compliance of the stop with the requirements for sidewalks;

$K_{CP}$ is the coefficient of compliance of the stop with the requirements for a stopping car pavilion;

$K_{PC}$ is the coefficient of compliance of a stop with the requirements for a pedestrian crossing;

$K_{PB}$ is the coefficient of compliance of the stop with the requirements for pedestrian barriers;

$K_{TCD}$ is the coefficient of compliance of the stop with the requirements for Traffic Control Devices,

$$K_{\mathrm{TDC}} = k_{\mathrm{s}} + k_{\mathrm{m}} \quad (5)$$

$K_{incl}$ is the coefficient of compliance of a stop with accessibility requirements for an inclusive group of users;

$K_{light}$ is the coefficient of compliance of the stop with the lighting requirements;

$K_{OD}$ is the coefficient of compliance of a stop with the requirements for the placement of stops in opposite directions.

To evaluate the results obtained, it is proposed to apply a system of compliance with the safety of a public transport stop in terms of the percentage of the presence or absence of these regulatory requirements. Thus, stops can be conditionally divided into:

- safe - meet the requirements by 90-100%;
- conditionally safe - meet the requirements by 70-90%;
- conditionally unsafe - meet the requirements by 40-70%;
- unsafe - meet the requirements by less than 40%.

## 3. Road Safety Audit of a public transport stop on the example of a single stop:

In accordance with the established methodology for conducting a survey of public transport stops, 16 stops of the same type were audited: Karmelyuka str. (to the city centre); Karmelyuka str. (from the city centre); Hertsena str. (to the city centre); Hertsena str. (from the city centre); The Monastery (to the city centre); The Monastery (from the city centre); Dormitory (to the city centre); Dormitory (from the centre); Sadova str. (to the city centre); Sadova str. (from the city centre); City Polyclinic 5 (to the city centre); City Polyclinic 5 (to the centre); Beauty Salon "Eva" (to the centre); Beauty Salon "Eva" (from the city centre); Fedkovycha str. (to the city centre); Oleksandra Petryshchuka str. (from the city centre). All of these stops are located in the historic centre of Chernivtsi, are permanent and serve at least 2 public transport routes of the city.

In accordance with the survey methodology described, the Karmelyuka Street bus stop (to the city centre) was studied (Fig. 2).



**Fig. 2.** Situational plan for organising a stop

Based on the results of processing the collected data, the safety level of this stopping point was determined by the formula (1) According to this indicator, in accordance with the standard

provision and arrangement of the stopping point, the safety level of the public transport stop was determined in terms of the percentage of the presence or absence of the specified regulatory requirements. According to the adopted gradation, this object is classified as "conditionally unsafe".

The results of the inspection of the bus stop for all selected parameters of the road safety audit can be displayed graphically (Fig. 3) in the form of a diagram. As can be seen from the diagram, the investigated stopping point fully complies with regulatory requirements for 31% of the parameters, partially complies 31% of the parameters, and does not complies 38% of the parameters. According to the accepted classification, it belongs to the “Conditionally Hazardous” category because the total share of compliance with the standard is 52%. Thus, we conclude that this stopping point needs to be improved and brought in line with all regulatory requirements to ensure comfortable and safe use.

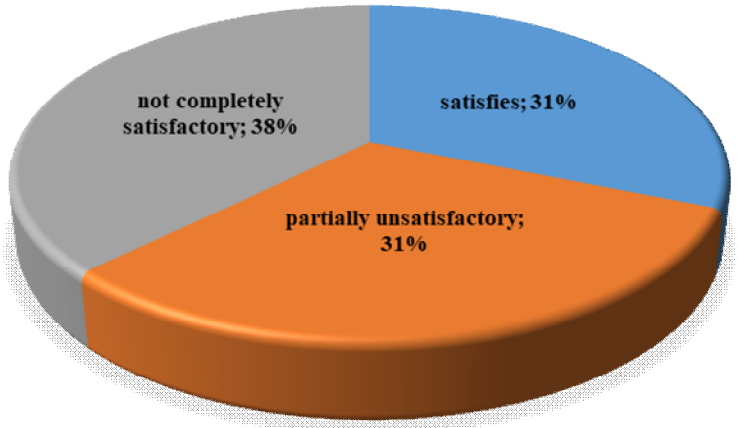



**Fig. 3.** Results of the safety inspection of the Karmelyuka Street bus stop

A similar methodology was used to study 16 bus stops located in the central part of the Shevchenkivskyy district of Chernivtsi on streets that are classified as residential and main district streets by technical parameters. The summary data is shown in Fig. 4.

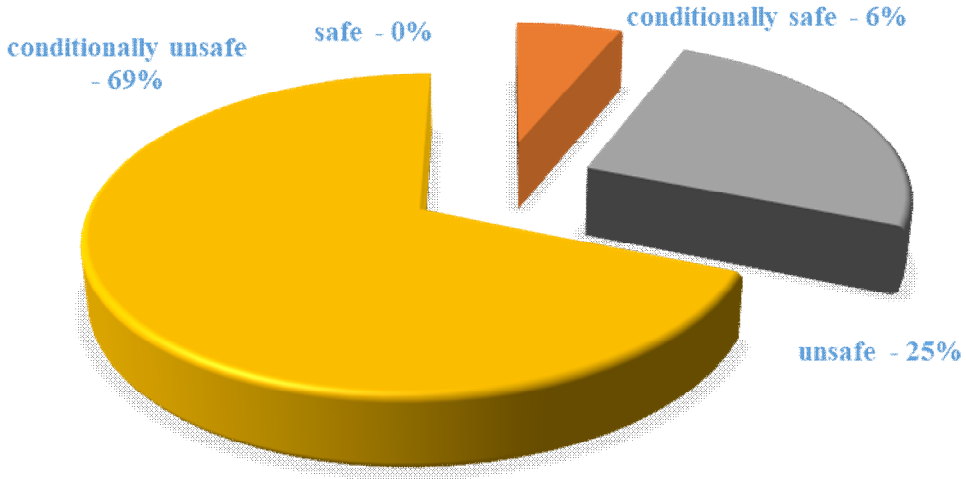



**Fig. 4.** Results of the safety survey at bus stops the central part of the Shevchenkivskyy district of Chernivtsi

## 4. Conclusions:

The conducted field observations of traffic conditions and the conditions of public transport stops arrangement allowed to form the necessary amount of initial information to determine the performance indicators of the selected objects. At the same time, a sheet of inspection of the conditions of arrangement of stops on the city's street and road network stretches was formed and proposed, which is proposed for further use in conducting an audit of road safety on the street and road network of cities. According to the proposed methodology, the safety

characteristics of the studied stops were determined: safe - 0%; conditionally safe - 6%; conditionally unsafe - 81%; unsafe - 13%.

Based on the above material, we draw the following conclusions:

1. Out of the 16 bus stops surveyed, none of them are adapted for an inclusive group of citizens;

2. Most of the stopping points are classified as "conditionally unsafe" (40-70% of the requirements are met);

3. To ensure safety at bus stops, it is necessary to bring them into compliance with regulatory requirements.

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**Contacts:**

[1] Ptytsia Hennadii, ass. prof., PhD, KhNAHU, Department of Traffic management and safety, Ya.Mudroho st., Kharkiv, Ukraine, +3(8050)6335893, e-mail:gennadij.ptitsa@gmail.com
[2] Abramova Liudmyla, prof., DSc, KhNAHU, Department of Traffic management and safety, Ya.Mudroho st., Kharkiv, Ukraine, +3(8057)7073706, e-mail:abramova_ls@ukr.net

# АДАПТИВНО ПЛАНИРАНЕ НА ТРАНСПОРТНОТО НАТОВАРВАНЕ В ГРАДСКИ B2C СЕГМЕНТНИ СИСТЕМИ ЗА ДОСТАВКА ПРИ УСЛОВИЯ НА НЕОПРЕДЕЛЕНО ТЪРСЕНЕ

# ADAPTIVE PLANNING OF TRANSPORT LOADS IN URBAN B2C DELIVERY SYSTEMS UNDER DEMAND UNCERTAINTY

**Natalia Ptytsia[1], Kateryna Kovtsur[2]**

**Abstract.** This study examines the optimization of B2C postal delivery systems based on the example of Nova Poshta B2C operations in Kharkiv. The research focuses on the analysis of statistical parameters of delivery volumes and quantities, taking into account the stochastic nature of demand. Using statistical modeling and the Pearson chi-square test, the hypothesis of a normal distribution for delivery volumes was confirmed. Key characteristics such as the mean and standard deviation were calculated for further transport system optimization. The findings enable more accurate forecasting, efficient route planning, and rational vehicle load distribution, ultimately enhancing cost-effectiveness and operational reliability. Special attention is given to reducing fuel consumption and improving the performance of transport engines under urban logistics conditions. The study contributes to improving the efficiency of express delivery operations by aligning economic and environmental priorities in transport planning.

**Keywords**: delivery system, B2C, road transport, transport efficiency, logistics costs.

## 1. Introduction:

The B2C (Business-to-Consumer) delivery segment represents a dynamic and rapidly evolving component of modern logistics systems. Driven by the exponential growth of e-commerce and the increasing expectations of end consumers, B2C delivery systems are under continuous pressure to improve responsiveness, service quality, and operational efficiency.

Unlike traditional B2B (Business-to-Business) models, where deliveries are often planned in advance and involve predictable volumes and routes, B2C logistics operates under conditions of high variability in both demand and geography. Orders are typically smaller in size but larger in number, and delivery locations are more dispersed. These characteristics present considerable challenges in terms of fleet optimization, scheduling, vehicle routing, and energy consumption.

## 2. B2C Segment Delivery Systems:

A key distinguishing factor of B2C delivery systems is the necessity to perform last-mile deliveries with high frequency and minimal delays. This significantly increases operational complexity and intensifies the technical demands on the transport fleet, especially in dense urban environments. As a result, logistics operators must prioritize vehicle efficiency, route flexibility, and load adaptability while keeping delivery costs and environmental impact under control.

In the Ukrainian context, operators such as Nova Poshta have developed extensive delivery networks that enable twice-daily pickups and deliveries to branches across urban centers. This frequency of operation within a stochastic environment, where shipment volumes vary from day to day, highlights the importance of integrating data-driven forecasting models into planning processes. Effective use of statistical methods to predict shipment flows and optimize vehicle utilization is becoming a critical success factor for ensuring both service quality and resource efficiency.

Furthermore, the shift toward more sustainable and energy-conscious logistics practices has emphasized the need to evaluate the performance of delivery vehicles not only in terms of cost, but also in terms of technical efficiency, fuel consumption, and adaptability to fluctuating loads. These considerations align closely with the broader goals of enhancing the operational resilience and ecological compatibility of urban transport systems in the B2C sector.

Thus, the study of B2C delivery systems requires an interdisciplinary approach, combining transport modeling, logistics planning, and transport engineering – with a focus on achieving high-performance standards in a complex, real-time delivery environment.

## 3. Description of Nova Poshta's logistics system:

The subject of the study was selected data on the delivery of postal goods by the express delivery operator Nova Poshta B2C. Nova Poshta B2C is the only postal network that covers all regions of Ukraine and is a leading operator in the national postal market. The company started its operations in 2001. Since then, Nova Poshta B2C has been offering its customers convenient, affordable, and high-quality services – delivery of goods and correspondence to any location in Ukraine. Transportation is carried out using all possible delivery technologies: "Warehouse-Warehouse", "Door-Door", "Warehouse-Door", and "Door-Warehouse" [1].

Nova Poshta B2C was one of the first operators in the express delivery market to provide a full range of services for the transportation of documents and cargo. Today, the company remains an undisputed leader in this sector in terms of turnover, volume, and quality of customer service [1]. A key focus of the company is the B2C segment, where fast and efficient delivery is essential for client satisfaction and loyalty.

This thesis examines the "Branch-to-Branch" segment in the Nova Poshta B2C logistics network in Kharkiv. The organization of this process involves the consolidation, storage, and processing of goods at a distribution terminal, after which they are loaded onto vehicles and transported to specific branches of Nova Poshta B2C. There are a total of 129 Nova Poshta branches in Kharkiv, including 15 cargo branches that handle items without weight restrictions. To maintain a high level of service, shipment delivery and pickup operations occur twice daily. Deliveries to the distribution terminal follow a fixed schedule and are carried out in accordance with all transport regulations and required accompanying documentation.

Previous research did not fully address the integrated process of transport service; instead, it focused primarily on the technological aspects of individual interactions. However, the overall efficiency of road transport significantly depends on the quality of planning and the level of organization of the delivery of material resources. Therefore, it is necessary to analyze all components of the delivery system without excluding any element.

The approaches proposed in [2, 3] for organizing and planning road transport allow the development of optimal delivery routes using criteria that consider the economic interests of both carriers and cargo owners. A key characteristic of express delivery operators such as Nova Poshta B2C is that from the moment the goods are accepted at the branch, the "carrier" effectively becomes the "cargo owner", pursuing a single economic goal – to maximize profit from the provided service.

Criteria for evaluating the efficiency of road transport operations are generally divided into two groups [2, 3]: natural and cost-based. Natural criteria (such as number of vehicles, material consumption, vehicle productivity, delivery time, etc.) are advantageous due to the relative simplicity of mathematical modeling. However, choosing a single evaluation criterion often leads to inevitable trade-offs, creating potential conflicts in decision-making.

To comprehensively assess the economic efficiency of transport operations in B2C delivery systems, it is essential to apply integrated evaluation methodologies that combine both operational performance indicators and technical characteristics of the transport fleet. In this regard, several approaches have been developed in transport economics and logistics engineering that aim to balance cost optimization with service reliability and environmental considerations. One such approach is multi-criteria decision analysis (MCDA), which allows for the simultaneous consideration of conflicting objectives – such as minimizing fuel consumption and delivery time while maximizing vehicle utilization [4]. MCDA techniques (e.g., AHP, TOPSIS) are particularly useful in urban express delivery systems, where trade-offs between speed, cost, and ecological impact are pronounced.

Another relevant methodology involves life cycle cost analysis (LCCA), which evaluates the total cost of vehicle operation over its lifespan, including acquisition, maintenance, fuel

consumption, and environmental externalities [5, 6]. This method enables a long-term view of transport engine performance and supports the selection of vehicle types best suited for specific delivery scenarios, particularly in high-frequency B2C networks.

Simulation-based modeling is also widely used for testing and optimizing delivery schedules under real-world constraints. By simulating delivery scenarios using stochastic demand inputs, planners can identify bottlenecks, evaluate energy usage, and adjust fleet configurations to better match demand patterns. Such models often incorporate emissions data and engine performance characteristics, allowing for environmentally conscious route planning.

Moreover, transport energy efficiency indicators – such as ton-kilometers per liter of fuel or $CO_2$ emissions per delivery unit – are becoming increasingly important in both regulatory and strategic contexts [7]. These indicators help express delivery operators align their logistics models with national sustainability goals and international standards on emissions reduction.

Integrating technical, economic, and environmental performance assessments into delivery planning is a critical step toward enhancing the overall efficiency of transport engines used in B2C systems. The adoption of such methodologies not only contributes to cost reduction and operational resilience but also plays a vital role in reducing the ecological footprint of urban logistics.

The efficiency and environmental impact of transport engines used in express delivery – including their fuel consumption, emissions, and suitability for urban logistics – are also crucial in the context of sustainable transport. Therefore, optimizing routing, vehicle load, and delivery scheduling contributes not only to economic efficiency but also to environmental performance.

The emergence of demand for postal delivery services, i.e., the volume of demand for items, is almost always unknown. Therefore, the main statistically uncertain indicator that affects the cost and organization of goods delivery is the volume of postal shipments to a single branch. The economic outcomes of a distribution center are thus random in nature, which negatively impacts the operational stability of an express delivery company.

The time intervals during which mail is delivered to the end consumer may vary significantly. An analysis of statistical data on the volume of shipments received at the distribution center and the volume of deliveries from the center to the branches confirms the stochastic character of this parameter. As a result, it is necessary to determine the stochastic properties of relevant random variables, such as the mean and standard deviation of shipment volumes. One of the key challenges in managing the daily flow of postal goods is the high variability of both the quantity and weight of items. Therefore, it is important to establish stochastic parameters such as the mean and standard deviation of the quantity and volume of postal items – both for the inbound flow from branches to the distribution center and for the outbound flow to branches.

The system of operational constraints includes: vehicle route durations must not exceed 10 hours; the delivery volume to each branch must not exceed vehicle capacity; each route must serve more than one branch; the maximum cargo load per vehicle must not exceed 10 tons due to city traffic conditions; all branches must be serviced within the operating time frame; and delivery is carried out using a uniform vehicle type.

Hence, it can be concluded that one of the fundamental conditions for ensuring the effectiveness of urban branch-based cargo transportation is the full and timely satisfaction of postal office demand for shipments – while maintaining minimal logistical costs. At the same time, the variability in demand, strict scheduling requirements, and urban infrastructure constraints place increased demands on the technical performance, reliability, and adaptability of the transport vehicles in use. This highlights the growing importance of optimizing transport unit performance and operational efficiency as a strategic factor in sustainable logistics systems.

**4. Analysis of statistical parameters of the system:**

Based on the analyzed values of the average volumes of postal goods and using statistical methods to determine the distribution law of the variation series, it was established that the

fluctuations in order volumes can be described by a normal distribution. The hypothesis of a normal distribution law was confirmed using the Statistica 10.0 software.

The parameters of this distribution law are the mathematical expectation (mean) and the standard deviation of the volume of postal goods. A graphical representation of the distribution of postal goods volumes delivered to and collected from the branches is presented in the Fig. 1.

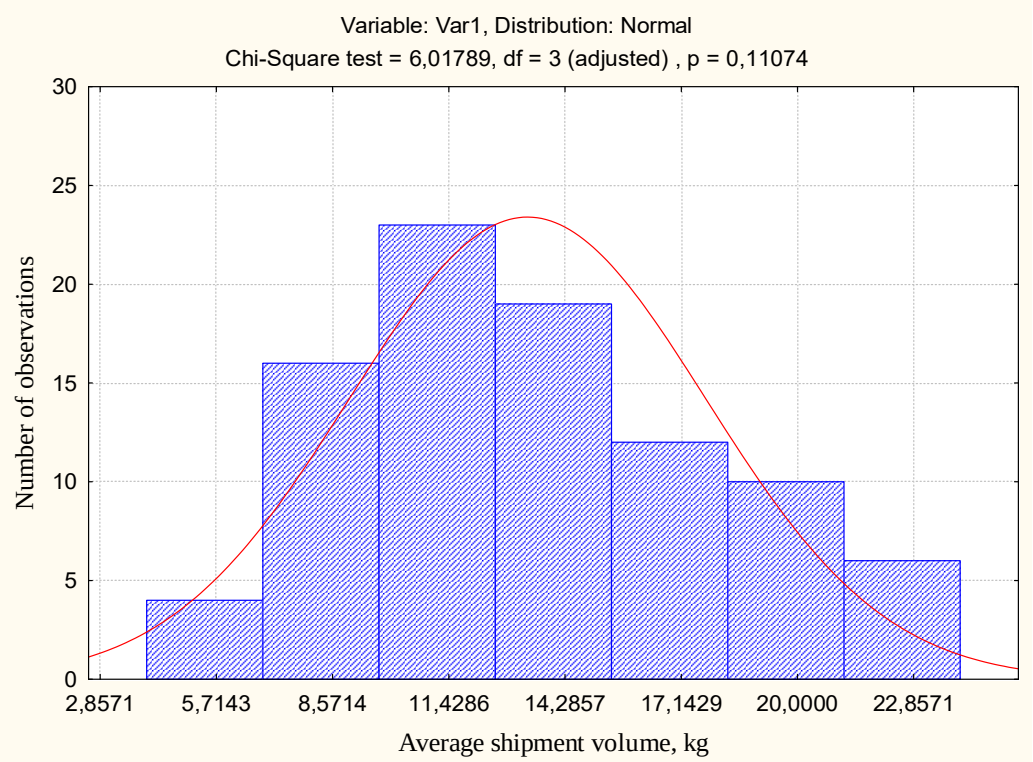



**Fig.1**. Distribution of postal goods in Nova Poshta offices

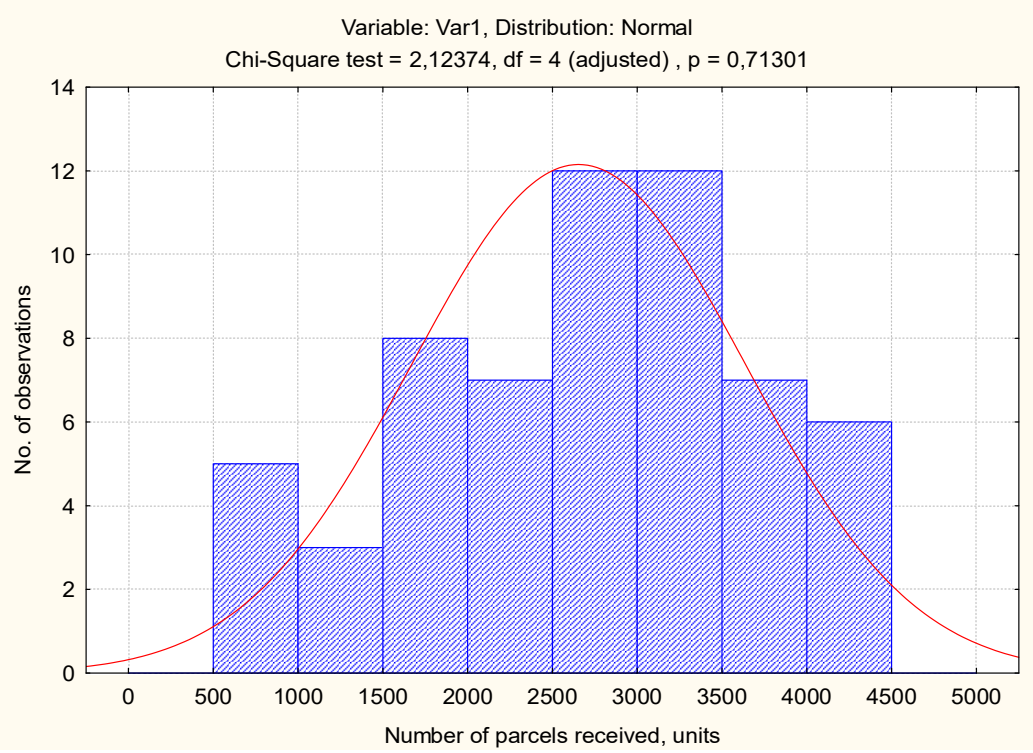



**Fig.2**. Distribution of the number of postal goods exported from Nova Poshta offices

Further analysis was conducted on the average number of postal goods received by branches from consumers and issued to consumers, as well as the stochastic parameters used

to determine the appropriate distribution law. Graphical representations of the distribution of the number of postal goods delivered to and collected from the branches are shown in Figures 2 and 3.

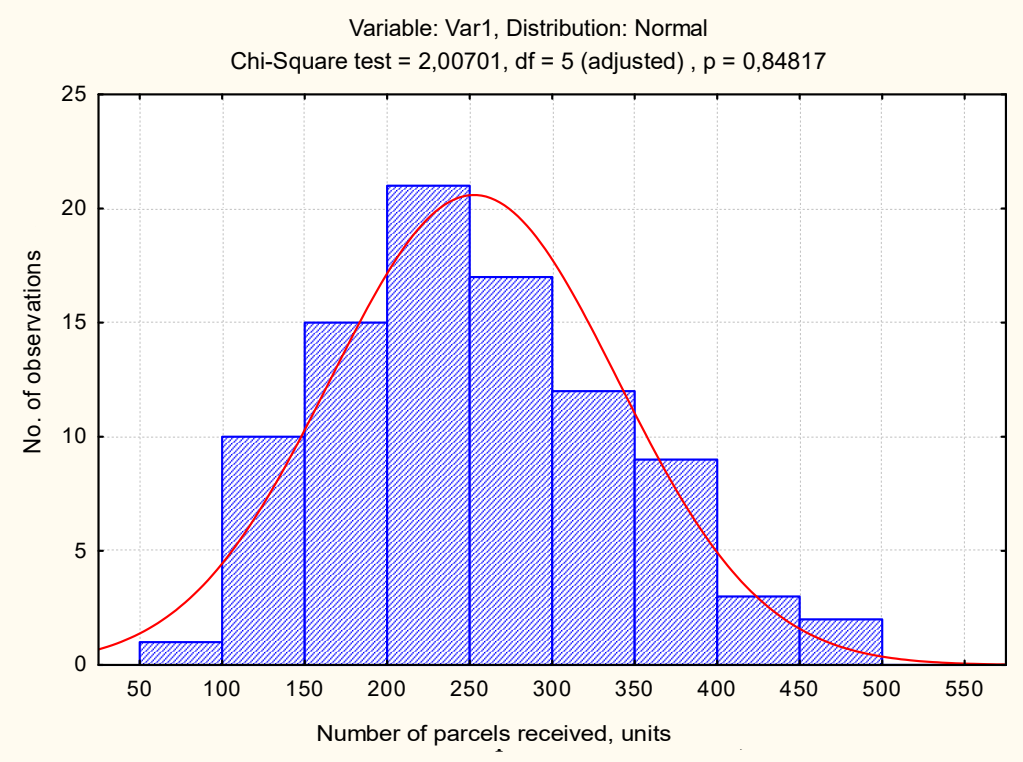



**Fig.3**. Distribution of the number of postal goods imported to Nova Poshta offices

To assess how well the processed data align with the normal distribution, the Pearson's chi-square ($\chi^2$) goodness-of-fit test was applied. The degrees of freedom, as well as the calculated and critical values of the Pearson criterion, are presented in Table 1.

Thus, the tabular values of $\chi^2_{0\cdot0.5;5}$ for all indicators exceed the calculated values, confirming the hypothesis that the data follow a normal distribution. The obtained numerical characteristics of the distribution parameters make it possible to adjust the transport component of postal delivery costs more accurately. This, in turn, contributes to optimizing vehicle load planning, reducing empty mileage, and increasing the overall efficiency of the delivery system—both in terms of operational performance and transport energy use.

**Table 1**. Indicators of determining the law of distribution

| Indicator | The law of distribution | Number degrees freedom | Indicators of determination distribution law | |
|---|---|---|---|---|
| | | | $\chi^2_{calc}$ | $\chi^2_{tabl}$ at $p$ = 0,05 |
| Volume of postal goods | Normal | 3 | 6,017 | 9,5 |
| Number of postal goods exported from offices | Normal | 4 | 2,027 | 12,6 |
| Number of postal goods delivered to offices | Normal | 5 | 2,007 | 11,1 |

**5. Conclusions:**

During the research, it was established that the primary task in improving the efficiency of postal goods delivery is to identify evaluation criteria that comprehensively reflect the parameters of the technological process. The analysis confirmed the need to develop a methodology for designing a rational delivery system, which would enhance the overall

efficiency of the enterprise's logistics operations and underline the relevance of the research topic.

The examination of the subject revealed key priorities and development directions for the enterprise. It was determined that a characteristic feature of the logistics system of a B2C express delivery operator such as Nova Poshta is the twice-daily delivery and pickup of postal items according to a fixed schedule. However, the volume and quantity of goods for delivery and pickup are random variables, which significantly complicates the process of accurate logistics planning.

Based on the analysis of statistical parameters of the delivery system, the average daily volume of postal goods delivered to and collected from a single Nova Poshta branch in Kharkiv was found to be 13.4 kg. The hypothesis of a normal distribution law for the average daily volume and quantity of inbound and outbound postal goods was confirmed. This statistical insight enables more accurate forecasting and supports the optimization of the transport component in cost calculations.

Given the specifics of the B2C delivery model, where logistics operations must flexibly adapt to constantly changing consumer demands, this approach becomes especially relevant. The ability to anticipate fluctuations in shipment volumes facilitates more efficient resource allocation, optimized vehicle scheduling, and improved overall service quality. Moreover, stable logistics under volatile conditions requires not only organizational responsiveness but also a high level of reliability and adaptability of the transport units used in the delivery process.

As delivery vehicles operate under tight schedules, variable load levels, and dense urban conditions, their operational efficiency directly influences the sustainability and resilience of the entire logistics chain. Therefore, the issue of optimizing transport performance goes beyond economic considerations and involves assessing the technical capabilities and energy efficiency of the vehicle fleet.

Further stages of this research will involve experimental studies of the postal delivery system, taking into account actual volumes and quantities of items transported to and from the branches, as well as the impact of these operational loads on transport efficiency under real-world conditions.

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**Contacts:**

[1] Ptytsia Natalia, Ph. D. of Engineering, Kharkov National Automobile And Highway University, Department of Transport Systems and Logistics, Yaroslava Mudrogo st., 25, Kharkiv, Ukraine, +38(057)707-37-83, e-mail: nataliya.ptitsa@gmail.com
[2] Kovtsur Kateryna, Ph. D. of Engineering, Kharkov National Automobile And Highway University, Department of Transport Systems and Logistics, Yaroslava Mudrogo st., 25, Kharkiv, Ukraine, +38(057)707-37-83, e-mail: kovtsyr@ukr.net

# ИЗСЛЕДВАНЕ НА ПРИЛАГАНЕТО НА ПАКЕТ ОТ ВЗАИМНО ДОПЪЛВАЩИ СЕ ИНВЕСТИЦИИ, НАСОЧЕНИ КЪМ РАЗВИТИЕТО НА СЪВРЕМЕНЕН, ЕКОЛОГИЧЕН И БЕЗОПАСЕН ГРАДСКИ ТРАНСПОРТ, ФИНАНСИРАНИ ПОСРЕДСТВОМ ИЗПЪЛНЕНИЕТО НА ПРОЕКТИ

# STUDY OF THE IMPLEMENTATION OF A PACKAGE OF COMPLEMENTARY INVESTMENTS AIMING AT THE DEVELOPMENT OF MODERN, ECOLOGICAL AND SAFE URBAN TRANSPORT, FINANCED THROUGH THE IMPLEMENTATION OF PROJECTS

**PhD Mihail Ivanov**

**Abstract.** The report examines the opportunities that project management provides as a tool for achieving modern, environmentally friendly and safe public transport in the city of Varna, located in the Northeastern planning region. The conducted studies show that the main part of the investments in urban transport of large municipalities are realized through the implementation of European projects. Investments aimed at purchasing new buses, trolleybuses, electric buses, automated ticketing systems and building accompanying infrastructure for the needs of public transport have been examined in detail. The study presents the effects of the implementation of the projects related to achieving the highest environmental standards, integration, increasing the number of passengers and improving the transport infrastructure in urban conditions.
**Keywords**: Urban transport, ecological, project management, trolleybuses, electric buses, eco-standards.

## Въведение

Изследвания на съотношението на населението на ЕС живеещо в градовете показва, че то се е увеличило от 71% през 2000 година до 73% към 2010 година. Очакванията са тази тенденция да се задълбочи и към 2050 година делът на градското население до достигне внушителните 82%. Нарастващия брой на градското население в големите европейски градове и периферните зони изправя местните администрации пред сериозни проблеми свързани с транспорта. Тенденцията една част от жителите на градовете да търсят спокойствието на близките предградия води до възникването на големи селищни структури с дълги разстояния за пътуване между тях. Стихийната урбанизация съчетана с увеличения брой на собствениците на автомобили и натоварения трафик водят до рязко удължаване на времето необходимо за пътуване. Модернизацията на градския транспорт, намаляването на задръстванията, пътнотранспортните произшествия и замърсяването представляват сериозно предизвикателства за всички големи градове. Статистическите данни показват, че натоварения трафик в градските и прилежащи зони води до преки загуби на европейската икономика и екологични замърсявания, които се изчисляват на 98 милиарда евро годишно [1]. Изследвайки и наболелия проблем с пътната безопасност виждаме, че приблизително 32% от пътнотранспортните произшествия с фатален край са се случили в градски условия. Мобилността в градовете е причина за около 40% от емисиите на въглероден диоксид от шосеен транспорт и над 25% от шумовото замърсяване в тези зони.

За тази цел Европейската комисия предоставя проектно финансиране, подпомага изследванията и разпространява добри практики като изготвянето на планове за градска мобилност за улесняване преминаването към други видове транспорт, т.е. намаляване на употребата на частни автомобили и увеличаване на използването на градски транспорт, както и на немоторизирано придвижване (колоездене и ходене).

**Изложение:**

**1. Състояние на градския транспорт в Община Варна преди прилагането на пакет от взаимодопълващи се инвестиции, насочени към развитието на съвременен, екологичен и безопасен градски транспорт**

Преди реализацията на проектите за модернизация на градски транспорт на Варна състоянието на предоставяната транспортна услуга и автобусния парк не отговаря на съвремените изисквания за екологичност и комфорт при превоз на пътници. Към онзи момент компанията „Градски транспорт” ЕАД - Варна разполага с над 170 автобуса. Голяма част от подвижния състав се състои от транспортни средства произведени в периода 1982-1997 година, които не отговарят на екологичните норми и са силно амортизирани. Последната партида фабрично нови транспортни средства дружеството „Градски транспорт” ЕАД - Варна получава през 1997 година, като доставката включва 33 автобуса марка „Мерцедес”. През 2003 година бяха закупени 20 рециклирани автобуса марка "Рено 312-С", които са произведени в периода 1991-1994 година. Извършения анализ на автобусния парк показва, че 45% от подвижния състав не разполага с екологична норма, а останалите разполагат едва с норма Euro 1 и Euro 2, като възрастта на транспортните средства е между 20 и 26 години. . Над 85% от използваните за превоз на пътници автобуси не разполагат с климатична инсталация или тя е технически неизправна. Наблюдават се следи от амортизация в купетата и корозия в 75% от превозните средства. Анализи показват, че разходът на гориво на голяма част от подвижния парк надвишава 42 литра на 100 километра, което допълнително увеличава разходите за експлоатация. Нуждата от ремонтни дейности е постоянна, като средния престой на един автобус в депата за ремонтни дейности е над 27 дни на годишна база. Компанията „Градски транспорт” ЕАД - Варна осъществява също и тролейбусен транспорт от 1986 година, като използва контактна мрежа с дължина от 51 километра и обслужва три автобусни линии. Преди реализацията на проектите за модернизация се използват около 40 броя тролейбуси произведени в периода 1986-1997 година, които постоянно аварират и имат силно завишени експлоатационни разходи. При официалния пуск на транспортните линии са закупени 30 нови тролейбуса марка „Шкода-14Tr”, които са произведени през 1986 година, а в периода 1999-2006 година са въведени в експлоатация още 12 броя рециклирани тролейбуси „Шкода-15Tr”.

При тролейбусните превозни средства също се наблюдава постоянна нужда от ремонтни дейности, като средния престой на един тролейбус в депата за ремонтни дейности е над 25 дни на годишна база [2,3].

Амортизацията на транспортния състав съчетана с липсата на комфортни условия за пътуващите води и до силно намален пътникопоток към автобусните линии. Статистиката показва, че един автобус във Варна превозва средно по 500 души на ден. Далеч по-ефективни се оказват градските автобуси в Бургас, където е изпълнен пилотен проект за интегриран транспорт. Там всеки автобус вози по 780 пътници дневно, а в София те са около 1400.

**2. Изпълнение на инвестиционни проекти финансирани от Европейските структурни и инвестиционни фондове насочени към модернизация на градския транспорт в град Варна**

След приемането на България в ЕС през 2007г. и последващия достъп до Европейските структурни и инвестиционни фондове позволи на редица населени места да се възползват от възможността за прилагане на мерки и реализацията на проекти насочени към развитието на модерен и екологичен градски транспорт. Финансирането се осъществява по Оперативни програми "Регионално развитие", "Региони в растеж" и "Околна среда" през отделните програмни периоди. В град Варна са изпълнени четири големи проекта включващи мерки насочени към цялостна подмяна на подвижния състав,

намаляване на шумовото замърсяване и увеличаване на енергоефективността, значително намаляване на вредното въздействие върху човешкото здраве в следствие на отделените газове, изграждане на BRT коридори, внедряване на интелигентни транспортни системи, изграждане на мрежа от зарядни станции за електробуси и изцяло нова билетна система, като проектите са на стойности вариращи между 28 млн. лева и 114 млн. лева.

Целевите групи, които пряко се възползват от изпълнението на проектите са следните:

- Население на град Варна – 350 705 жители по настоящ адрес;
- Туристи и гости на град Варна – 368 275 средно годишно;
- Фирми и организации, осъществяващи дейност на територията на град Варна – 27 733 стопански и неправителствени организации.

### 2.1. ПРОЕКТ № BG161PO001-1.5.03-0002 „ИНТЕГРИРАН ГРАДСКИ ТРАНСПОРТ НА ВАРНА”

Бенефициент по проекта: Община Варна

Изпълнени основни дейности по проекта:

- Изградена автоматична билетна система включваща: 60 машини за продажба на билети (МПБ) по едно на всяка спирка;
- Инсталирана Система за осигуряване на предимство на превозните средства на масовия градски обществен транспорт на кръстовищата;
- Изградена система за информация на пътниците в реално време включваща: Монтирани информационни табла на спирките – 84 бр. по едно за всяка спирка по BRT – коридора, както и на спирките на 12 стратегически места в града;
- Изграден център за управление на масовия градски транспорт – закупен софтуер и хардуер за автоматична локализация на превозните средства (регистрира закъснения, води статистика за експлоатацията, изчислява времето за пристигане на спирките и пренася данните до съответните терминали);
- Изграден BRT коридор - дължина – 14,850 км; BRT спирки – 28/29 двойни + 2 крайни.
- Обновен подвижния състав – закупени 30 бр. съчленени автобуса с дизелови двигатели, емисионен клас ЕВРО 6, които да обслужват BRT линията;
  20 бр., единични автобуса с дизелови двигатели, емисионен клас ЕВРО 6 бр.;
  20 бр. единични автобуса с двигатели на сгъстен природен газ;
- Изградени съоръжения за колоездене - три трасета за вело-алеи с обща дължина – 14,5 км. и още 1,8 км свързващи с вече съществуващите; проведена информационна кампания за насърчаване на колоезденето;
- Извършени подобрения на 3 крайни спирки – Владиславово, Бриз и Аспарухов мост.
- Извършени подобрения в производствено-техническата база на „Градски транспорт” ЕАД;
- Реализирани мерки за подобряване на достъпността в т.ч. мерки за достъпност за пътуващите за МГОТ – понижени тротоари до спирките; изградена нова специална настилка на спирките и рампите срещу заледяване; качена информация за движението на превозните средства на сайта на общината, както и посредством приложение за мобилни телефони; изпълнени мерки за достъпност за хора със специфични потребности – звукова сигнализация за слепи хора на кръстовищата, на автобусните спирки и в автобусите; изградени рампи за инвалидни колички в 30 от старите превозни средства на масовия градски транспорт. Закупени 3 нови микробуса за трудно подвижни хора.

**Бюджет на проекта:**

Обща стойност на проекта: 114 438 436,44 лева.

Безвъзмездна финансова помощ: 90 999 831,43 лева [4].

### 2.2. ПРОЕКТ №DIR-51315001-1-195 „ПРИЛАГАНЕ НА МЕРКИ ЗА ПОДОБРЯВАНЕ КАЧЕСТВОТО НА ЖИВОТ В ГРАДОВЕТЕ БУРГАС, ВАРНА, СТАРА ЗАГОРА И ПЛЕВЕН"

Бенефициенти по проекта: Община Бургас, Община Варна, Община Стара Загора и Община Плевен

Изпълнени основни дейности по проекта:

- Доставка и въвеждане в експлоатация на тролейбуси за нуждите на обществения транспорт в градовете Бургас, Варна, Стара Загора и Плевен, както следва: за община Бургас- 22 тролея, за община Варна- 30 тролея, за община Стара Загора- 8 тролея, за община Плевен- 40 тролея.

Специфични цели:

• Подобряване качеството на въздуха

• Намаляване на шумовото замърсяване /тролейбусите са най- безшумната форма на обществен градски транспорт към момента-при новите тролейбуси нивата на излъчвания шум от агрегатите по време на движение и по време на престой са значително по-ниски/

• Увеличаване на енергоефективността /посредством промяна на старите енергоемки тролейбуси с нови и значително по-икономични и имайки предвид, че тролейбусите по принцип са 1,9 пъти по-енергоефективни от автобусите/

• Осигуряване на среда, която не предлага вредно въздействие върху човешкото здраве

**Бюджет на проекта:**

Максимална стойност на ДБФП: 92 051 773,24 лева

Бюджет на Община Варна: 28 061 791 лева [4].

### 2.3. ПРОЕКТ № BG16RFOPO01-1.002-0003 „ИНТЕГРИРАН ГРАДСКИ ТРАНСПОРТ НА ВАРНА - ВТОРА ФАЗА“

Бенефициент по проекта: Община Варна

В рамките на проекта са включени 3 компонента, които са взаимосвързани:

Компонент 1 – Разширени и реконструирани улични артерии, свързани с оптимизацията на масовия градски обществен транспорт (МГОТ)

Конпонент 2 – Закупени нови превозни средства за МГОТ: Предвижда се закупуването на нови стандартни автобуси - 15 броя, отговарящи на европейски стандарт ЕВРО 6.

Конпонент 3 – Изградени интелигентни транспортни системи: Интелигентни системи за преброяване на трафика и координирано управление на светлинно регулираните кръстовища по трасетата на МГОТ. Системата за информация на пътниците в реално врене. Система за безопасност на пешеходците. Система за достъпност на пътните кръстовища.

Изпълнени основни дейности по проекта:

- Създаден е икономически по-изгоден градски транспорт, чрез изпълнение на дейности по разширяване обхвата на системата за осигуряване на приоритет на превозните средства (ПС) на масовия градски обществен транспорт (МГОТ) и закупуване на нов подвижен състав с по-нисък разход на гориво.
- Осигурен е устойчив, екологично чист градски транспорт с по-малко потребление на енергия, чрез доставка на нов подвижен състав, който ще има приоритет пред личните автомобили.
- Насърчена е мултимодалната устойчива градска мобилност чрез създаване на възможности за алтернативни форми на транспорт и тяхното подходящо комбиниране, в това число обществен транспорт, велосипеден, придвижване пеша, връзки с други видове транспорт.
- Увеличен е дела на ползващите услугата градски транспорт, посредством подобряване условията за ползване на обществения транспорт: чрез нов подвижен състав, бързо и комфортно придвижване с осигурения приоритет на превозните

средства, информираност за движението на всеки автобус, както и времето на пристигането му, вследствие на което е и спестеното време за придвижване.
- Подобрена е достъпността – нископодови автобуси с обособени места за специализирани колички за хора с увреждания, изграждане на подходи и платформи за хора с увреждания, улесняващи достъпа до спирки и светофари.
- Повишена е пътната безопасност на пешеходците чрез изграждане на нови пешеходни подлези и светофари за пешеходците „Умно управление“ и интелигентни пешеходни пътеки.

**Бюджет на проекта:**
Обща стойност на проекта - 34 954 419,60 лева.
Безвъзмездна финансова помощ - 26 743 077,42 лева [4].

### 2.4. ПРОЕКТ „ЕКОЛОГИЧНО ЧИСТ ТРАНСПОРТ ЗА ВАРНА“

Бенефициент по проекта: Община Варна
Изпълнени основни дейности по проекта:
- Доставени екологични, незамърсяващи превозни средства и зарядни станции. В изпълнение на дейността са обновени превозните средства, обслужващи масовия обществен градски транспорт в Община Варна, чрез закупуване на 60 броя нови електрически автобуса, които се приемат за най-екологичния вид превозни средства.
- В рамките на дейността е изпълнена доставка на: 40 броя електрически автобуси тип "соло" с приблизителна дължина 12 м, минимум седящи места 20 човека, с общ капацитет на пътници най-малко 65 човека, с оборудване ABS и ASR, с батерии от модулен тип с възможност за подмяна на отделни клетки/пакети и възможност за бързо и бавно зареждане, климатик и допълнително отопление; рампа за колички за трудно подвижни лица и детски колички.
- 20 броя електрически автобуса тип "съчленен", с приблизителна дължина 18 м, с минимум седящи места 36 бр., общ капацитет на пътници най-малко 80 човека.
- 60 броя бавни зарядни станции и 2 броя бързи зарядни станции, които са монтирани в депата на оператора „Градски транспорт” ЕАД.

**Бюджет на проекта:**
Обща стойност на проекта - 34 954 419,60 лева.
Безвъзмездна финансова помощ - 26 743 077,42 лева [4].

**Таблица 1.** Реализирани проекти за модернизация на градския транспорт [4]

| Наименование на проекта | Бенефициент | Сума на проекта | Основни дейности |
|---|---|---|---|
| ПРОЕКТ „ИНТЕГРИРАН ГРАДСКИ ТРАНСПОРТ НА ВАРНА – ФАЗА 1” | Община Варна | Обща стойност на проекта: 114 438 436 лева. Безвъзмездна финансова помощ: 90 999 831 лева. | Изградена автоматична билетна система; Инсталирана система за осигуряване на предимство на превозните средства на масовия градски транспорт; Изградени BRT коридор и велоалеи; Закупени 70 броя нови автобуса. |
| ПРОЕКТ „ПРИЛАГАНЕ НА МЕРКИ ЗА ПОДОБРЯВАНЕ КАЧЕСТВОТО НА ЖИВОТ В ГРАДОВЕТЕ БУРГАС, ВАРНА, СТАРА ЗАГОРА И ПЛЕВЕН" | Община Бургас Община Варна Община Стара Загора Община Плевен | Обща стойност на проекта: 92 051 773 лева Бюджет на Община Варна: 28 061 791 лева. | Доставка и въвеждане в експлоатация на 30 броя тролейбуси за нуждите на град Варна |
| | | | Разширени улични артерии; Доставка и въвеждане в експлоатация на 15 броя |

| | | | |
|---|---|---|---|
| ПРОЕКТ „ИНТЕГРИРАН ГРАДСКИ ТРАНСПОРТ НА ВАРНА – ФАЗА 2“ | Община Варна | Обща стойност на проекта: 34 954 419 лева. Безвъзмездна финансова помощ: 26 743 077 лева. | автобуси; Повишена е пътната безопасност на пешеходците чрез изграждане на нови пешеходни подлези и светофари; Подобрена е достъпността – нископодови автобуси с обособени места за специализирани колички за хора с увреждания |
| ПРОЕКТ „ЕКОЛОГИЧНО ЧИСТ ТРАНСПОРТ ЗА ВАРНА“ | Община Варна | Обща стойност на проекта - 34 954 419,60 лв. Безвъзмездна финансова помощ - 26 743 077,42 лв. | Доставка и въвеждане в експлоатация на 60 броя електрически автобуси; Доставка и монтаж на 60 броя бавни зарядни станции и 2 броя бързи зарядни станции Проектиране и изграждане на електропреносна мрежа за зарядните станции |

След изпълнението на проектите подвижния състав използващ ДВГ покрива следните екологични норми: 15 на брой автобуси са с еконорма Евро 6; 20 транспортни средства използват за гориво метан и също покриват еконорма Евро 6; 50 броя автобуси със стандарт Евро 5. Целия използван автобусен парк вече е на възраст до 10 години от въвеждането му в експлоатация.

**3. Заключение:**

В проведеното изследване на пакета от взаимодопълващи се проекти, насочени към развитието на съвременен, екологичен и безопасен градски транспорт в град Варна можем да изведем следните изводи:

1. За една година работа всеки нов автобус с еконорма Euro VI спестява изхвърлянето в атмосферата на 12,6 тона CO2 в сравнение със старите превозни средства стандартизирани с Euro I и Euro II; Сумарно на годишна база в атмосферата са изхвърлени над 1076 тона CO2 по-малко в сравнение с периода преди изпълнение на проектите. /40% по-малко вредни емисии в атмосферата/
2. Броят на жителите и гостите на града възползвали се от обновения масов градски обществен транспорт – над 78 хиляди човека дневно [2].
3. Намаление на разходите за подръжка, горива и текущи ремонти с 20%. /спрямо годината предхождаща началото на изпълнение на проектните дейности за модернизация/
4. Намаляване на шумовото натоварване в град Варна и автобусните спирки от градския транспорт, като на 68% от спирките нивата на шумово замърсяване са в нормите при едва 55% към 2008 г., преди изпълнението на проектите насочени към развитието на съвременен, екологичен и безопасен градски транспорт на база на “План за действие, с цел управление, предотвратяване и намаляване на шума в околната среда на територията на агломерация Варна” [5].
5. Изградена е автоматична билетна система включваща 60 машини за продажба на билети (МПБ) по едно на всяка спирка и система за информация на пътниците в реално време;
6. Инсталирана и въведена в експлоатация е система за осигуряване на предимство на превозните средства на масовия градски обществен транспорт на ключови кръстовища и пътни алтерии;
7. За първи път в града е изграден BRT коридор за автобусния транспорт и са цялостно ремонтирани над 45 километра пътни отсечки.

В заключение може да се обобщи, че приложения в град Варна пакет от взаимодопълващи се инвестиции, насочени към развитието на съвременен, екологичен и безопасен градски транспорт може със сигурност да се определи, като успешеи и ефективен. Градския транспорт на Варна получи подкрепа посредством проекти и национални програми на обща стойност над 212 млн. лева, като на база на тези целенасочени инвестиции се постигна цялостна подмяна на подвижния състав, високи екологични стандарти, автоматизирани системи за управление на трафика и използване на електробуси за първи път в транспортната схема на града.

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**За контакти:** PhD Mihail Ivanov, Technical University of Varna, Department “Industrial Management”, str. Studentska №1, Varna, Bulgaria, 052/383 263, e-mail: mihail.ivanov@tu-varna.bg

# АНАЛИЗ НА ИЗПЪЛНЕНИЕТО НА ИНФРАСТРУКТУРНИ ПРОЕКТИ НАСОЧЕНИ КЪМ ПОДОБРЯВАНЕ НА ТРАНСПОРТНАТА ИНФРАСТРУКТУРА, СВЪРЗАНОСТТА И ПЪТНА БЕЗОПАСНОСТ В СЕВЕРОИЗТОЧЕН РЕГИОН НА БЪЛГАРИЯ, ФИНАНСИРАНИ ОТ НАЦИОНАЛНИЯ БЮДЖЕТ И ЕВРОПЕЙСКИТЕ СТРУКТУРНИ И ИНВЕСТИЦИОННИ ФОНДОВЕ

# ANALYSIS OF THE IMPLEMENTATION OF INFRASTRUCTURE PROJECTS AIMED AT IMPROVING TRANSPORT INFRASTRUCTURE, CONNECTIVITY AND ROAD SAFETY IN THE NORTHEASTERN REGION OF BULGARIA, FINANCED BY THE NATIONAL BUDGET AND THE EUROPEAN STRUCTURAL AND INVESTMENT FUNDS

**PhD Mihail Ivanov**

**Abstract.** This article aims to analyze the road infrastructure projects implemented in the Northeastern Planning Region of Bulgaria. The strategic geographical location of the country and the transport standards imposed by the European Union after Bulgaria's accession to the community have had an impact on the quality and quantity of roads in the country. The study is based on an analysis of the implemented projects based on indicators measuring the rehabilitated and newly constructed road infrastructure. The analysis leads to the categorical conclusion that the implemented projects significantly improve transport connectivity, road safety and economic opportunities of the Northeastern planning region. A future key project for the development of transport connectivity in Eastern Bulgaria is the Black Sea Highway, which would have a serious impact on tourism, trade and industry in this part of the country.
**Keywords**: Roads, infrastructure projects, regional development, environmental, highways.

## Въведение

Североизточния район за планиране включва областите Варна, Добрич, Търговище и Шумен. Площта на района е 14 487 кв. км, съставляваща 13,05% от територията на страната. Транспортът има ключова роля за цялостното социално-икономическо развитие на обществото. Напредъкът на транспортната система обхваща комбинация от четири стратегически насоки – транспортна осигуреност, икономическо развитие, екологична устойчивост и социално развитие. Географско разположение на страната и транспортни стандарти налагани от Европейския съюз след присъединяването на България в общността оказват своето влияние върху качеството и количеството на пътищата в страната. Североизточният регион на България е важен стратегически участък, свързващ основни транспортни мрежи, икономически и индустриални центрове. В последните години пътната инфраструктура в този район претърпява значителни трансформации, благодарение на редица мащабни проекти, които целят да подобрят транспортната свързаност, да ускорят икономическото развитие и да осигурят безопасността на пътуващите. В тази статия ще разгледаме основните пътни проекти в Североизточния регион на страната и тяхното значение за развитието на района.

## Изложение:

### 1. Пътнотранспортната инфраструктура в Североизточен район на България – състояние, възможности и перспективи

Общата дължина на пътищата от републиканската пътна мрежа в Североизточния район за планиране е 2697 километра, но структурата на мрежата показва, че 78% от пътищата или 2100 километра са от втори и трети клас. Автомагистралите съставляват едва 4% от пътната мрежа, а първокласните пътища – около 18%.

В област Варна общата дължина на републиканските пътища е 715 километра, като 197 километра са магистрали и първокласни пътища /28%/, а 518 километра са второкласни и третокласни пътища /72%/. Гъстотата на пътната мрежа е 18,70 километра на 100 квадратни километра. В добро или задоволително състояние се намират 56% от пътищата в областта (при 40% в страната). [1]

Област Шумен е сред добре представящите се области на национално ниво при оценка и анализ на пътната инфраструктура. Общата дължина на пътната инфраструктура в областта е 629 километра. Гъстотата на пътната мрежа е значително по-висока от средната за страната. Шумен е областта с най-голям дял на първокласните пътища и автомагистралите - 234 километра или 37% (при 19% средно на национално ниво) по данни към 2024 година. Качеството на пътищата обаче се влошава и остава под средното в страната, като делът на пътната настилка в добро състояние е 30% (при 40% в страната). Пътната мрежа има гъстота от 18,50 километра на 100 квадратни километра.

Гъстотата на пътната инфраструктура в област Добрич, остава сред най-ниските на национално ниво. Близо двойно по-нисък от средния на национално ниво остава делът на автомагистралите и първокласните пътища в областта - 83 километра или 10% при 19% в страната. Трябва да се констатира и факта, че тези 83 километра са само първокласни пътища и няма изградени магистрални пътни участъци. Второкласните и третокласните пътища са 740 километра. В област Добрич гъстотата на пътната мрежа е 17,50 километра на 100 квадратни километра. В добро или задоволително състояние се намират едва 25% от пътищата на областно ниво. [1]

Област Търговище разполага с добре развита пътна мрежа, включително важни международни и национални пътни артерии. В областта общата дължина на републиканските пътища е 530 километра, като 83 километра са магистрали и първокласни пътища /16%/, а 447 километра са второкласни и третокласни пътища /84%/. Гъстотата на пътната мрежа е 19,60 километра на 100 квадратни километра. В добро или задоволително състояние се намират 48% от пътищата в областта. [1]

Таблица 1. Републиканска пътна мрежа според класа на пътя [1]

| Статистически зони Статистически райони Области | Пътища - общо | Автома-гистрали | Първо-класни | Второ-класни | Третокласни пътища и пътни връзки при кръстовища и възли |
|---|---|---|---|---|---|
| **Общо** | **19986** | **845** | **2886** | **4021** | **12234** |
| **Северна и Югоизточна България** | **12437** | **350** | **1958** | **2615** | **7514** |
| **Северозападен район** | **3442** | **16** | **405** | **765** | **2256** |
| Видин | 622 | - | 83 | 91 | 448 |
| Враца | 657 | - | 65 | 231 | 361 |
| Ловеч | 755 | 16 | 105 | 78 | 556 |
| Монтана | 614 | - | 55 | 159 | 400 |
| Плевен | 794 | - | 97 | 206 | 491 |
| **Северен централен район** | **2976** | **-** | **461** | **634** | **1881** |
| Велико Търново | 937 | - | 153 | 140 | 644 |
| Габрово | 518 | - | 86 | 30 | 402 |
| Разград | 506 | - | 56 | 162 | 288 |
| Русе | 509 | - | 110 | 155 | 244 |
| Силистра | 506 | - | 56 | 147 | 303 |
| **Североизточен район** | **2697** | **111** | **486** | **468** | **1632** |
| Варна | 715 | 58 | 139 | 43 | 475 |
| Добрич | 823 | - | 83 | 242 | 498 |
| Търговище | 530 | 6 | 77 | 105 | 342 |
| Шумен | 629 | 47 | 187 | 78 | 317 |
| **Югоизточен район** | **3322** | **223** | **606** | **748** | **1745** |
| Бургас | 1197 | 51 | 258 | 243 | 645 |
| Сливен | 581 | 44 | 85 | 202 | 250 |
| Стара Загора | 907 | 93 | 167 | 215 | 432 |
| Ямбол | 637 | 35 | 96 | 88 | 418 |
| **Югозападна и Южна централна България** | **7549** | **495** | **928** | **1406** | **4720** |
| **Югозападен район** | **3441** | **302** | **512** | **622** | **2005** |
| Благоевград | 727 | 57 | 73 | 152 | 445 |
| Кюстендил | 621 | 44 | 84 | 54 | 439 |
| Перник | 573 | 32 | 59 | 66 | 416 |
| София | 1520 | 169 | 296 | 350 | 705 |
| **Южен централен район** | **4108** | **193** | **416** | **784** | **2715** |
| Кърджали | 649 | - | 73 | 81 | 495 |
| Пазарджик | 753 | 51 | 59 | 203 | 440 |
| Пловдив | 1023 | 50 | 129 | 239 | 605 |
| Смолян | 539 | - | - | 110 | 429 |
| Хасково | 1144 | 92 | 155 | 151 | 746 |

Трансевропейската траспортна мрежа (TEN-T) играе ключова роля за осигуряването на свободното движение на пътници и товари в рамките на Европейския съюз (ЕС-28). Тази мрежа включва всички видове транспорт (шосейни и жп трасета, вътрешни водни пътища, речни и морски пристанища, летища и важни сухопътни терминали за товарни превози) и осъществява пътническите и товарните превози на Съюза, както е отговорна и за връзките със съседните държави. В картата на разширената мрежа, освен направленията и възлите в съществуващата карта на TEN-T, са включени и следните нови предложения: – направлението София – Велико Търново – Шумен – Варна, Скоростен път Рила, по направлението „Кюстендил- Дупница – Самоков – ПВ Богородица – АМ „Тракия”/ АМ „Хемус”, Скоростен път I-2 „Русе – Шумен”, Скоростен път „Варна – Дуранкулак” и Път „Пловдив – Рудозем”, Пристанище Силистра, като в този проект попадат и железопътните връзки към Варна. От гореизброените проекти е видно, че четири имат пряка връзка с развитието на пътнотранспортната свързаност на Североизточния район на България.

За да се подкрепи прилагането и развитието на TEN-T мрежата, ЕС допълва националното финансиране за проектите по линия на TEN-T чрез Механизма за свързване на Европа, като специална програма за финансиране, както и чрез европейските структурни и инвестиционни фондове, програмата InvestEU и Европейската инвестиционна банка (ЕИБ). През 2021 г. няколко държави членки решиха също да използват част от своето финансиране, предоставяно от ЕС във връзка с целите за възстановяване и устойчивост след пандемията, за постигане на напредък по пътни и железопътните проекти по линия на TEN-T мрежата.

В плановете за териториално развитие на региона е заложено и изграждането на интермодален терминал „Варна”. Целта на изграждане на интермодален терминал в района на град Варна е подобряване на интермодалността в югоизточния регион на ЕС, чрез създаване на условия за оптимално взаимодействие и интеграция на различните видове транспорт. Като резултат от осъществяването на проекта се очаква предоставянето на възможност за ефективно транспортиране на големи обеми товари от Черно море до Централна Европа и търговските възли в ЕС. С изграждането на ИМТ „Варна” се цели да се обезпечат възможности за добри транспортни връзки в направленията: - Варна – София и обратно; - Варна – Русе с възможност за ефективна връзка с Констанца и обратно; - Варна – Бургас с възможност за ефективна връзка с Истанбул и обратно.

От стратегическо значение за транспортната свързаност на Североизточния район е реализирането проектът за Лот 9 на автомагистрала „Хемус“ в участъкът между Лозница и Буховци в област Търговище. Дължината на трасето е 11.9 километра и е в напреднала фаза на подготовка, като се очаква строителството да започне през 2026 г. и да приключи до 2028г. Завършването на този участък ще осигури важна връзка между Лозница и Буховци, част от цялостната магистрална мрежа между София и Варна.

Проектът за автомагистрала „Черно море“ е в напреднал етап на планиране. Планираната дължина на магистралата е около 113 километра, като трасето ще започва от автомагистрала „Хемус“ в района на село Слънчево, Варненса област, ще преминава през Белослав, пресичайки Белославското езеро, и ще се свързва с автомагистрала „Тракия“ при квартал „Ветрен“ на град Бургас. Към момента агенция „Пътна инфраструктура“ (АПИ) е внесла в Министерството на околната среда и водите (МОСВ) разширен идеен проект за магистралата, като процедурата по оценка на въздействието на околната среда е сложна, тъй като трасето преминава през девет зони, включително и защитени територии от мрежата Натура 2000. Ако процедурите по ОВОС и последващите стъпки с изработване на подробен устройствен план, разрешение за строеж и отчуждаването на имотите протекат без забавяния, строителството на магистралата може да започне в началото на 2027 г. Според Интегрираната транспортна стратегия на България до 2030 година, която беше приета през 2017 година, доизграждането на магистралата ще струва 450 милиона лева. Към момента финансирането на проекта се

очаква да се поеме от националния бюджет, но има възможност за осигуряване на средства и по инициативата „Три морета“ или други финансиращи програми.

**2. Анализ на изпълнението на инфраструктурни проекти насочени към подобряване на пътната инфраструктура, транспортната свързаност и пътната безопасност в Североизточен район на България**

Основните проблеми в транспортната инфраструктура на България се основават на недостатъчната изграденост и завършеност на пътната мрежа в страната и в частност автомагистралите и първокласните пътища. В периода след 2007 година с подкрепата на Европейските структурни и инвестиционни фондове и националния бюджет доизграждането на автомагистрали, републикански и общински пътища бележи значителен ръст, а така също и на тяхната рехабилитация и реконструкция. Като основни проблемни характеристики можем да откроим: неспазване на стандартите за качество на пътната настилка и използваните материали за ремонт и реконструкция, инвестиционните диспропорции в транспортния сектор в различните региони на страната, липсата на пътна маркировка, сигнализации, знаци и пешеходни пътеки. При изпълнението на инфраструктурните проекти наблюдаваме сериозни регионални диспропорции, които ясно разделят страната на транспортно развити региони и развиващи се. Анализа на данните показва сериозни различия между Северна България и Южна България. Сумарно в Северна България са разположени 14% от автомагистралите в страната, респективно 86% са разположени в Южна България. [2]

Националната програма за развитие България 2030, приета в началото на 2020 г., очерта, наред с другото, инфраструктурните инвестиционни приоритети в областта на транспортната свързаност, цифровата свързаност, кръговата и нисковъглеродната инфраструктура. През 2020 г. правителството пое ангажимент да инвестира общо 1.95 милиарда евро в транспортна инфраструктура чрез програмата за транспортна свързаност за периода 2021—2027 г. на Министерството на транспорта и комуникациите, приета през 2020 г. Друга важна инвестиционна програма беше Националният план за широколентова инфраструктура за свързана България с достъп от следващо поколение, който има за цел да насочи инвестициите към цифрова инфраструктура в страната. Тези инвестиции се допълват от Националния план за възстановяване и устойчивост, финансиран от Механизма за възстановяване и устойчивост от Европейския съюз, който до голяма степен е съсредоточен върху цифровата свързаност, транспортната свързаност, инфраструктурата за водоснабдяване и канализация и енергийната ефективност, с измерение, свързано с устойчивостта. В областта на транспорта планът включва значителни средства (666 милиона евро) за мерки за декарбонизация, като например въвеждане на ново електрическо оборудване за крайградския и междурегионалния железопътен транспорт; изграждане на нов участък от софийското метро; пилотна схема за устойчива градска мобилност, включително закупуване на превозни средства за обществен транспорт с нулеви емисии и инфраструктура за зареждане на електрически превозни средства.

Оперативните програми „Транспорт и транспортна инфраструктура" 2014-2023г. (ОПТТИ) и „Региони в растеж“ 2014-2023 г. с правилото N+3 търсят търсят надграждане и развитие на вече постигнатите успехи по Оперативни програми „Транспорт” 2007 – 2013г. и Оперативна програма "Регионално развитие" 2007-2013 г., а така също и устойчивост в средносрочен и в дългосрочен план. Програмите се фокусират върху няколко стратегически приоритета за транспортна свързаност и балансиран икономически растеж и предвиждат модернизацията и доизграждането на пътни инфраструктурни проекти и направления, които са от ключово значение за развитието на регионите. Запазва се тенденцията от предходните програмни периоди голяма част от проектите и бенефициентите да са предварително приоритизирани, като фокуса е върху стратегическите национални проекти и проектите свързващи ни с трансевропейската траспортна мрежа.

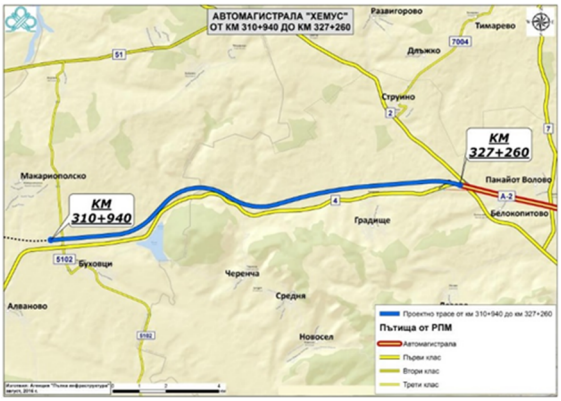
**2.1. Проект АМ „Хемус“, участък от км 310+940 до км 327+260 - от п. в. Буховци до п. в. „Белокопитово“**

Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: Държавен бюджет на Република България
Изпълнени основни дейности по проекта:

- Изграден автомагистрален участък с дължина: 16,32 км;
- Пътен възел – 1 бр.;
- Пътна връзка с път I-4 Коритна – Белокопитово;
- Виадукти - 7 бр.;
- Мост – 1 бр.;
- Надлез – 1 бр.;
- 10 бр. пресичания със селскостопански пътища.

**Бюджет на проекта:**

Обща стойност на проекта: 143 742 000 лева
Проектът се финансира от републиканския бюджет. [3]




Фиг. 1. АМ „Хемус“ от п. в. Буховци до п. в. „Белокопитово“

**2.2. Проект BG16RFOP001-7.001-0004, Лот 4 „Път II-29 Варна – Добрич от км 20+394.73 до км 23+199.86 и от км 25+342 до км 38+100.31, с обща дължина 15,563 км, области Варна и Добрич“**

Бенефициенти по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация, разширение и реконструкция на 15,5 километра пътни участъци;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови облицовани окопи и дренажна система;
- Рехабилитация на пътни кръстовища по трасето.

Специфични цели:
• Повишена безопасността на движение;
• Осигуряване на постоянна скорост на движение;
• Подобряване на връзките между населените места в региона и увеличени възможности за предоставяне на гражданите на качествени и конкурентни здравни, социални и образователни услуги;
• Инфраструктура, която е предпоставка за увеличаване на инвестициите в региона и откриването на нови работни места.

**Бюджет на проекта:**

Обща стойност на проекта - 8 952 652,89 лева [4].

**2.3. Проект Лот 5 „Път II-29 Добрич – Кардам от км 38+100,31 до км 52+168,81, с обща дължина 14,069 км, област Добрич“;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация, разширение и реконструкция на 14,1 километра пътни участъци;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови облицовани окопи и дренажна система;
- Рехабилитация на пътни кръстовища по трасето.

**Бюджет на проекта:**
Обща стойност на проекта - 14 454 665,97 лева [4].

**2.4. Проект Лот 8 „Път III-904 Старо Оряхово – Гроздьово от км 0+000 до км 17+377,07, с обща дължина 17,377 км, област Варна“**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“

Изпълнени основни дейности по проекта:

- Рехабилитация и реконструкция на 17,4 километра пътни участъци;
- Рехабилитация на три стоманобетонови моста;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови отводнителни канали на части от пътното трасе;
- Поставени нови бордюри и тротоари по протежение на пътя в населените места;
- Рехабилитация на пътни кръстовища по трасето.

**Бюджет на проекта:**
Обща стойност на проекта – 10 938 032,24 лева [4].

**2.5. Проект Лот 9 „Път III-904 Гроздьово – Провадия от км 23+403 до км 29+928,99 и от км 36+205 до км 41+705,18, с обща дължина 12,026 км, област Варна“;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Подновена пътната настилка и стабилизирана земната основа на две отсечки с дължина 12 километра;
- Подменени бордюри и възстановени части от тротоарите в населените места;
- Поставена нова пътна маркировка и пътни знаци;
- Ремонтирано е цялостното отводняването на настилката;
- Рехабилитация на пътни кръстовища по трасето.

**Бюджет на проекта:**
Обща стойност на проекта – 7 550 610,86 лева [4].

**2.6. Проект Лот 13 „Път II-49 Търговище – Разград от км 9+800 до км 11+832,85 и от км 11+942,87 до км 30+658,87, с обща дължина 20,749 км, област Търговище“;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация, разширяване и реконструкция на 21 километра пътни участъци;
- Рехабилитация на четири кръстовища по трасето;
- Изградена е колекторна система;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови отводнителни канали на части от пътното трасе;
- Поставени нови бордюри и тротоари по протежение на пътя в населените места;
- Изградени повдигнати пешеходни пътеки.

**Бюджет на проекта:**
Обща стойност на проекта – 15 357 826,67 лева [4].

**2.7. Проект Лот 29 „Път III-208 Провадия - Дъскотна от км 49+184 до км 65+933, с обща дължина 16,749 км, област Бургас и Варна“;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация и реконструкция на 17 километра пътни участъци;
- Ремонтирани 14 броя укрепителни стени;
- Рехабилитация на съществуващи подпорни стени и габиони;
- Основен ремонт на 66 броя съществуващи водостоци и 6 броя големи съоръжения;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови отводнителни канали;
- Рехабилитация на 4 пътни кръстовища.

**Бюджет на проекта:**
Обща стойност на проекта – 14 257 975, 41 лева [4].

**2.8. Проект Лот 30 „Път III-208 Дъскотна - Айтос от км 65+933 до км 82+749, с обща дължина 16,816 км, област Бургас и Варна“;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация и реконструкция на 17 километра пътни участъци;
- Рехабилитация на три мостови съоръжения;
- Поставена нова пътна маркировка и пътни знаци;
- Подобрено отводняване на цялото пътно трасе;
- Поставени нови бордюри по протежение на пътя в населените места;
- Рехабилитация на пътни кръстовища по трасето.

**Бюджет на проекта:**
Обща стойност на проекта – 9 732 925.76 лева [4].

**2.9. Проект Лот 36 Път III-9004 Варна - Белослав - Разделна - Падина - Житница от км 18+212 до км 21+176, от км 24+169 до км 25+604 и от км 27+400 до км 41+839, с обща дължина 18,838 км, област Варна;**
Бенефициент по проекта: Агенция "Пътна инфраструктура"
Финансираща програма: ОП „Региони в растеж“
Изпълнени основни дейности по проекта:

- Рехабилитация и реконструкция на 19 километра пътни участъци;
- Ремонтирани 5 броя укрепителни стени;
- Възстановени банкети и откоси;
- Изградена колекторна система в два от участъците;
- Основен ремонт на два моста, виадукт и надлез;
- Поставена нова пътна маркировка и пътни знаци;
- Изградени нови отводнителни канали;
- Рехабилитация на пътните кръстовища по ремонтираното трасе.

**Бюджет на проекта:**
Обща стойност на проекта – 18 051 922,34 лева [4].

**Обща дължина на рехабилитираните и реконструираните второкласни и третокласни пътни участъци: 133 километра.**

**Обща стойност на проектите реализирани по ОП „Региони в растеж“ насочени към рехабилитиране и реконструиране на второкласни и третокласни пътни участъци в Североизточния район за планиране: 99 296 607 лева.**

**2.10. Ремонт и реконструкция на общински пътища в Североизточен регион финансирани по Програма за развитие на селските райони**

**Процедура:**BG06RDNP001-7.019 Пътища „Строителство, реконструкция и/или рехабилитация на съществуващи общински пътища и съоръженията и принадлежностите към тях“ по подмярка 7.2. „Инвестиции в създаването, подобряването или разширяването на всички видове малка по мащаби инфраструктура“

**Бенефициенти:**

Община Аксаково - Рехабилитация и реконструкция на пътен участък с дължина 2,5 километра. **Бюджет на проекта:** 2 927 213.71 лева [4].

Община Девня - Рехабилитация и реконструкция на пътни участъци с дължина 8 километра. **Бюджет на проекта:** 2 622 884.48 лева [4].

Община Добричка - Рехабилитация и реконструкция на пътни участъци с дължина 9 километра. **Бюджет на проекта:** 2 888 999.53 лева [4].

Община Долни Чифлик - Рехабилитация и реконструкция на пътни участъци с дължина 5 километра. **Бюджет на проекта:** 2 812 829.91 лева [4].

Община Попово - Рехабилитация и реконструкция на пътни участъци с дължина 4,5 километра. **Бюджет на проекта:** 2 440 462.26 лева [4].

**Обща дължина на рехабилитираните и реконструираните общински пътни участъци: 29 километра.**

**Обща стойност на проектите реализирани по процедурата в Североизточния район за планиране: 13 692 387 лева.**

Таблица 2. Инфраструктурни проекти насочени към подобряване на пътната инфраструктура в Североизточен район на България

| Вид инфраструктура | Новоизградени/рехабилитирани пътни участъци | Стойност на проектите | Финансираща програма |
|---|---|---|---|
| **Автомагистрали** | 16 км. новоизграден участък | 143 742 000 лв. | Национален бюджет |
| **Второкласни и третокласни пътища** | 133 км. рехабилитирани участъци | 99 296 607 лв. | ОП „Региони в растеж“ |
| **Общински пътища** | 29 км. рехабилитирани участъци | 13 692 387 лв. | ПРСР |
| **Общо:** | **178 км.** | **256 730 994 лв.** | **Национален бюджет и ЕСИФ** |

В резултат на успешната реализация на инфраструктурните проекти са изградени и напълно рехабилитирани 178 километра пътни участъци, като в тези дейности са инвестирани 257 милиона лева от Европейските структурни и инвестиционни фондове и националния бюджет. След изпълнението на проектите се наблюдава значително подобрение на пътната безопасност и намаление на пътнотранспортните произшествия спрямо началото на изследвания период към 2014 година, като тук следва да отбележим, че това се дължи също така и на пакет от мерки прилагани от компетентните държавни институции. В началото на разглеждания период през 2014 година в област Варна са станали 4256 пътнотранспортните произшествия с 1402 пострадали, през 2019 има регистрирани 2696 произшествия с 886 пострадали, а през 2024 година наблюдаваме 2152 пътнотранспортни произшествия с 790 пострадали водачи и пътници. Драстично е намалял и броя на загиналите от 45 души през 2014 годино до 22 души към 2024 година [1].

Следва да се отбележи и факта, че всички новоизградени и рехабилитирани пътни участъци имат в договорите си за изпълнение гаранционни срокове от 5 до 10 години след въвеждането им в експлоатация.

**3. Заключение:**

След реализацията на изследваните проекти ключови участъци от регионалната пътна инфраструктура бяха основно ремонтирани и модернизирани, което доведе от своя страна до подобрена транспортна свързаност, ускорен икономически растеж, възможности за инвестиции и безопасност на транспорта. Важно е да се отбележи и факта, че обвързването на инфраструктурните проекти с националните и европейски политики в сектор „Транспорт”, дава положителен резултат, както на областно така и на общинско ниво.

От анализа на изпълнените проекти и извършените дейности, можем да изведем следните изводи:

1. Изграден е нов автомагистрален участък с дължина от 16 километра, 7 виадукта, мостово съоражение и надлез;
2. Основно ремонтирани и рехабилитирани са 162 километра пътни участъци, 53 кръстовища, 7 мостови съоражения, укрепителни стени, отводнителни канали и пътна маркировка [4].;
3. Подобрена пътна безопасност, като отчитаме и намаление на пътнотранспортните произшествия спрямо началото на изследвания период към 2014 година;
4. Съкратено е времето за пътуване между основните икономически центрове в региона;
5. Значително завишени възможности за свързаност с основните транспортни мрежи на национално ниво.

Въпреки предприетите мерки за подобряване на пътната инфраструктура, Североизточния регион се сблъсква с предизвикателства, свързани с качеството на пътищата от по-нисък клас и необходимостта от редовна поддръжка, модернизация и рехабилитация. Изпълнението на планираните стратегически инфраструктурни проекти е стъпка към по-добрата свързаност с Трансевропейската траспортна мрежа (TEN-T), икономическото развитие, безопасността и екологизирането на транспорта.

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**За контакти:** PhD Mihail Ivanov, Technical University of Varna, Department “Industrial Management”, str. Studentska №1, Varna, Bulgaria, 052/383 263, e-mail: mihail.ivanov@tu-varna.bg

# МЕТОД ЗА ДИАГНОСТИКА НА СТРУКТУРНИТЕ МЕХАНИЧНИ ПАРАМЕТРИ НА ДВИГАТЕЛЯ

# METHOD FOR DIAGNOSING STRUCTURAL MECHANICAL PARAMETERS OF THE ENGINE

**Irina Saraieva[1], Kozlov Oleksandr [2], Mykhailo Sukhanov [3], Andrii Sokhin[4]**

**Abstrsct.** The developed system for diagnosing the CPG and valve tightness of the gasoline engine includes a modern analog-digital diagnostic stand; a technique that covers the entire process from connecting the sensor to processing and obtaining diagnostic information and is universal with respect to various brands of car engines. The problem of distinguishing characteristic engine malfunctions associated with violations of the tightness of the combustion chamber of the cylinders was solved. A synthesis of diagnostic parameters was performed: the compression values in the cylinders and the crankcase pressure. The system provides the process of diagnosing the CPG and the tightness of the engine valves for 20-30 minutes. The error of the measured value does not exceed 1.7%, which is 0.3-1.3% less than that of known analogues.
**Keywords:** measurement, pressure, air mixture, engine, diagnostics, car

## 1. Introduction:

Known methods for diagnosing a cylinder-piston group (CPG) of the engine allow the monitoring process to be carried out both with the help of gauges and with the help of electronic measuring instruments. The use of electronic measuring instruments implies the presence of certain sensors, analog and digital means of processing information with the subsequent receipt of a diagnostic conclusion. Therefore, when developing diagnostic tools, it is necessary first of all to determine the conditions that correspond to the requirements of the developed diagnostic process.

The developed diagnostic model of the CPG provides a direct process for measuring gas pressure at several points of the engine. Accordingly, the diagnosis can be carried out by connecting one sensor to the required measurement points or simultaneously connecting sensors to all engine cylinders.

As the primary element for obtaining diagnostic information, you can use both analog and discrete sensors. The cost of discrete sensors is an order of magnitude higher, and the resolution of the frequency survey is an order of magnitude lower than that of analog sensors. In this regard, discrete sensors have not yet been widely used in automobiles and in diagnostic systems, but the ability of discrete sensors to transmit information digitally, without the use of an additional analog-to-digital converter (ADC), greatly simplifies the design of the diagnostic system unit.

A feature of the process of diagnosing the engine's CPG is that it is desirable to compare the results of diagnostic measurements of the same engine, for example, before service and repair, and after adjustment and repair, as well as throughout the life of the engine. This task is complicated by an unlimited number of cars, which will require diagnostic work. Therefore, the designed diagnostic system must have the ability to memorize a large amount of information. With the help of portable electronic devices, such a problem of long-term storage and reproduction of information is difficult to solve. Therefore, there is a need for the use of electronic means with a large amount of memory, for example, personal computers, when developing a diagnostic system for the CPG engine. In addition to a permanent memory for storing information, the diagnostic system must have a sufficiently high random access memory to work in the environment of modern operating systems and programming languages.

## 2. Presentation:

### *Analysis of the methods of implementation of the diagnostic system*

Initial analysis of possible ways to implement a modern diagnostic system allows you to build a differential chain to select a possible functional diagram of the process of diagnosing an



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engine CPG. The pressure sensor is connected in series to the measuring points. Information is transmitted through an analog-to-digital converter to the microprocessor and displayed on the monitor. The received information is recorded in the computer memory for further storage and playback. The application software processes all the information received according to the diagnostic model, after which a conclusion is made about the technical condition of the object [1-13].

The diagnostic model of the CPG can be implemented in various ways - diagnosis using pressure gauges and diagnosis using electronic means of obtaining and processing information. Sensors can be analog or discrete type. The consistent use of one analog sensor in conjunction with an analog to digital converter (ADC) is a sufficient condition for obtaining primary diagnostic information.

The conditions of the process of diagnosing a CPG determine the requirements that must be presented to the choice of a sensor, as to the primary element for obtaining diagnostic information. First of all, the sensor must have small overall dimensions that would allow the sensor to be installed in the immediate vicinity of the engine cylinder. To do this, the dimensions of the sensor must not exceed the dimensions of the spark plug. The measuring part of the sensor must be resistant to aggressive media, such as gasoline and its derivatives, oil and gases.

The pressure in the cylinders is measured in test mode, when there is no ignition of the combustible mixture in the cylinders and the temperature of the medium being measured does not exceed the operating temperature of the engine - 80˚-100˚C. The temperature of crankcase gases also corresponds to this temperature. Therefore, the temperature range of the sensor must be between 0˚ and 100˚. The need for continuous installation of the sensor determines its resistance to mechanical stress. If the sensor breaks down, it must be possible to replace it, i.e. The sensor must be mass-produced.

The pressure in the cylinder of gasoline engines in one working cycle varies between 0 - 1.6 MPa, therefore, the gauge characteristic of the sensor should correspond to this range. In order for the cost of the diagnostic system, and, consequently, the cost of carrying out diagnostic work to be available, the price of the sensor must be commensurate with the price of the main elements of the system and the complexity of the work.

The Siemens company proposed the design of a piezoelectric pressure sensor to assess the quality of the combustion process in the engine [1]. Such a sensor is easily mounted on the cylinder head of the engine without dismantling the parts. Along with the simplicity of the diagnostic process, it is not possible to directly measure pressure and localize the malfunction within one cylinder.

The AVL Institute has developed a new miniature piezoelectric quartz pressure sensor, model QC31D, with water cooling and increased accuracy, designed to build an indicator diagram of an internal combustion engine (ICE) [2]. The compensation membrane of the sensor coated with nitride and titanium reliably protects the measuring element from thermal loads with a maximum temperature of 25,000 ° C, exposure to aggressive components of fuel and gases, and from soot particles. The guide elements for water provided in the sensor head create conditions for its intensive and uniform cooling. The sensor favorably provides a diagnostic process in the engine’s functional mode, but at the same time, a number of other factors affect the change in the indicator pressure along with the technical condition of the CPG: nozzle performance, spark plug operation, which undoubtedly makes an accurate diagnosis difficult.

In [3], the problems of measuring pressure in the combustion chamber of an internal combustion engine are considered. Two measurement methods are evaluated: indirect, which measures acceleration, vibration, and deformation of cylinder head parts, and direct, by measuring the gas pressure in the chamber using a quartz sensor cooled by water. A new design of the piezoceramic sensor, which is installed outside the combustion chamber, is proposed. The piezoelectric constant of the applied piezoceramics improves the accuracy of measurements, but

does not solve the existing problems of analogues, which are associated with difficulties in making a diagnosis regarding CPG and the tightness of the valves of a gasoline engine.

Another principle is based on the action of an optical sensor, which is a cylindrical tube filled with a light-conducting substance and closed from below with a thin membrane [4]. The sensor is installed in the spark plug hole. A light channel is adjacent to the tube above. By a change in the intensity of light passing through the tube, due to and.

The process of converting between analog and digital quantities is the main operation in computing and control systems. By converting physical parameters such as pressure, force, displacement, temperature, and many others, high-speed, stable, and relatively inexpensive data measurement and transmission systems are implemented using digital-to-analog converter (ADC). A comparative analysis of the existing technical characteristics of the ADCs of leading companies, such as: Fastwel, Advantech, Dataforth, Diamond Systems, ADDI-DATA, allows us to conclude that at the present stage of technical development, 8, 12 and 16-bit converters having widespread use 8 differential or 16 potential inputs and a sampling frequency of 40-100 kHz and higher.

For the developed diagnostic complex, the main criteria for choosing an ADC are the following conditions: constructive compatibility of the ADC with the computer system unit; the ability to interrogate a sensor with a high degree of discretization, which provides pressure measurement in the engine cylinder at each degree of crankshaft rotation; satisfactory accuracy characteristics; the cost of the ADC should be commensurate with the cost of the system unit [14].

The compatibility of the ADC with the computer system unit is determined, firstly, by the ability to connect them via existing communication channels, and secondly, by the ability to exchange information between ADC operating systems and the processor. The resolution of the ADC by the frequency of the probe can be determined on the basis of the required number of measurements per revolution of the crankshaft, taking into account the specified speed of the crankshaft:

$$\nu_d = q\frac{n_b}{60}, \tag{1}$$

where q – is the number of measurements of the pressure in the cylinder per revolution of the crankshaft;

$n_b$ – crankshaft rotation frequency.

For scientific research, of interest is the change in pressure in the cylinder at various angles of the crankshaft position. The ideal case is when the pressure in the cylinder is measured at every degree of rotation of the crankshaft, i.e. at least 360 times in one revolution of the crankshaft. The maximum speed of the crankshaft driven by the starter can reach 350-450 min-1. Under such conditions, the resolution sampling frequency of the ADC should be at least 2100-2700 Hz.

The accuracy parameters of the ADC characterize the static and dynamic components of the conversion process. When the ADC voltage is applied to the input, a change in codes is observed at the output from it. The binary logarithm of the nominal number of output code values, rounded to the nearest integer, determines the resolution of the ADC.The ADC, which was developed by the Kharkov Aviation Institute and is produced in small series, fully satisfies the conditions of the process of diagnosing the engine’s CPG. By electrical safety, the equipment corresponds to protection class II, type of protection BF. The equipment uses components of general industrial production, the materials and coatings of which are not toxic. The devices are designed to work indoors at an ambient temperature of 0 ºC ... +55 ºC. The system provides

switching and analog-to-digital signal conversion, setting the gain for each of the 6/12 channels, programmatically setting the signal sampling frequency, controlling the operating modes and calibrating the amplifier.

The ADC can simultaneously transmit information on 8 channels with a sampling frequency of 400 Hz, or transmit information on one channel with a frequency of 3.2 kHz (software sampling frequency switching). The digit capacity of the analog-to-digital conversion is 8/10, the range of input signals is 0.2 ... 2V (it is regulated by a potentiometer when setting the ADC). The constant component on any channel is not worse than ± 1 unit. ml discharge. The nonlinearity of the amplitude characteristic can be no more than 1.5% and an additional 0.05% per 1 °C. The error in measuring time intervals is 0.1% of the measured value. The relative error of the measuring channel, taking into account the errors of the ADC, pressure sensor, time measurement and temperature variation, will be 1.67%.

***Development of diagnostic system***

Mathematical processing of diagnostic information allows you to set the values of diagnostic parameters and perform the logical operations that are necessary for the objective formation of a diagnostic conclusion. The program for processing digital information is written in the modern Delphi language, which allows you to process large arrays of primary information in the Windows environment and reproduce the measurements made stored in the computer's memory. The program provides a reproduction of the curve of the pressure in the cylinder versus time.

Since the selected sensor and ADC provide a linear conversion of pressure into an analog-to-digital signal, the inverse process of converting a digital signal into a physical quantity is described by a linear function of the form. In order to minimize the influence of the technical condition of electrical equipment, the battery and the starter on the process of diagnosing the CPG in the test mode, the program automatically monitors the change in the frequency of revolutions of the crankshaft. Given that the engine runs in two rotations of the crankshaft, it is possible to accept with a high degree of probability the assumption that the extremes of compression in the cylinder are noted every two turns of the crankshaft. This position is confirmed experimentally by graphically reproducing the process of measuring pressure in the cylinder by the angle of rotation of the crankshaft.

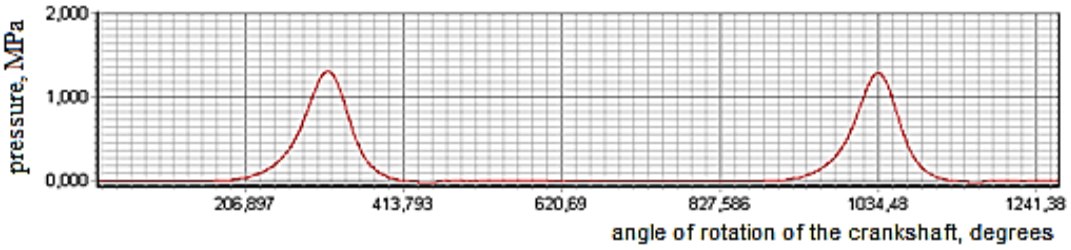



Fig. 1. The graph of the pressure in the cylinder, which depends on the angle of rotation of the crankshaft

Knowing the interval between two extremes of the pressure value, it seems possible to determine the crankshaft rotation speed by the formula:

$$n_{p.c} = \frac{120}{t_c} \text{ min}^{-1}, \quad (2)$$

where $t_c$ – is the time of one working cycle of the engine (two turns of the crankshaft), sec.

The diagnostic system functions normally at an ambient temperature of 5 °C to 35 °C and a relative humidity of 5 to 95% without moisture condensation and ensures the following operations:

- the presentation of diagnostic information is displayed on the monitor in digital and graphic form;
- Enters and adjusts the tuning coefficients of the measured parameters;

- represents the calibration of the sensor;
- Performs logical operations and calculations for specified functions;
produces the construction of separate schedules for each function;
- generates and issues (at the command of the operator) a diagnostic report;
- provides long-term storage and viewing of diagnostic information.

***Experimental research results***

Due to the fact that the subject matter of the study is closely related to the lack of the necessary theoretical basis for studying the process of diagnosing the CPG of modern gasoline engines, there is an objective need for an experiment. The purpose of the search experiment is to establish a relationship between structural and diagnostic parameters, on the basis of which it is possible to further develop a mathematical model for the automated diagnosis of the technical condition of the CPG and the tightness of the engine valves. The engines of the VAZ, Opel, Audi, Ford, Skoda, ZAZ-Daewoo, BMW, Mazda, Mitsubishi, Honda engines with a compression ratio of 9.5 to 10.5 units, with working volumes of 1200, 1300, 1500, 1600, 1800 were diagnosed. 2300, 2800 cm3, with two, four and five valves per cylinder. Checks were performed on 100 engines [15, 16].

When diagnosing, such influencing parameters as engine speed, engine coolant temperature, and the angle of rotation of the throttle valve were taken into account and stabilized. We investigated how obviously well-functioning engines - new, after major repairs or with low mileage, and faulty engines. Diagnosis of faulty engines was accompanied by subsequent disassembly and measurement of structural parameters using special tools (micrometers). The search experiment was carried out using the developed diagnostic system, which allows you to display measurements in graphical and digital form.

The results of the study of faulty engines showed that the occurrence (coking, loss of elasticity) of the piston rings in the piston grooves is caused by two reasons. Firstly, scoring on the piston and cylinder wall occurs when metal particles fall between the ring and the piston groove (Fig. 2, a). Secondly, the occurrence of piston rings occurs due to deformation or fracture of the partitions between the piston grooves (Fig.2, b).

The occurrence of scoring in the engine's CPG occurs due to overheating of the engine or is caused by the use of low-quality engine oils. Deformation and kink of the piston groove baffles occur in engines operating with detonation at high loads. The combustion of a combustible mixture, proceeding with detonation, is, as is known, the result of improper installation of the ignition moment and the use of low-octane fuel.



a b

**Fig. 2.** Typical malfunctions that are identified when diagnosing an engine CPG:
a - seizure on the surface of the piston, causing the occurrence of the piston rings;
b - deformation and kink of the piston partitions with the occurrence of the piston rings

When the piston rings lie, deformation and fracture of the piston grooves, the controlled structural parameter is the smallest limit value of the gap between the ring and the piston groove,

that is, in fact the absence of such. The measured values of compression in the cylinders and crankcase gas pressure of the engine having this malfunction are presented in the graphs.

If the compression in the engine cylinders is within acceptable limits, then the CPG can be in one of two states: working and working, and faulty, but working. Moreover, CPG wear is accompanied by increased crankcase pressure of more than 0.45 MPa [18]. If, under operating conditions, the engine piston rings are replaced without repairing the worn cylinder, then the piston rings quickly take the form of a cylinder during the running-in period, of course, the gap in the ring locks increases to the limit and the engine's CPG continues to be in a malfunction state.

Burnout of the engine exhaust valve is currently a very common malfunction. The causes of the malfunction lie in the high-temperature conditions of its operation. The temperature of the gases in the combustion chamber of a gasoline engine at the beginning of the exhaust stroke is 1100-1300 ° C. The high-temperature flow from all sides flows around the exhaust valve, the plate of which is intensively heated to a temperature of 650-700 ° C. To ensure the operability of the exhaust valve in such conditions, the heat flux perceived by the valve disc must be intensively removed. The main part of the heat is removed from the plate to the valve seat, and the smaller part to the valve stem. The contact between the seat and the valve in the closed state is broken due to various reasons, for example: insufficient thermal clearance or its absence in the valve drive, wear of the chamfer of the valve, and deformation of the valve stem. The consequence of a loose fit of the valve to the seat is its overheating and burnout.

Based on the obtained experimental data, a relationship was established between the characteristic failures of the CPG, the valve leakage and the diagnostic parameters (Table 1).

**Table 1.** Faults and diagnostic parameters that were set during measurements

| Malfunctions of the engine CPG, which were identified during the diagnosis | Diagnostic signs | The limiting values of the diagnostic parameters that were established by the results of a multivariate experiment, MPa |
|---|---|---|
| Worn engine parts CPG | The increased gas pressure that forms in the crankcase | 0,045 |
| Overlapping compression rings, deformation and kink of piston grooves | Significant compression difference between engine cylinders | 0,25 |
| | The increased gas pressure that forms in the crankcase | 0,045 |
| Burnout, valve deformation | Significant compression difference between engine cylinders | 0,25 |

Thus, the conducted experimental studies using the developed diagnostic system made it possible to clarify the boundaries of allowable values of the diagnostic parameters of the tightness of the combustion chamber of the engine, to solve the technical problem of distinguishing characteristic malfunctions associated with a violation of the tightness of the combustion chamber of the cylinder, without disassembling the engine.

**3. Conclusion:**

Using the developed diagnostic system, experimental studies have been performed to evaluate the pressure changes in the cylinders and the crankcase. The engines of VAZ, Opel, Audi, Ford, Skoda, ZAZ-Daewoo, BMW, Mazda, Mitsubishi, Honda and others were diagnosed with a compression ratio from 9.5 to 10.5 units, with working volumes of 1200, 1300, 1500, 1600 , 1800, 2300, 2800 cm3, with two, four and five valves per cylinder. A diagnosis of 100 engines was performed. During experimental studies, the most common engine malfunctions were: burnout of the exhaust valve, loose seating of the valve in the seat, deformation of the valve stem, violation of the thermal gap in the valve mechanism, seizure on the piston, seizure on the cylinder wall, loss of elasticity or breakage of compression rings, deformation and kink of the piston baffles,

wear of the cylinder in the vicinity of the top dead center, wear of the piston rings and piston grooves. Experimental studies have shown that the wear of the engine's CPG parts is accompanied by an increase in crankcase pressure above 0.045 MPa; the occurrence of compression rings, deformation and kink of the piston grooves is accompanied by a step out of the range of two simultaneously possible diagnostic parameters - this is an increase in the difference in compression between the engine cylinders by more than 0.25 MPa and increased crankcase gas pressure; burnout, valve deformation are associated only with a decrease in compression in the faulty cylinder by more than 0.25 MPa relative to the serviceable cylinder.

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За контакти:
[1] Irina Saraieva, Associate Professor (Assoc. Prof.), Candidate of Science in Engineering (Ph. D. (Eng.)), Kharkiv National Automobile and Highway University (KhNAHU), St. Yaroslav Mudriy, 25, Kharkiv, 61002, Ukraine, e-mail: sarayeva9@gmail.com, tel.: +38-050-640-07-87.

[2] Kozlov Oleksandr[2] – postgraduate (PHd), Kharkiv National Automobile and Highway University (KhNAHU), St. Yaroslav Mudriy, 25, Kharkiv, 61002, Ukraine, e-mail: alexandrelcars@gmail.com,
[3] Mykhailo Sukhanov - postgraduate (PHd), Kharkiv National Automobile and Highway University (KhNAHU), St. Yaroslav Mudriy, 25, Kharkiv, 61002, Ukraine
[4] Andrii Sokhin[4]- postgraduate (PHd), Kharkiv National Automobile and Highway University (KhNAHU), St. Yaroslav Mudriy, 25, Kharkiv, 61002, Ukraine

# ДЕКОМПОЗИЦИЯ НА КОЮНКТИВНИ ФОРМУЛИ В АЛГЕБРАТА НА КРАЙНИТЕ ПРЕДИКАТИ ЗА МОДЕЛИРАНЕ НА ЛОГИЧЕСКИ СТРУКТУРИ НА ТРАНСПОРТНИ МРЕЖИ

# DECOMPOSITION OF CONJUNCTIVE FORMULAS IN THE ALGEBRA OF FINITE PREDICATES FOR MODELING LOGICAL STRUCTURES OF TRANSPORT NETWORKS

**V. Volkov[1], I. Shubin[2], G. Pliekhova[3], D. Kopytkov[4], T. Volkova[5]**

**Abstract.** *The development of conjunctive decomposition tools in algebra of finite predicates focused on building logical network models is the main topic of this article. The possibility of using such tools for the development of linguistic information processing systems determines the relevance of the chosen topic. The relationship between operations in relational algebra and in the algebra of finite predicates is de-scribed. With the help of relational statements about dependencies, the algebra logical apparatus of decomposition of predicates was further developed. The method of binary decomposition of functional predicates is founded, which differs from the general method of Cartesian decomposition in that the number of values of the auxiliary variable is minimized. The research used the methods of mathematical modeling, complex logical analysis, and method for constructing logic networks. The following results were obtained: a theoretical model was developed that integrates the principles of logic networks and predicate logic for analyzing student academic performance; the model accounts for both probabilistic transitions between states and logical dependencies among student parameters; the mathematical model also incorporates logical rules to enhance the accuracy of logical analysis within the academic context. The model was tested on a dataset of student performance, demonstrating its effectiveness in accurately predicting academic outcomes and confirming the validity of the integrated approach. Conclusions. The scientific novelty of the results obtained is as follows: 1) a theoretical model for analyzing data was developed by integrating logic networks and predicate logic, allowing for the simultaneous consideration of probabilistic transitions and logical dependencies among student parameters; 2) the approach enhances the analysis process by incorporating logical rules into the probabilistic framework, providing a more nuanced and accurate tool for analyzing academic data; 3) this combined model offers a novel method for addressing complex logical analysis tasks in educational settings, paving the way for further research and practical applications in intelligent data analysis. The successful testing of the model on actual data further underscores its potential as a powerful tool in educational data analysis.*

**Keywords:** Algebra of Finite Predicates, Logical Networks, Binary Decomposition, Cartesian Decomposition.

## 1. Introduction:

Among the many formalisms applicable to one degree or another to the tasks of processing informal information, the most appropriate is the use of predicate algebra, systems of equations which are technically implemented in the form of a logical network. One of the advantages of this approach is its direct applicability to all the following types of problems, which is provided by the declaratives of the logical network as a method of solving systems of predicate equations. The notation of the predicate equations itself becomes possible due to the algebra of predicates [1].

On the example of processing test information by artificial intelligence, we can consider the general classification of tasks that arise in the process of working with primary informal information:

• analysis (for example, recognition – obtaining from informal information specific parameters necessary for the application of some formalism);

• normalization – bringing information to some reference form, which is relevant in the search for information;

• synthesis – the expression of the internal representation of information stored in accordance with the formal requirements in a form adapted for human perception;

• mixed tasks.

Another advantage of logical networks is the wide parallelization of calculations, which, provided the correct construction of the task model guarantees high efficiency.

In addition, the brain-like computer, based on the technology of logical networks, is close in structure to the structure of the human brain, which gives reason to hope for the creation of information technology-based systems based on the capabilities of human [2].



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The study of categories quickly became an independent abstract discipline and is now an important branch of pure mathematics. In addition, it influenced the conceptual foundations of mathematics and the language of mathematical practice. It offers elegant and powerful tools for expressing connections between major branches of mathematics and provides mathematicians with tools for mathematical research that occupy more and more space in the arsenal of mathematics.

However, to date, the theory of categories still does little to solve problems such as the description of the mechanisms of human intelligence, such as the development of artificial intelligence, the creation of parallel computers, intelligent radar systems, and so on.

Therefore, it is necessary to establish a connection between the theory of categories and modeling of systems based on artificial intelligence using an intermediate field of knowledge - the algebra of finite predicates, by which a predicate interpretation of the category can be built. Based on this interpretation, elements of the theory of the modified category for the processes of modeling the functions of artificial intelligence are developed [3].

The ability of a computer to provide a high degree of information processing is becoming increasingly important. The insufficiency of computing machine software has shown the necessity of creating intelligent systems that can assist in designing and creating software products. The form in which this information is represented in the computer significantly impacts the speed and quality of information processing by intelligent systems [4]. Various information systems use different methods for representing knowledge depending on specific application areas. Knowledge representation involves formalizing beliefs through records or languages. A formalization that is perceived by the computer is particularly interesting, for which formal languages are developed to represent knowledge in the computer’s memory.

Recently, numerous practical applications of modern abstract algebra have been found in databases and intelligent systems, which led to increased interest in the possibilities of algebraic description of information [2]. Various high-level language translators and algorithmic algebras were developed based on algebraic methods in programming theory.

Automation of software development and design of computer systems is an important and urgent problem of computer technology. One of the main tasks of this theory is the problem of the optimal translator from one language to another, which consists of finding the optimal implementation of the algorithm in another language. The use of algebraic methods allows you to create effective algorithms for translating and optimizing programs [5].

## 2. Presentation:

### *Usage of Logical Networks*

A distinctive feature of artificial intelligence tasks is that they are difficult to formalize, necessary to enable the automation of their solutions. Thus, it is expedient to study the universal tool of informal information processing – the human brain and to model some of its functions related to the tasks based on modern technologies. The essence of the approach is that human intelligence is seen as logic in action, as some material embodiment of the mechanism of logic. Works on logic algebraization were performed [6].

Schematic implementation of formulas describing algebraic-logical structures leads to characteristic engineering networks that have not been used before, and which are called logical networks. When comparing these networks with the main types of neural structures, a deep similarity in the structure of technical and biological structures is revealed. Based on this similarity, we can determine the functions of different types of neural structures and describe in exact mathematical and technical terms the principles of brain function.

The main thing in this method is the movement from top to bottom: from general system considerations to algebraic-logical structures, and from them to logical networks, which are then identified with biological neural structures [7].

Unlike the traditional information technology algorithmic approach, the declarative task model is not an algorithm. The task model presented in a declarative form is usually a set of facts,

knowledge of facts and rules, according to which actions are taken on facts that allow to obtain new knowledge based on old ones.

A logical network is a method for solving systems of predicate equations and has descriptive capabilities of predicate algebra. The property of a logical network is the parallel execution of all elementary logical operations – that is, the maximum possible at the logical level of parallel calculations. This approach guarantees high efficiency in solving problems that are reduced to a logical conclusion or to the solution of logical equations [8].

To formalize the tasks of processing informal information using logical networks, it is necessary to explore the possibilities of rational application of the algebra of finite predicates. To this end, it is necessary to model the most common tasks from different areas of the subject area. Examples include areas such as: the task of modeling the recognition mechanisms of inconspicuous radar objects.

### *Mathematical Decomposition Tools*

The mathematical tools developed for the decomposition of relations and predicates are designed primarily to create logical networks, which, in turn, are the basis for building a parallel-action computer. The mathematical results of the work can be used in automatic language processing systems, computer-aided design systems for information systems. Logical networks can be effective in creating specialized parallel-action devices designed to simulate complex computing systems, for example, a system of complete adequate morphological analysis of natural language texts [9], [10].

Mathematical model suitable for implementation in the form of a logical network should be represented by a system of binary equations, i.e., each equation of such a system should have two variables. This form of presentation is a logical network model. In this case, the system of binary equations should be as compact as possible in order to save hardware resources when implementing the model.

Converting a model into a compact binary form requires conjunctive decomposition of predicates. In the area of the decomposition apparatus, a shortage of justified methods, that does not require checking the equivalence of the obtained result to the original predicate, and at the same time rational methods that allow obtaining a compact binary representation for a given formal model. When developing models of logical networks for processing linguistic information, developers mostly used their own intuitive methods, rather than strict, justified methods. The logical network models obtained in this way need experimental verification of their adequacy to the described object [11].

Almost all available formal means of decomposition of predicates in these works do not consider the relationship between variables. Taking these features into account in the structure of a predicate allows one to decompose it in a more rational way. Meanwhile, the theory of relational databases offers a means of decomposing relations in the form of statements about the dependencies between attributes (in the section on normalizing relations). Given the deep connection between relations and predicates, the means of decomposition of relations can be applied to solve the problem of decomposition of predicates. As an analysis of the literature has shown that such tools are currently not available in the apparatus of predicate algebra [12].

### *Analysis of Objectless Categories*

The only difference between category theory and predicate algebra is that the former moves from top to bottom, aims to learn higher logical mechanisms and therefore uses as starting points the concept of a record level of commonality. The second, starting from the needs of informatization, moves in the study of the same logic of thinking from the bottom up. If it were possible to give a convincing interpretation of the concepts formed by the theory of categories and the methods developed by it in terms of predicate algebra, i.e., concretizing, to bring them closer to informatization, it would significantly enrich the tools of predicate algebra. It is the algebra of predicates that we are going to use as such an intermediate field of knowledge [13].

A logical network copies a person's actions, but with the only difference that a person acts sequentially and a network acts in parallel. The network works in cycles. In the first half-bar of the $i$-th bar, the network for each of its equations of the form $K(x, y) = 1$ ($K$ is the relation given by such equation) finds:

1. according to the known knowledge of $P_i(x)$ about the value of the variable $x$ at the beginning of $i$-th bar knowledge $Q'_i(y)$ about the value of the variable at the end of the $i$-th bar;

2. according to the known knowledge of $Q_i(y)$ about the value of the variable $b$ at the beginning of the $i$-th bar, knowledge of $P'_i(x)$ about the value of the variable $x$ at the end of the $i$-th bar.

Mathematically, these two operations are expressed by formulas:

$$\begin{aligned} x \in A\big(K(x,y)P_i(x)\big) &= Q'_i(y), \\ x \in B\big(K(x,y)Q_i(y)\big) &= P'_i(x), \end{aligned} \tag{1}$$

where $A$ and $B$ are the variable areas of $x,\ y$.

In the second half of each bar, the network finds the common part $P_{i+1}(x)$ of all knowledge $P_{i1}(x), P_{i2}(x), \dots, P_{il}(x)$ about the value of each of its objective variables $x$ parties, which come through the branches of the network from all to the pole $x$. This operation is expressed as follows:

$$P_{i1}(x) \wedge P_{i2}(x) \wedge \dots \wedge P_{il}(x) = P_{i+1}(x). \tag{2}$$

The obtained knowledge $P_{i+1}(x)$ is then used as the state of the pole $x$ at the initial moment of the $i$ + 1st cycle. The symbol $l$ denotes the number of branches approaching the pole $x$. Before the beginning of the $i$ + 1st bar, knowledge of the set $P_{i+1}(x)$ is formed in each pole, which is always included in the knowledge of the set $Pi(x)$, which was kept in the same pole at the beginning of the $i$-th bar. Thus, the only result of the logical network is the refinement of the knowledge contained in all its poles in accordance with the original data.

With the introduction of the theory of categories, along with the usual concept of category, there was a more general concept of objectless category [14], [15].

Let $M$ be some set. Its elements, denoted by the symbols $f, g, h, \dots$, are called morphisms. Suppose, moreover, that some, in the general case, partial operation $fg = h$ is given, which acts with $M \times M$ in $M$. It is called the multiplication of the morphisms $f$ and $g$. The morphism $h$ is called the product of the morphisms $f$ and $g$. Any morphism $e \in M$ is called singular or identical if it satisfies the following conditions:

- for any $f \in M$ for which there is a product $fe \in M$, the equality $fe = f$;
- for any $f \in M$ for which there is a product $ef \in M$, the equality $ef = f$ holds.

This definition tacitly allows the existence in the category of many units. It is the presence of many units (and only this) that distinguishes a category from other known algebraic structures. The singular morphisms $ef$ and $e'f$ are named according to the right and left for the morphism $f \in M$, if $fef = f$ and $fe'f = f$. For any morphism $f \in M$ there are a single right and a single left morphisms. This statement is called the law of identity. Thus, for each $f \in M$ there is a single right unit ef and a single left unit $e'f$, such that $fef = fe'f = f$.

Multiplication of morphisms is associative: $(fg)h = f(gh)$ for any $f, g, h \in M$ for which there are products: $(fg)h$ and $f(gh)$. The set $M$, which contains at least single morphisms, and on which the operation of multiplication of morphisms with the above properties is called an object-free classical category $K$. Write $M = Mork, f \in M, f \in Mork$. $Mork$ is the set of all morphisms of category $K$. If $f \in Mork$, then we say that the morphism $f$ is a $K$-Morphism.

***Tools Based on DCPA***

Next, we will talk about the development of new predicate decomposition tools based on statements about dependencies from the normalization of relational relations. At the beginning,

an exact definition of the decomposition procedure with respect to relational relations and predicates is given; statements about dependencies that allow decomposition of relational relations are considered; their generalizations are proposed. Based on the relations between relational algebra and predicate algebra, dependency statements are transformed into new predicate decomposition tools [16].

A predicate in the basis of a disjunctive conjunctive predicate algebra (DCPA) is usually regarded as an analytic notation of a relation. Therefore, a predicate decomposition is a decomposition of a relation at the analytical level (simply manipulating formulas), when not the relations themselves are processed, but the corresponding predicate formulas [17].

Modern educational systems, especially in the context of virtual universities and digital learning, are faced with the need to effectively analyze large volumes of academic data. Without proper analysis, such data remains unstructured and underutilized to make informed decisions on improving the educational process [18], [19]. Virtual learning platforms and digital learning systems generate a huge amount of information, including data on student performance, their participation in educational programs, attendance, and many other parameters.

In the era of digitalization of education, traditional statistical analysis methods are often insufficient to identify complex relationships and trends in academic data. Simply accumulating information, such as academic records of millions of students, does not allow for a deep understanding of the dynamics of their learning and engagement. In educational analytics, it is important not only to collect data, but also to build models that can interpret and analyze this information in order to create recommendations based on it for improving the educational process [20].

Intelligent analysis of academic data using advanced mathematical methods allows you to identify hidden patterns and trends that remain unnoticed by traditional approaches. This is especially important in the context of digital learning, where data systematization is necessary for their deep analysis and effective use [21].

In this context, the method finite predicate-driven logic networks offers a new approach to solving the problems of analyzing students' academic performance. This method allows analyzing and analyzing data, taking into account both logical dependencies between students' parameters and probabilistic transitions between different states of their academic activity.

Intelligent data analysis employs mathematical techniques to uncover patterns and trends that traditional methods often fail to identify due to the complexity of the relationships or the vastness of the data involved. By defining and integrating these patterns into a cohesive model, researchers can achieve a deeper understanding and more effective utilization of existing data. Such analysis methods are particularly crucial when dealing with logical analysis, where the process of analyzing objects requires careful selection of characteristic values to determine the object's membership in a specific class.

As an example, the study [22] performs classification of binary feature vectors. The proposed methodology finds application in a wide range of data analysis problems in various fields. The classification process is based on the analysis of logical-dynamic systems, considering certain initial states. The research detailed in [23] developed specialized correction functions for methods used in logical object identification, presenting an innovative logical analysis algorithm that integrates these functions to refine the precision of object analysis based on logical principles.

Another significant contribution to the field is presented in [24], which explores the application of Boolean data analysis of hyperspectral images. This method uses the binary simplicity of Boolean algebra to manage the intricate data structures inherent in hyperspectral imaging, facilitating more effective data interpretation. The study in [25] delves into the combinatorial aspects of inferential analysis. Here, the authors applied their theoretical insights to the practical challenge of classifying proteomic expressions linked to Alzheimer's disease, demonstrating the potential of combinatorial logic in addressing complex biological data analysis.

Furthering the application of logical methods, the work in [26] describes logical algorithmic techniques for constructing decision trees, a fundamental tool in various decision-making

processes across different industries, from healthcare to finance. In the realm of text analysis, [27] proposes a logic-based quantitive analysis method specifically designed for text recognition. This approach adapts logical principles to the challenges posed by textual data, illustrating the adaptability of logical methods to diverse types of data.

The study in [28] introduces a logic approach to machine learning, including the development of a specialized logic classifier. This approach aims to integrate logical reasoning into machine learning frameworks, enhancing model interpretability and accuracy. The concept of combining multiple weak classifiers to design an effective overall classifier is explored in [29]. This research discusses ensemble methods, which leverage the collective strength of several simple models to achieve superior data analysis performance. An extensive integration of various methods, including logical analysis, was empirically tested in a study referenced in [30]. This integration underscores the potential benefits of hybrid approaches in solving more complex data analysis tasks. Text message data analysis based on logical inference is the focus of [31], highlighting how logical methods can be effectively utilized for the real-time analysis of dynamic text data.

In the field of radar technology, [32] examines finite predicate networks, demonstrating the application of logical networks in environments where rapid and accurate data processing is critical. Innovative techniques in logical analysis and recognition are presented in [33], where new approaches are explored to refine the methodologies used in logical data analysis across various applications.

The study in [34] explores the subsystems of systems of Boolean equations, providing deeper insights into the nuances of Boolean systems that are crucial for understanding and developing complex logical models.

A method for the distributive solution of logical equations is introduced in [35], aiming to enhance the efficiency and feasibility of solving logical equations, which are foundational to many computational logic applications.

We clarify the concept of decomposition, as it is understood in relational databases. To do this, we give the concept of the dependence of the compound, which is used in the theory of dependencies.

Let $\Gamma = \{X_1, \dots, X_l\}$ be a subset family of sets $H$. If $= \cup_{i=1}^{l} X_i$ , then $\Gamma$ is called overlapping of set $H$. An overlapping $\Gamma$ is called a partition of a set $H$ if the sets $X_1, \dots, X_l$ are pairwise disjoint.

Let $R$ be some relation, and the family of sets $\{X_1, \dots, X_l\}$ forms the covering of the set $at(R)$. The relationship $R$ satisfies the connection $[X_1, \dots, X_l]$ dependencies if

$$R = R[X_1] \circ R[X_2] \circ \dots \circ R[X_l]. \quad (3)$$

Expression (3) is the so-called algebraic restriction of integrity.

Other types of dependencies that are used in the theory of dependencies – functional and multi-valued dependencies – are special cases of the connection dependency. Therefore, any dependence made $R \in Re(T)$ in allows us to represent $R$ in the form of a natural connection of their projections (3). In the theory of relational databases, it is usually this procedure that is called *decomposition of* $R$. Based on the expression (3), decomposition itself is carried out by designing the initial relation for different groups of its attributes. This suggests that the projection operator is the decomposition operator, while the composition (reassembly) operator is a natural join.

However, splitting a relation can be carried out in different ways: along with projection, for example, sampling can be used as a decomposition operator. Then the composition operator will no longer be a natural join, but a join operation. When in database theory we are talking about the decomposition of relations, then almost always we mean a decomposition of the form (3). Other types are practically not used. Nevertheless, for accuracy, the decomposition of relations in the form (3) will sometimes be called projection-connective decomposition.

***Predicate Decomposition***

A predicate decomposition of P is the derivation of some predicates $P_1, P_2, \dots, P_l$ based on a predicate P with the possibility of its reverse recovery from these predicates, which is called the predicate composition of P. An important particular case of decomposition is the so-called binary predicate decomposition of P, characterized in that each of the predicates $P_1, P_2, \dots, P_l$ resulting from the decomposition of the predicate P has exactly two significant arguments. If the conjunction serves as the composition (restoration) operator, then decomposition is called conjunctive.

The predicate analogues of relational projection operations are existence quantifiers. Then the predicate analogue of the projection-connective decomposition will be the quantifier-conjunctive form of decomposition.

Let $T \subseteq V \times U$ be a spanning tree with a finite set of variable names $V = \{x_1, x_2, \dots, x_n\}$, $S =$ Dom $x_1 \times$ Dom $x_2 \times \dots \times$ Dom $x_n$ Let $P$ be some predicate from Pre$(S)$, and the family of sets $\{X_1, X_2, \dots, X_l\}$ form a covering of the set $V$. We say that a predicate $P$ satisfies conjunction dependences $\wedge \{X_1, X_2, \dots, X_l\}$ if

$$\exists Y_1(P) \wedge \exists Y_2(P) \wedge \dots \wedge \exists Y_l(P) = P, \tag{4}$$

where $Y_i = V \backslash X_i$, $i = 1, \dots, l$.

Representation of the predicate $P$ in the form of (4) will be called a quantifier-conjunctive decomposition.

Some methods for decomposing predicates boil down to replacing the original predicate $P$ with some auxiliary predicate $P'$, which is built based on the original predicate $P$ by introducing one or more auxiliary variables $y_1, y_2, \dots, y_k$. The idea of these methods is that the auxiliary predicate $P'$ is constructed in advance so that it satisfies some required quantifier-conjunctive dependence. Then, using the existential quantifiers, the predicate $P'$ is decomposed directly. This predicate is related to the original predicate $P$ by equality

$$P = \exists y_1 \exists y_2 \dots \exists y_k (P'). \tag{5}$$

Although in fact a quantifier-conjunctive decomposition of the auxiliary predicate $P'$ is performed, the original predicate $P$ is restored using equality (5). Therefore, they say that the predicate is decomposed.

Thus, the predicate decomposition can be performed either without the help of auxiliary variables, or with the help of them. In the first case, decomposition is called equivalent, in the second – nonequivalent. So, the decomposition of the mentioned predicate $P'$ is equivalent, and the decomposition of the original $P$ is nonequivalent. Quantifier conjunctive decomposition is equivalent.

***Functional Dependence***

Let us consider the concepts of dependencies and some statements regarding them. The latter allow for a given relationship to resolve the question of the admissibility of a projection-connective decomposition. Consider special cases: functional and multi-valued dependencies [15].

Let a relation $R \in Re(T)$ be given and $X$, $Y$ be arbitrary subsets of the set at$(R)$. It is said that $Y$ *depends functionally* on $X$ if for any two functional data $f_1, f_2 \in R$ from equality $f_1[X] = f_2[X]$ follows the equality $f_1[Y] = f_2[Y]$. If $Y$ depends functionally on $X$, it is written $X \to Y$ and said that the relation $R$ satisfies the functional dependence $X \to Y$ or that the functional dependence $X \to Y$ is fulfilled in the relation $R$.

It follows directly from the definition that if the dependence $X \to Y$ is satisfied in $R$, then it is executed in any of its projections containing many attributes $X \cup Y$.

If $R \in Re(T)$ is an arbitrary relation, then the set of pairs $(X, Y)$ such that $X \to Y$ in $R$ is denoted by FD$(R)$. It is called the *structure* of the functional dependencies of the relationship $R$.

Let be an arbitrary relation $R$. It is proved that the structure of functional dependencies FD$(R)$ has the following properties ($X, Y, Z, W$ is a subset of a set at$(R)$).

$$\text{If } X \supseteq Y, \text{ then } X \to Y. \tag{6}$$

$$\text{If } X \to Y \text{ and } Y \cup Z \to W, \text{ then } X \cup Z \to W. \tag{7}$$

For a deductive system defined by rules (6) – (7), the problem of derivability or logical sequence is algorithmically solvable, which means that the analysis of the structures of functional dependencies can be carried out automatically. There are algorithms that allow for a given set of functional dependencies $\Sigma$ to find the set of all dependencies $\phi(\Sigma)$ that logically follow from the set according to the rules (6) – (7). In addition, there is an algorithm to determine whether some functional dependence $\sigma$ is a consequence of many dependencies $\Sigma$ or not. To analyze relationships with functional dependencies, all these algorithms are based on the apparatus of Boolean functions.

***Multi-valued Dependence***

Statement 1. Haag's theorem. Let $R$ be some relation from $Re(T)$, and the family of sets $\{X, Y, Z\}$ forms a partition of the set *at*$(R)$. If $X \to Y$ in $R$, then

$$R = R[X \cup Y] \circ R[X \cup Z]. \tag{8}$$

In other words, Haag's theorem says that functional dependence $X \to Y$ in relation $R\{X, Y, Z\}$ implies connection dependence for it.

Let us consider the concept of multi-valued dependence. Let a relation $R \in Re(T)$ be given and let $X$ and $Y$ be arbitrary subsets of the set at$(R)$. It is said that $X$ ambiguously determines $Y$ if $R = R[X \cup Y] \circ R[X \cup Z]$, where $Z = \text{at}(R) \setminus (X \cup Y)$. If $X$ defines $Y$ ambiguously, it is written $X \twoheadrightarrow Y$ and said that the relation $R$ satisfies the ambiguous dependence $X \twoheadrightarrow Y$ or that the ambiguous dependence $X \twoheadrightarrow Y$ is fulfilled in the relation $R$.

The above definition shows that a multi-valued dependence is a special case of a connection dependence and is also determined through an algebraic integrity constraint.

If $R \in Re(T)$ is an arbitrary relation, then the set of pairs $(X, Y)$ such that $X \twoheadrightarrow Y$ in $R$ is denoted by MVD$(R)$. It is called the structure of multi-valued relationship dependencies $R$.

Let $R$ be an arbitrary relation. It is proved that the structure of multivalued dependencies MVD$(R)$ has the following properties ($X$, $Y$, $Z$, $W$ - subsets of a set at$(R)$).

$$\text{If } X \supseteq Y, \text{ then } X \twoheadrightarrow Y. \tag{9}$$

$$\text{If } X \twoheadrightarrow Y \text{ and } Y \cup Z \twoheadrightarrow W, \text{ then } X \cup Z \twoheadrightarrow W \setminus (Y \cup Z). \tag{10}$$

$$\text{If } X \twoheadrightarrow Y \text{ and } X \twoheadrightarrow Z, \text{ then } X \twoheadrightarrow Y \cup Z. \tag{11}$$

$$\text{If } X \twoheadrightarrow Y, \text{ then } X \twoheadrightarrow \text{at}(R) \setminus (X \cup Y). \tag{12}$$

Property (12) suggests that multi-valued dependencies always form connected pairs; therefore, the notation is used $X \twoheadrightarrow Y|Z$ to relate $R$ to at$(R) = \{X, Y, Z\}$ and the dependence $X \twoheadrightarrow Y$. As for functional dependencies, for the deductive system defined by rules (9) – (12), the derivability problem is algorithmically solvable, therefore, the analysis of the structures of multi-valued dependencies can also be carried out automatically using Boolean functions.

Statement 2. Let $R \in Re(T)$ be an arbitrary relation, and $X$ and $Y$ be arbitrary subsets at$(R)$ of the set $Z = \text{at}(R) \setminus (X \cup Y)$. The relation $R$ satisfies the dependence $X \twoheadrightarrow Y$ if and only if

$$\sigma_{(X=A)\wedge(Z=C)}(R)[Y] = \sigma_{X=A}(R)[Y] \tag{13}$$

for every $\{X: A\} \in R[X]$ and every $\{Z: C\} \in \sigma_{X=A}(R)[Z]$.

Equality (13) shows, that for every $\{X: A\}$ from $R[X]$ set $\sigma_{(X=A)\wedge(Z=C)}(R)[Y]$ does not depend on $\{Z: C\} \in \sigma_{X=A}(R)[Z]$. It means that multivalued dependency $X \twoheadrightarrow Y$ in $R$ defines the displaying of $\{X: A\} \to \sigma_{(X=A)\wedge(Z=C)}(R)[Y]$ from $R[X]$ to Boolean $P(R[Y])$ that can be related as multivalued function from $R[X]$ in $R[Y]$.

This statement in less formal form is chosen as a definition to multivalued dependency by Date. Except for the notation, this definition is as follows.

Let there be some relation $R \in Re(T)$, $X, Y, Z \subseteq \text{at}(R)$ and $X \cup Y \cup Z = \text{at}(R)$, and the sets $X, Y, Z$ do not intersect in pairs. $Y$ multivalued depends on $X$ if and only if the set of values $Y$ corresponding to a given pair (value $X$ and value $Z$) of the ratio $R$ depends only on $X$ but does not depend on $Z$.

At the same time, Date cites the definition of multivalued dependence adopted in this paper as Feigin's theorem, which is formulated in terms of “if and only if”.

Statement 3. Let $R \in Re(T)$ be an arbitrary relation, and $X$ and $Y$ be arbitrary subsets of the set $\text{at}(R)$, $Z = \text{at}(R) \setminus (X \cup Y)$. The relation $R$ satisfies the dependence $X \twoheadrightarrow Y$ if and only if

$$\sigma_{X=A}(R)[Y \cup Z] = \sigma_{X=A}(R)[Y] \circ \sigma_{X=A}(R)[Z] \tag{14}$$

for every $\{X: A\} \in R[X]$.

Note that the natural combination of two relations that have no common attributes can be viewed as an extended version of the Cartesian product. Equality (14) expresses just such a case. In fact, Statement 3 expresses another way that multivalued dependency can be defined.

According to Statement 3, the presence of a multivalued relationship $X \twoheadrightarrow Y$ in a relation $R\{X, Y, Z\}$ means that its attributes $Y$ and $Z$ are mutually independent: the set of values of each of them depends only on the value of the attribute $X$. In other words, multivalued dependencies $X \twoheadrightarrow Y|Z$ appear when, for a meaningful group of characteristics $X$, the set of values of characteristics from groups $Y$ and $Z$ must occur in any combinations with a fixed value of the $X$-component.

Each functional dependence is a multivalued dependence, i.e. if $X \to Y$ at $R$, then $X \twoheadrightarrow Y$ at $R$. Therefore $\text{FD}(R) \subseteq \text{MVD}(R)$. Thus, multivalued dependencies are a generalization of functional dependencies.

However, there is a significant difference between functional and multivalued dependencies. According to (12) dependences $X \twoheadrightarrow Y$ and $X \twoheadrightarrow \text{at}(R) \setminus (X \cup Y)$ always form connected pairs, which is denoted as $X \twoheadrightarrow Y|Z$, where $Z = \text{at}(R) \setminus (X \cup Y)$. Property (12) has no analogue for functional dependencies, therefore, in the general case, they do not form connected pairs.

The following statement generalizes Statement 2, and this time uses the notion of connection dependency.

Statement 4. Let $R$ be some relation from $Re(T)$, and the family of sets $\{X, Z_1, Z_2, \dots, Z_m\}$ forms a partition of the set $\text{at}(R)$. The relation $R$ satisfies the connection $[X \cup Z_1, X \cup Z_2, \dots, X \cup Z_m]$ dependence if and only if

$$\sigma_{X=A}(R)[Z_1 \cup Z_2 \dots \cup Z_m] = \sigma_{X=A}(R)[Z_1] \circ \sigma_{X=A}(R)[Z_2] \circ \dots \circ \sigma_{X=A}(R)[Z_m] \tag{15}$$

for each $\{X: A\} \in R[X]$.

Statement 5. Generalization of Feigin's theorem. Let $R$ be some relation from $Re(T)$, and the family of sets $\{X, Z_1, Z_2, \dots, Z_m\}$ forms a partition of the set $\text{at}(R)$. A relation $R$ satisfies the connection dependency $[X \cup Z_1, X \cup Z_2, \dots, X \cup Z_m]$ if and only if it simultaneously satisfies multivalued dependencies $X \twoheadrightarrow Z_1, X \twoheadrightarrow Z_2, \dots, X \twoheadrightarrow Z_m$.

According to Statement 3, the multivalued dependence $X \twoheadrightarrow Y|Z$ performed in relation to $R$ with $\text{at}(R) = X \cup Y \cup Z$ expresses the mutual independence of attributes $Y$ and $Z$ in relation to $R$ considering that the set of values of each of them is determined by the value of the attribute $X$. In

the same way, Statement 3 allows us to consider the dependence $X \twoheadrightarrow Z_1|Z_2|\ldots|Z_m$ performed in $R$, at$(R) = X \cup Z_1 \cup \ldots \cup Z_m$: it expresses the mutual independence of attributes $Z_1, Z_2, \ldots, Z_m$, from each other, given that the set of values of each of them is determined by the value of the attribute $X$.

According to Haag's theorem, functional dependence acts as a sufficient condition for decomposition of a given relation into two of its projections. Statements 2 and 3 can be considered as criteria for the presence of a certain multivalued dependence in a given relation. Statement 4 is a criterion for the presence of a connection dependence of a certain type, and Statement 5 establishes the equivalence of such a dependence to a group of multivalued dependencies with the same determinant. Due to this, Statement 4 can be viewed as a generalization of Statement 3 to the case of a group of multivalued dependencies.

***Defining Predicate Dependencies***

The functional dependence of the argument $x_n$ on the arguments $x_1, \ldots, x_{n-1}$ in the predicate $P(x_1, \ldots, x_n)$ is expressed by the following formula:

$$\forall x_1 \forall x_2 \ldots \forall x_n \forall x_n' (P(x_1, \ldots, x_{n-1}, x_n) \wedge P(x_1, \ldots, x_{n-1}, x_n') \Rightarrow x_n = x_n'). \quad (16)$$

Any functional dependence of one group of predicate variables $P(x_1, \ldots, x_n)$ on another group can be specified either by several formulas of the form (16), or by one such formula in which, after implication, there will be a conjunction of several equality predicates. If $X$ and $Y$ are subsets of predicate variables $P(x_1, \ldots, x_n)$ and $Y$ functionally depends on $X$, then we the predicate $P(x_1, \ldots, x_n)$ *satisfies the functional dependence* $X \to Y$.

The multi-valued dependence for predicates can be expressed in terms of the conjunction dependence. We say that a predicate $P \in$ Pre$(S)$ *satisfies* a multi-valued dependence $X \twoheadrightarrow Y$ if it satisfies the dependency of the conjunction $\wedge \{X \cup Y, X \cup Z\}$, where $Z = V \setminus (X \cup Y)$. In this case the dependence $X \twoheadrightarrow Z$ will also be fulfilled, which together can be denoted as $X \twoheadrightarrow Y|Z$.

As with relational relationships, dependency structures can also be defined for predicates. Let be $P \in$ Pre$(S)$, , $Y \subseteq V$ . Then the set of pairs $(X, Y)$ such that $X \twoheadrightarrow Y$ in $P$, is denoted by MVD$(P)$ and will be called the structure of the functional dependences of the predicate. Similarly, the set of pairs such that in, is denoted by and will be called the structure of multivalued dependencies of the predicate.

Apparently, sets FD$(P)$ and MVD$(P)$ will have the same properties as dependency structures for relationships. But to verify this assumption, additional research is required, which is beyond the scope of this paper.

Connection dependency properties are derived from the properties of a natural join operation. An analogue of the natural connection of relations is the conjunction of predicates, which, like the natural connection, is idempotent, commutative, and associative. Two other properties of the natural compound are easily extended to the conjunction operation. If we show the fulfillment of the latter for the conjunction, then it can be argued that the dependencies of the conjunction have the same properties as the dependencies of the connection.

***Cartesian Decomposition***

The only justified binary predicate decomposition method that guarantees the correctness of the result is the Cartesian decomposition, which allows decomposition of any finite predicates, not just functional ones. Although the disadvantages of this method were discussed earlier, we will consider the Cartesian decomposition as a starting point for finding a more rational method in the sense of saving hardware resources.

To perform the Cartesian decomposition of a predicate $P \in$ Pre$(S)$, it is necessary to explicitly represent its region of truth. As such, you can use the PDNF (Principal Disjunctive Normal Form) for predicate $P$. Let $P_T$ be the region of truth of the predicate $P$, $P_T \subseteq S$. Then

$$P(X,Z) = \bigvee_{(a_1,a_2,\dots,a_m,c_1,c_2,\dots,c_n)\in P_T} x_1^{a_1}x_2^{a_2}\dots x_m^{a_m}z_1^{c_1}z_2^{c_2}\dots z_n^{c_n} = \bigvee_{i=1}^{r} x_1^{a_{i1}}x_2^{a_{i2}}\dots x_m^{a_{im}}z_1^{c_{i1}}z_2^{c_{i2}}\dots z_n^{c_{in}}, \quad (17)$$

where $r$ is the number of tuples of the relation $P_T$ (which will of course be due to the finiteness of the predicate $P$).

According to the Cartesian decomposition method, an auxiliary variable is introduced with values $B = \{b_1, b_2, \dots, b_r\}$ that are interpreted as unique names of relationship tuples.

Cartesian decomposition $P(X,Z)$ is performed by constructing an auxiliary predicate $Py(X,Z,y)$ and subsequent binary decomposition $Py(X,Z,y)$ using existential quantifiers.

As noted above, the disadvantage of this decomposition is that the variable $y$ takes as many values within the predicate $Py$ and its projections as the number of tuples contains the region of truth of the predicate $P$. We assume that this is the maximum number of values of the auxiliary variable that is required for binary decomposition of the predicate, since such a quantity is always sufficient. In real language models, this number is usually large. It was previously explained that this complicates the circuitry implementation of such models on a microcircuit. In addition, during Cartesian decomposition, no structural features of the predicate are considered in order to reduce the number of values of the auxiliary variable.

The task is to use a binary function (and other dependencies if they exist in the predicate) to perform binary decomposition either directly using existence quantifiers or with the preliminary introduction of one auxiliary variable with a minimum number of values.

The principle of the proposed method of binary decomposition consists in the methods of constructing auxiliary predicates, based on which with the help of existential quantifiers (by eliminating variables) many binary predicates are formed. The latter are the result of binary decomposition of the original predicate. The construction of auxiliary predicates can be performed in different ways, or it may not be necessary at all. From the point of view of the structure of the initial functional predicate, three different situations are possible that determine the sequence of actions to achieve binary decomposition at a minimum price.

When binary decomposition of a functional predicate $P(X,Z)$ is necessary, firstly, it is necessary to check whether the arguments $\{x_1, x_2, \dots, x_m\}$ of the described function $p: A \to C$ are independent of each other. Mutual independence of variables $x_1, x_2, \dots, x_m$ in a predicate $P(X,Z)$ means that the dependency $Z \twoheadrightarrow x_1|x_2|\dots|x_m$ is fulfilled. To strictly check the predicate $P(X,Z)$ for a dependency $Z \twoheadrightarrow x_1|x_2|\dots|x_m$, it is necessary to perform a disjunctive expansion of the predicate $P(X,Z)$ by variables $Z$. After that, the form of this decomposition will allow us to establish exactly whether the dependence $Z \twoheadrightarrow x_1|x_2|\dots|x_m$ in the predicate $P(X,Z)$ is fulfilled or not.

If the predicate $P(X,Z)$ satisfies the dependencies $Z \twoheadrightarrow x_1|x_2|\dots|x_m$, then binary decomposition is quite simple. There are two possible situations.

The first situation occurs when a group of variables $Z$ consists of one variable – $z$. Then an auxiliary variable is not required: binary decomposition $P(X,z)$ is performed using existence quantifiers directly based on a given conjunction dependence, which can be represented as $\wedge\{\{x_1,z\},\{x_2,z\},\dots,\{x_m,z\}\}$. This is the simplest case. A slightly more complicated case is when a group $Z$ consists of two or more variables; then the second situation takes place.

In the second situation, it is necessary to replace the group $Z$ of variables with one auxiliary variable $y$, and then make the transition to two auxiliary predicates – $P_1(X,y)$ and $P_2(y,Z)$, which are the result of intermediate decomposition of the predicate $P(X,Z)$. The binary decomposition of predicates $P_1(X,y)$ and $P_2(y,Z)$ is carried out using existence quantifiers based on conjunction dependencies $\{\{y,x_1\},\{y,x_2\},\dots,\{y,x_m\}\}$ and $\{\{y,z_1\},\{y,z_2\},\dots,\{y,z_n\}\}$ respectively, which, as will be shown below, are performed by virtue of the construction of these predicates.

When $P(X,Z)$ does not satisfy the dependency $Z \twoheadrightarrow x_1|x_2|\dots|x_m$, then the most difficult situation of the three possibly takes place. Here, the transition to auxiliary predicates $P_1(X,y)$ and

$P_2(y, Z)$ also follows, followed by binary decomposition of the latter. However, the method of generating these auxiliary predicates in this case is much more complicated.

The last and most difficult situation from the point of view of binary decomposition of a functional predicate $P(X, Z)$ occurs when the dependence $Z \twoheadrightarrow x_1|x_2|\ldots|x_m$ is not satisfied. In this case, an auxiliary variable is also required. It will be introduced after the system of special subsets of the set $A$ is formed. The values of the auxiliary variable in this case will act as the names of these subsets. With this approach, on the one hand, dependencies will be built in auxiliary predicates that will allow their binary decomposition to be performed. On the other hand, the minimum required number of the indicated subsets will be formed, which will minimize the number of values of the auxiliary variable.

As with Cartesian decomposition, the advantage of this algorithm for executing the binary decomposition of functional predicates is the ability to process the formula or relation not in whole but in parts: for each complete inverse image, its minimum parallelepiped coverage is selected separately.

All available methods of nonequivalent decomposition, i.e., decompositions involving auxiliary variables oriented to static predicates or relations. The described method is no exception. Meanwhile, relationships in databases are dynamic objects that are constantly updated. Therefore, nonequivalent decomposition methods are not suitable for use in databases. However, they are good at describing natural language grammar, which (in comparison with industrial or commercial databases) can be considered a static object.

***Inflection Model***

On the way to creating a logical network that simulates a significant part of the natural language, there are several goals that can be described as follows. The first goal is to present the entire model of inflection by the logical network, and not just the individual parts of speech. The next goal is to provide a logical model of a word; this model should accurately express the entire morphology of the language, so the size of such a network seems quite impressive. The main goal is to provide the logical network with a general model of semantic-syntactic processing of phrases, which should cover most of the language.

In order to consistently move towards achieving your goals, you need to start with a model of inflection. So, to date, models of logical networks for the inflectional processing of some nominal parts of the speech of the language are already available: a model of inflections (end declension mechanism) of full non-possessive adjectives, a model of inflections of nouns of substantive declension. Other parts of speech, from existing models of inflectional processing, are not yet presented in the form of a logical network.

Using the arithmetic mean of the parameters significantly reduces the number of unique states, limiting them from 81 to single non-discrete value. This simplifies the calculations and reduces the size of the transition matrix, making the model more efficient in terms of computational resources.

Logic network, presented on Figure 1 reflecting the probabilities of transitions between different states of students during the course of study for 8 semesters. Each node on the graph represents the arithmetic mean of the students' states, ranging from 1.0 to 3.0, where 1.0 corresponds to low values of all parameters (grade point average, attendance, publications, participation in competitions), and 3.0 corresponds to high values of these parameters. Arrows between nodes display possible transitions of students from one state to another, and the probability of such a transition is indicated next to each arrow.

The chain demonstrates that transitions between states with similar values are most probable, reflecting the stability of students in certain categories. For example, students in a state with a low midterm grade (1.0) are likely to remain in this state or move to a slightly improved state (1.25 or 1.5). Conversely, transitions to higher states (e.g., from 1.5 to 3.0) are less probable and require significant changes in student behavior across multiple parameters at once.

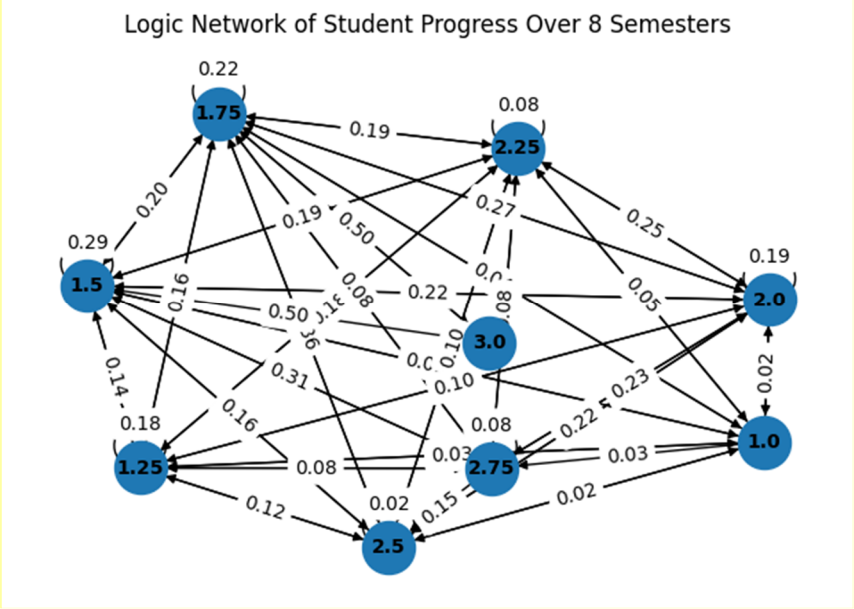



**Fig. 1.** Logic network transitions probabilities

The distribution graph of the final states (Figure 2) shows that most students are concentrated in the range from 1.5 to 2.0 by the average state score. This indicates that most students have states close to “Mid” (2) by the set of parameters (average score, attendance, publications, participation in competitions).

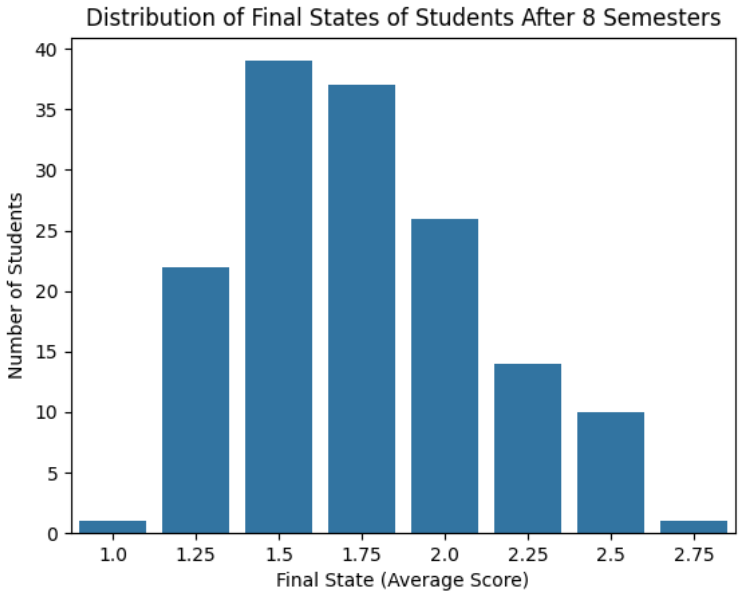



**Fig. 2.** Distribution of final states after 8 semesters.

Few students achieved values above 2.5, indicating the difficulty of achieving a high state, possibly due to the difficulty of achieving high values on multiple dimensions at once.

The average transition probability plot (Figure 3) shows that most students have an average transition probability in the range of 0.18–0.22.

This indicates that transitions between states are not easy and the highest probability remains stable. The different colors of the dots on the plot represent the final state of the students. The higher the value of the final state, the greater the probability of successful completion of the education.

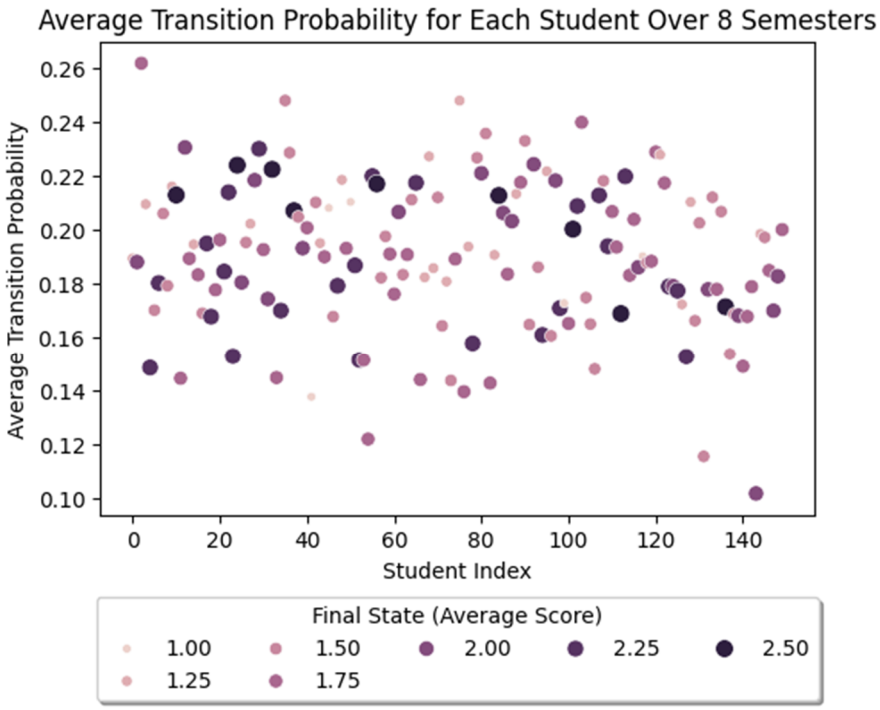



**Fig. 3.** Average transition probability for each student.

All formulas are presented in the basis of the disjunctive conjunctive predicate algebra (DCPA); therefore, the size or length of the formula is determined by the number of predicates of recognition of the subject contained in it. The binary predicate formulas obtained by decomposing $Xi, Eta$ and $Phi$ are written in compact form, which we will call the disjunctive-bracket form. It is in this form that the DCPA binary formulas form the basis of the circuitry implementation. The amount of hardware resources for the implementation of a model presented in the DCPA language is proportional to the number of recognition predicates in it. Therefore, the number of recognition predicates in the formulas of a certain model makes it possible to approximately estimate the amount of hardware resources that will be spent on its implementation.

Predicates serve as a means of describing finite discrete relations; therefore, one can also evaluate the result of decomposition by the size of relations corresponding to the obtained formulas. The size of a finite relationship is determined, like the size of any finite set, by the number of its elements. The dimension of relations (the number of attributes) can be ignored, since only binary relations are to be compared. Therefore, it is proposed for each method to calculate the total number of binary tuples in the obtained relations and, thereby, compare these methods with each other.

Such a calculation will be carried out by calculating the constituent units in the formulas, since the number of these constituents in the PDNF predicate coincides with the number of tuples of the corresponding relation. To move from the disjunctive-bracket form of a formula to its PDNF, you just need to open all the brackets in this formula. Therefore, to determine the number of constituents in the PDNF of a certain formula, it is necessary to calculate how many terms will be contained in the formula after the brackets are opened.

Based on the obtained binary formulas, one can calculate the length of each of them and the number of tuples in the corresponding relation. Cartesian decomposition of predicates $Xi, Eta$ and $Phi$ was not carried out, but the above parameters can be accurately calculated by determining the number of tuples in the relations corresponding to these predicates.

Cartesian decomposition is a rather trivial way to decompose, so the structure of the resulting binary predicates is very simple. Each such predicate is everywhere defined, surjective, and contains an auxiliary variable that uniquely determines the value of another variable. The

length of the formula of such a predicate in the minimum disjunctive-bracket form is determined as the sum of the areas of variation of its variables.

## 3. Conclusion

The main types of dependencies of attributes in relational relations are considered: functional, multivalued and connection dependencies. Considered assertions about dependencies that allow decomposition of relational relations.

Another direction in informatization is the creation of systems of integrated knowledge and the development of methods of active, mental navigation through these systems, including through global computer networks. Currently, the issue of hardware and software methods that effectively manipulate natural language information has turned into such a necessity that the effectiveness of public institutions and production systems begins to depend on it. It is no coincidence that among the most popular software tools are programs focused on the processing of natural language objects: text and linguistic editors and processors, programs for automatic correction of grammatical errors, automatic editing, natural language indexing, and searching, as well as machine translation programs, optical text recognition, etc. Recently, natural language modules are increasingly being introduced into the operating systems themselves.

Formal methods of intelligent systems were studied and analyzed in the work: methods of displaying knowledge depending on specific fields of application of systems; formal languages that allow representing knowledge in computer memory. Considered areas of application of algebraic methods in automated systems. Found computational practical applications of modern abstract algebra in databases and intelligent systems. Based on the application of algebraic methods in theoretical programming, various translators from high-level languages and various algorithmic algebras were developed. The perspective of using the considered method of solving logical equations in information systems provides the possibility of obtaining not only information directly stored in the database, but also derivative information obtained because of basic information.

All these problems cannot be solved without the involvement of a universal mathematical language. Developments in this field have been underway for several decades, work on algebraization has been carried out of logic, and a special mathematical apparatus was developed for the formula representation of relations and operations on them, which is called the algebra of finite predicates.

The central place in the algebra of predicates is occupied by relations, they reflect the properties of objects and the connections between them. But until now, there is no convenient method of formulaic communication of arbitrary relationships, which allows them to be implemented programmatically. The possibility of software implementation of formulas that describe predicates or relations is important when designing an automatic control system when developing a natural-language intelligent interface.

The results of the article aimed precisely at the creation of modern principled solutions in the construction of methods for the formal presentation of relations using the algebra apparatus of finite predicates focused on the real calculation of the capabilities of the modern computer and computing base and new requirements for information technologies, can be applied to modeling any - any logical structures that require a large range of calculations in real-time.

Although, in the main, the work was focused on the modeling he decomposition of the model of inflectional processing of regular verb word forms was performed using the method of binary decomposition of functional predicates developed in this work. As a result, a logical network was built for this model.

The analysis of the hardware implementation of the constructed logical network showed that such a network, implemented on a modern inexpensive programmable logic integrated circuit, works three orders of magnitude faster than a computer program that simulates the same logical network on a modern personal computer of average power.

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**За контакти:**
[1] Volodymyr Volkov, Dr. Sc. (Eng.), Professor, Head of the Department of Technical Operation and Service of Automobiles, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, e-mail: volf-949@ukr.net, https://orcid.org/0000-0003-2202-3441.
[2] Ihor Shubin, Assistant professor, Ph.D. in Technical Science (Software Engineering). Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, 61176, Nauky Ave 14. e-mail: igor.shubin@nure.ua, https://orcid.org/0000-0002-1073-023X.
[3] Ganna Pliekhova, Ph. D. (Eng.), Associate Professor, Head of the Department of Computer Science and Information Systems, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, e-mail: plehovaanna11@gmail.com, https://orcid.org/0000-0002-6912-6520.
[4] Denys Kopytkov, Associate Professor at the Department of Transport Systems and Logistics, O.M. Beketov National University of Municipal Economy in Kharkiv, Kharkiv, Ukraine, 61002, Chornohlazivska str. e-mail: kopytkov_dm@ukr.net. https://orcid.org/0000-0001-7861-4836.
[5] Tetiana Volkova, Ph. D. (Eng.), Associate Professor, Associate Professor at the Department of Transport Technologies, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, e-mail: wolf949@ukr.net, https://orcid.org/0000-0001-8546-4119.

# ИЗУЧАВАНЕ НА ЕКСПЛОАТАЦИОННИТЕ ХАРАКТЕРИСТИКИ НА АВТОМОБИЛНИТЕ ГУМИ

# STUDYING THE PERFORMANCE CHARACTERISTICS OF CAR TYRES

**Volodymyr Volkov [1], Volodymyr Karpenko [2], Eduard Neskreba [3], Tetiana Volkova [4]**

**Abstrsct.** The aim of the study is to determine the operational parameters of the interaction of car tyres with the road surface while driving. The process of interaction of car tyres with the road surface during driving is complex and can be implemented using the proposed mathematical models, which make it possible to predict the processes of tyre wear more easily. The analysis of research has shown that one of the main causes of tyre wear is the presence of friction forces that occur in the contact zone when the tread elements slip relative to the bearing surface. Therefore, the specific friction work or power produced by friction forces is taken as the wear criterion. It is assumed that if there is no slippage in the contact zone, then the displacement of an arbitrary point of the tyre carcass relative to the bearing surface can be determined by the values of circumferential and meridional deformations, which in turn makes it possible to determine the tangential stresses. This approach makes it possible to determine the specific friction work. As a result of the experiments, the distribution of tangential stresses and slip of tread elements relative to the bearing surface was obtained.
**Keywords:** car, car tyres, operational parameters, mathematical model, process of interaction between tyre and bearing surface, specific friction work, tyre wear.

## 1. Introduction:

Modern trends in the development of automotive tyres, in addition to automating the operation process, are also aimed at improving their performance. One of the criteria that determines the condition and behaviour of tyres is their performance [1]. The term tyre performance refers to the ability of a tyre to resist wear, which, in turn, leads to an increase in service life. It is clear that fuel efficiency, vehicle comfort, and driving safety also directly depend on these tyre characteristics [2]. Therefore, the study of tyre wear resistance properties in order to further improve the efficiency of tyres in general is currently an urgent task. This study presents a fairly detailed analysis of existing methods for assessing the wear resistance parameters of a car tyre.

When a tyre is deformed, normal and tangential stresses arise, and tread elements slip relative to the bearing surface, which causes tyre wear [3]. In addition to the design parameters, the operating parameters also have a significant impact on the wear process. This paper presents a more detailed study of both the design and operational parameters of the tyre. Based on its results, it is possible to formulate conclusions about the prospects for the development of the design of car tyres and recommendations for operation in order to improve performance and, above all, traffic safety.

Since the process of interaction between tyres and the road surface during driving is complex, it is necessary to move to mathematical models that make it easier to predict tyre wear processes, and at the same time achieve high accuracy, i.e. the results will be reliable.

First, let us consider the existing mathematical models describing the interaction of car tyres with the bearing surface during driving [1]. In the simplest case, the interaction of a tyre with a bearing surface can be considered as a special case of contact between two elastic bodies that are compressed with each other with a certain force. The road is assumed to be a smooth, undeformable surface (absolutely rigid), and the tyre can be represented by any elastic model. The rolling of an elastic wheel on a solid base was one of the first to be considered in [4]. Based on the proposed design scheme, rolling friction is accompanied by sliding friction. The contact area of the wheel with the bearing surface has areas of slipping and adhesion. In the area where slipping occurs, friction forces arise that are proportional to the normal pressure of the tyre on the bearing surface. The first studies on the interaction of tyres with the bearing surface were carried out under static conditions. The distributions of specific pressures and tangential stresses in the tyre-bearing surface contact zone were investigated. The saddle-shaped nature of the distribution of specific pressures in the transverse contact plane was

noted. The tangential stresses acting on the bearing surface in the contact zone near the tyre are directed towards its centre.

From the analysis of data obtained during the operation of pneumatic tyres, it was found that their service life is greatly influenced by the internal air pressure and the load perceived by the vehicle wheel. It was also noted that there is a combination of these parameters that can achieve maximum tyre mileage (service life). The internal pressure was usually selected according to the value of the relative deflection, which is accepted as the norm for a given class of tyres. However, this method of selecting the inflation pressure does not take into account all the design features of the tyre and its operating conditions. It provides only an approximate determination of the optimum pressure. For a more accurate determination of the optimum internal pressure, it is necessary to have data on the distribution of normal and tangential stresses over the contact area and the sliding of the tread elements relative to the bearing surface.

One of the main causes of tyre wear is the presence of friction forces that occur in the contact area as the tread elements slide against the bearing surface. Therefore, the specific friction work or power produced by friction forces is used as a wear criterion. There are examples of studies where the ratio of volume loss to friction work is taken as the criterion for assessing abrasion.

The purpose of the study is to determine the operational parameters of the interaction of car tyres with the road surface during driving.

### *2. Statement:*

Radial deformation of the tyre causes deformations in the circumferential and meridional directions. In [1], it was found that the carcass is parallel to the bearing surface within the contact area. However, according to the tread pattern (Fig. 1), this condition is not met.

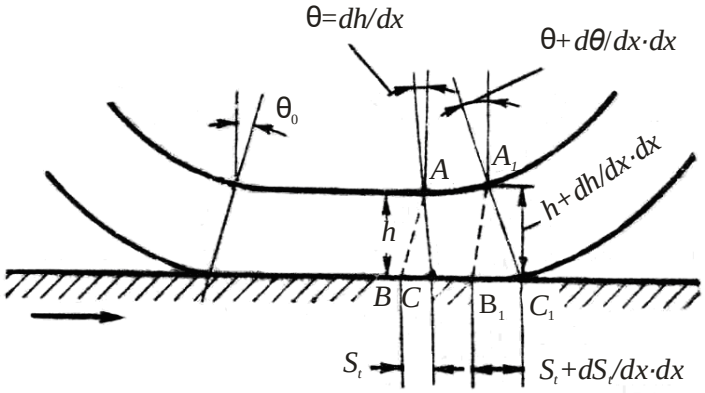



**Fig. 1.** Scheme for determining the displacements of tangential forces in the circumferential direction

Based on the assumption that there is no slippage in the contact area, the displacement of an arbitrary point of the tyre carcass relative to the bearing surface can be determined from the values of circumferential and meridional deformations, which in turn allows determining the tangential stresses (1, 2):

$$\tau_t = \frac{h_0}{3\psi_1\psi_2}\left(\frac{\ddot{a}q_0}{\ddot{a}x} - \frac{\ddot{a}q}{\ddot{a}x}\right) + \frac{G}{h_0\psi_1}\int_0^x\left(\varepsilon_t - \frac{r_\kappa}{r_0} + 1\right)dx; \quad (1)$$

$$\tau_m = \frac{G}{h\psi_1}\int_0^y\left(\varepsilon_m - \varepsilon_m^o\right)dy - \frac{G}{3\psi_1\psi_2}\left(\frac{\partial q}{\partial y} - \frac{\partial q_0}{\partial y}\right), \quad (2)$$

where $h_0$ – is the tyre tread thickness at the entrance to the contact;

$h$ – is the current value of the tyre tread thickness;

$\psi_1$, $\psi_2$ – coefficients depending on the shape of the tyre tread pattern;

$h$ – current value of normal stress;

$G$ – Young's modulus;

$\varepsilon_t$, $\varepsilon_m$ – current value of the circumferential and transverse deformation of the carcass;

$r_\kappa$ – tyre rolling radius;

$r_0$ – free radius of the tyre;

$\varepsilon_m^0$ – is the transverse deformation of the carcass at the contact entry.

Slippage in the sliding zone is proposed to be determined by the amount of displacement relative to the bearing surface (3):

$$s_m = a_m + \Delta m\,; \tag{3}$$

$$s_t = a_t + \Delta t\,, \tag{4}$$

where $s_m$, $s_t$ – are the longitudinal and transverse displacements of the frame point relative to the bearing surface, respectively;

$\Delta m$, $\Delta t$ – components of tread deformation;

$a_m$, $a_t$ – slip components.

The intensity of tangential forces in the slip zone is determined by dependence (5):

$$\tau = \sqrt{\left(C_m \Delta m\right)^2 + \left(C_t \Delta t\right)^2}\,, \tag{5}$$

where $C_m$ – transverse stiffness of the tread pattern elements;

$C_t$ – - longitudinal stiffness of the tread pattern elements.

Since the direction of an infinitesimal slip of a point during its transition from one position to the next coincides with the direction of the tangential force, we can write expression (6):

$$\frac{da_m}{da_t} = \frac{C_m \Delta m}{C_t \Delta t}\,. \tag{6}$$

Solving this equation, we obtain expressions (7, 8):

$$da_m = \frac{C_m \Delta m}{C_m^3 \Delta m^2 + C_t^3 \Delta t^2}\left(C_m^2 \Delta m ds_m + C_m^2 \Delta t ds_t - \phi^2 q dq\right); \tag{7}$$

$$da_m = \frac{C_t \Delta t}{C_m^3 \Delta m^2 + C_t^3 \Delta t^2}\left(C_m^2 \Delta m ds_m + C_m^2 \Delta t ds_t - \phi^2 q dq\right). \tag{8}$$

Knowing the values of slip and tangential forces, the specific friction work can be determined (9):

$$A_{mep} = \int \left( C_m \Delta m da_m + C_t \Delta t da_t \right). \tag{9}$$

In [5], the crown part of the tyre is modelled by a tape that is rigid in cross-section and flexible in the circumferential direction, and the role of the elastic base is played by compressed air - a tape on an elastic base (Fig. 2).

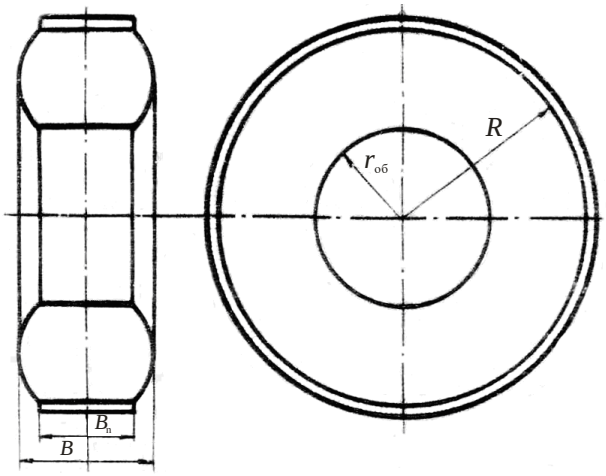



**Fig. 2.**Tyre model ‘elasticated belt’

From the consideration of the equilibrium of the element of the crown part of the tyre (Fig. 3), we obtain equation (10):

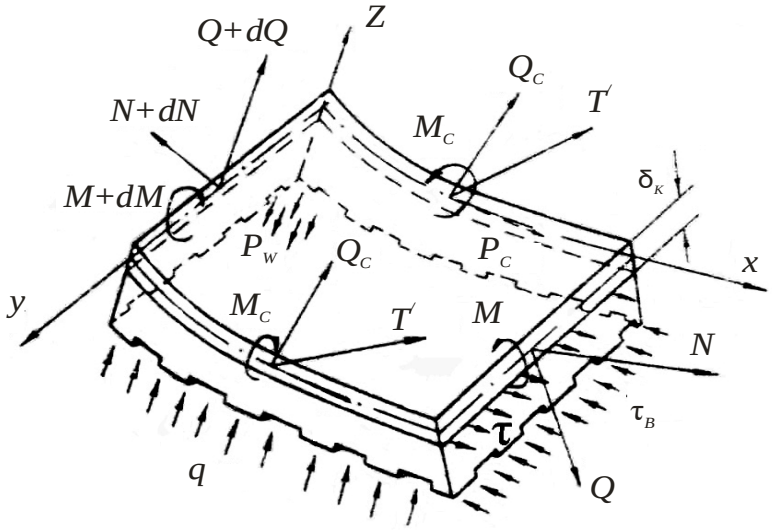



**Fig. 3.** Loads acting on the elements of the tyre model belt

$$\Sigma F_Z = B_n dQ + NB_n \left( \frac{1}{r_0} + \frac{d^2\omega}{dx^2} \right) dx - p_w B_n dx + KqB_n dx + 2Tidx + 2Qdx\,; \tag{10}$$

$$\Sigma F_X = B_n dN - 2T_X idx - \tau B_n dx - 2P_c dx = 0\,, \tag{11}$$

where $N$ – tensile force acting in the middle surface;

$Q$ – vertical force;

$P_c$ – horizontal force;

$M$ – bending moment acting on the side faces;

$K$ – proportionality coefficient;

$r_0$ – free radius of the tyre;

$B_n$ – tread width;

$i$ – circumferential density of cord yarns;

$T$ – cord tension;

$p_w$ – internal air pressure in the tyre.

Considering the same model of a tyre ‘tape on an elastic base’, work [5] also solves the problem of determining the distribution of longitudinal stresses in the plane of contact of a rolling wheel. Based on the known vertical stress distribution curve, tangential stresses are determined in the slippage zones, where they cannot exceed the limit of adhesion of the tyre elements to the bearing surface.

Paper [6] presents a contact problem for a radial tyre compressed on a plane. A model of a circular ring extending in the circumferential direction is presented, which is connected to the rim by springs. The outer surface of the ring has an elastic layer that simulates the tread of a tyre. In cross-section, the ring with the elastic layer is a rectangle, and in the process of deformation, all points of the cross-section receive the same radial displacement to the wheel axis and the same circumferential displacement.

However, since a real tyre has a curvature in its cross-section, the results of the calculations carried out using the previously described model differed from the experimental ones.

The performance properties of a tyre can also be indirectly assessed through the parameters of tyre stiffness and rolling resistance. Paper [7] presents the results of analysing the condition and behaviour of a car tyre during the period of starting movement. The peculiarity is that the main parameter for assessing the condition of a tyre is its stiffness characteristics. The research was conducted under conditions that can often occur during the operation of car tyres, namely at low ambient temperatures. To solve the problem, the authors used a numerical analytical approach. Similar approaches to modelling the interaction of a car wheel are presented in [8]. Therefore, the initial data necessary to perform a correct analysis in [7] were obtained from the results of experimental studies in road conditions. Using the results obtained, it is possible to provide recommendations on the peculiarities of the operation of car tyres under ‘unfavourable’ conditions. The main part of the paper is devoted to solving the differential equations of motion of a mechanical system, which is represented as a mass-spring-damper model. The research presented in this paper confirms the hypothesis that under adverse operating conditions, the operation of a car tyre and suspension differs from their behaviour under normal conditions. In other words, the suspension is generally more rigid, which significantly affects such operational properties of the vehicle as comfort and, above all, traffic safety.

The problem of studying the influence of tyre performance and design parameters on tyre wear, despite the huge amount of work, remains not fully resolved. For example, many scientific papers, analysing the effect of internal pressure, wheel load, and deflection angle, note that tyre design affects its interaction with the bearing surface, but no clear recommendations are given for optimising tyre design.

The variants of mathematical models considered in this paper are quite adequate, but when choosing models, it is necessary to clearly define what assumptions were made when creating the model and take into account all the shortcomings of the models.

The practical use of the proposed analytical expressions (1-9) is difficult, since it is quite difficult to determine many of the quantities included in these expressions. The nature of the deformation of the tread pattern elements is more complex than unilateral compression, as assumed in the derivation of these formulas.

The disadvantage of the elastic-base belt model is that the equation requires the consolidated stiffness of the tyre casing to be available. The model does not take into account the uneven distribution of stiffness across the width of the tyre and the distribution of the displacement of the centre surface in the slip zone.

The results of modelling the suspension and car tyre are shown in Figure 4 [8].

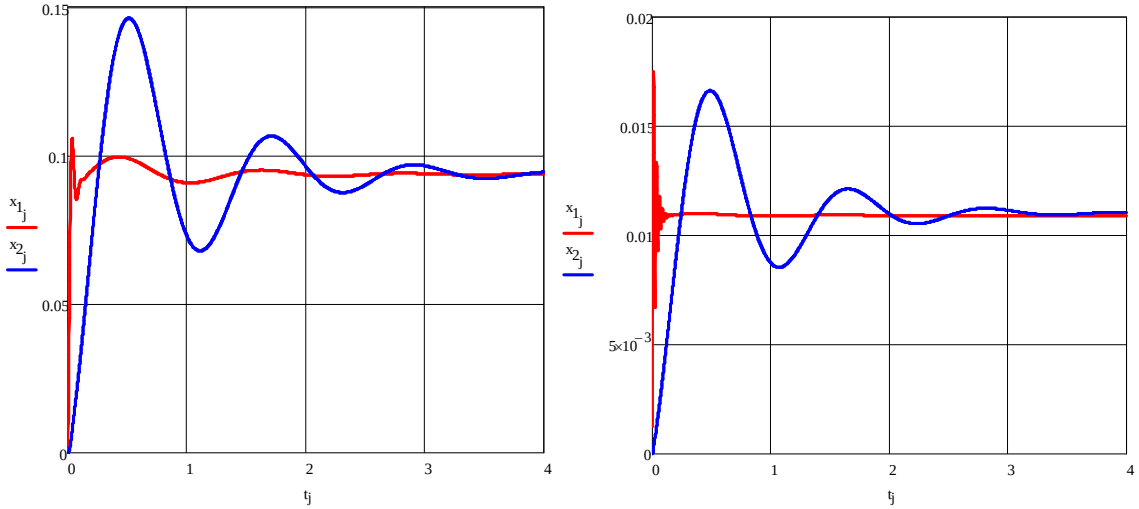



**Fig. 4.** Results of modelling the displacement of the unsprung and unsprung vehicle mass, a - under normal operating conditions; b - under ‘unfavourable’ operating conditions

## 3. Conclusions:

When studying the performance properties of tyres, it is convenient to use mathematical models, which greatly simplifies the process of assessing and determining the wear resistance parameters of a tyre. Such an operational parameter as the value of the internal air pressure has a significant impact, because with an increase in the internal pressure, there is an increased wear of the central tread zone and tensile stresses in the carcass, while a decrease in it leads to an increase in wear of the outer tread zones and bending stresses in the carcass.

The expressions obtained in the study of the elastic-belt model make it possible to determine the stress distribution depending on the load, internal pressure and tyre construction. Tyre twist caused by torque and braking torques is also taken into account. However, this model does not take into account the slippage of tread elements at the beginning and end of the contact patch and the uneven distribution of tyre stiffness in the transverse direction.

As a result of the experiments, the diagrams of the distribution of tangential stresses and slip of the tread elements relative to the bearing surface were obtained. At the beginning and end of the contact zone, the friction work increases, while in the middle zone, the friction work remains almost constant. This indicates that at the beginning and end of the contact area there are sliding zones, and in the middle there is a grip zone.

Also, when assessing the performance properties of a tyre, indirect methods of assessing the performance parameters of a tyre can be used, for example, the method described in [7] can be used to assess the stiffness of a tyre, which in turn directly affects the wear resistance parameters of a tyre. These tyre parameters are also significantly influenced by tyre operating conditions, which is confirmed by the results of research.

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За контакти:
[1] Volodymyr Volkov, Dr. Sc. (Eng.), Professor, Head of the Department of Technical Operation and Service of Automobiles, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, tel.: (+38067) 747-21-77, e-mail: volf-949@ukr.net, https://orcid.org/0000-0003-2202-3441.
[2] Volodymyr Karpenko, Dr. Sc. (Eng.), Professor, Professor, of the Department of Machine Elements and Theory of Mechanisms and Machines, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, e-mail: karpenko4dm@gmail.com, https://orcid.org/0000-0001-7376-7585
[3] Eduard Neskreba, Assistant of the Department of Machine Elements and Theory of Mechanisms and Machines, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, https://orcid.org/0009-0007-0326-3905
[4] Tetiana Volkova, Ph. D. (Eng.), Associate Professor, Associate Professor at the Department of Transport Technologies, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, 61002, Yaroslava Mudrogo Str. 25, e-mail: wolf949@ukr.net, https://orcid.org/0000-0001-8546-4119.

# ВЛИЯНИЕТО НА НАПОМПВАНЕТО НА ГУМИТЕ ВЪРХУ ДИНАМИКАТА НА ПРЕВОЗНОТО СРЕДСТВО И СЪПРОТИВЛЕНИЕТО ПРИ ТЪРКАЛЯНЕ

# THE IMPACT OF TIRE INFLATION ON VEHICLE DYNAMICS AND ROLLING RESISTANCE

**Yuriy Zybtsev[1], Pavlo Voroshylov[2]**

**Abstract**. The primary function of car tires is to provide adequate traction. When tire pressure is at its recommended level, the load at the contact patch between the tire and the road is evenly distributed, which helps maintain good handling, maneuverability, and efficient fuel consumption. The optimal pressure for a specific car is determined not by the tire itself, but by the vehicle manufacturer, since the same tire size can be used on different car models with varying weights and specifications. Typically, the recommended pressure can be found in the vehicle's manual or on a label located on the driver's door frame, the B-pillar, the fuel filler flap, or inside the glove compartment. This label usually lists the cold tire pressure values for both front and rear wheels, the maximum vehicle load, and the suggested tire size. Additionally, several factors can influence tire pressure, including vehicle weight, tire size, how the load is distributed, and even seasonal conditions. It's important to note that tire pressure fluctuates with changes in climate. In warmer temperatures, for example, pressure increases — a 25°C rise can cause an increase of approximately 0.8 bar. If the car is fully loaded, this pressure will be even higher. That's why manufacturers also provide recommended values for a fully loaded vehicle, emphasizing the importance of maintaining proper pressure for safety. During winter, lower ambient temperatures lead to a pressure drop of around 0.8 bar, which should be considered when inflating the tires. The rolling resistance coefficient (f) of Kleber Viaxer 175/70 R13 82T tires was measured on a Lada-112 vehicle using coast-down testing. An increase in air pressure by 0.05 MPa resulted in a 1.3% decrease in rolling resistance, while a 0.05 MPa decrease led to a 1.7% increase in resistance.

**Keywords:** pressure, tire, drag coefficient, road, friction force, acceleration, temperature.

## 1. Introduction:

The automotive world is currently looking for ways to reduce CO2 emissions.

One of the areas of search is reducing rolling resistance, which takes up a significant share of the fuel burned (and in the city, the bulk). Tire manufacturers have made significant strides in this area. The task of operators is to properly operate the car, in particular, the tires. First of all, it is necessary to maintain the recommended air pressure in them.

Tires play a crucial role in the overall performance and safety of a vehicle. One of their primary functions is to ensure sufficient traction between the car and the road surface. Proper tire inflation allows for an even distribution of the vehicle's weight across the contact patch—the area where the tire meets the road. This balance is vital for maintaining optimal handling, directional stability, steering responsiveness, braking efficiency, and fuel economy. Any deviation from the recommended tire pressure can adversely affect the dynamic behavior of the vehicle and increase rolling resistance, leading to higher fuel consumption and premature tire wear.

The optimal tire pressure is not determined by the tire manufacturer, but rather by the automaker. This is because the same tire size can be installed on various car models, each with different weights, suspension settings, and load distributions. For this reason, car manufacturers specify the appropriate pressure values for front and rear tires based on the specific vehicle's configuration and operating conditions. These recommended values are typically printed on a label found on the driver’s side door frame, the B-pillar, the fuel filler flap, or inside the glove compartment. They can also be found in the owner's manual.

Conversely, in winter, lower ambient temperatures cause the air inside the tires to contract, leading to a drop in pressure. A decrease of 25°C may reduce the pressure by a similar margin of around 0.8 bar. Driving with underinflated tires in such conditions can severely affect vehicle control, increase tire deformation, and elevate fuel consumption due to increased rolling resistance. For this reason, it is advisable to check and, if necessary, adjust tire pressure more frequently in colder seasons.

In conclusion, tire pressure is a critical factor influencing vehicle dynamics and resistance to motion. Regular monitoring and adjustment of tire inflation—especially in response to seasonal changes and varying load conditions—are essential for ensuring optimal driving

performance, minimizing wear, and conserving fuel. Drivers should be aware of manufacturer recommendations and make tire maintenance a regular part of vehicle care.

**2. Presentation:**

***Analysis of Literary Data and Problem Statement***

Tire pressure is one of the critical parameters that significantly influence a car's fuel consumption. When tire pressure drops below the recommended level, the contact patch—the area where the tire meets the road surface—expands, especially in the sidewall area. This increases the deformation zone, leading to greater rolling resistance. As a result, the engine has to work harder and burn more fuel to maintain normal driving conditions, decreasing the vehicle's overall fuel efficiency.

In addition to increased fuel consumption, underinflated tires also affect vehicle handling. A drop in tire pressure combined with an increased load on the steering wheel leads to changes in steering tension and reduced steering precision. This can impair driver control, especially at higher speeds.

Proper pressure ensures optimal load distribution within the tire, which extends the life of the tread and enhances safety. At normal pressure, the contact patch is balanced, and the load is distributed evenly. However, underinflation causes increased stress on the tire’s shoulders—the outer edges of the tread—resulting in accelerated wear in these areas. Overinflated tires, on the other hand, concentrate the load on the center of the tread, leading to faster wear in the middle section. Both scenarios reduce the overall lifespan of the tire and can negatively impact driving performance.

Driving at high speeds with underinflated tires can result in delayed or vague steering response, sharper skids during cornering, and tire squealing. These conditions not only affect driving comfort but also compromise safety by increasing the risk of uncontrolled vehicle behavior, especially in the rear axle, and can lead to internal heating of the tire carcass, further accelerating wear.

In response to the safety issues posed by incorrect tire pressure, modern vehicles are increasingly equipped with Tire Pressure Monitoring Systems (TPMS), which have become mandatory in many countries. These systems are generally classified into two types based on how they measure tire pressure:

- Indirect TPMS, which estimates tire pressure based on the distance traveled by each wheel in one revolution.
- Direct TPMS, which uses individual pressure sensors mounted inside the tires to measure pressure in real-time.

The more commonly used type is the indirect system, which is integrated into the vehicle’s ABS (Anti-lock Braking System). These systems use wheel speed sensors to calculate the distance each wheel travels. However, since vehicles rarely move in a perfectly straight line, and the outer wheels always travel farther during turns, the system doesn’t compare individual wheels. Instead, it sums the speeds of diagonally opposite wheels, calculates the difference, and compares it to preset parameters. If the system detects a deviation beyond a certain threshold, it activates a warning light on the dashboard.

Advantages of the Indirect TPMS:

- Does not require additional hardware, making it more cost-effective.
- Can be recalibrated after tire replacement or servicing.

Disadvantages:

- Requires 30–50 km of driving to “learn” the normal parameters after reset.
- Does not indicate which tire has lost pressure.
- Cannot detect rapid pressure drops (e.g., punctures).
- Fails to detect simultaneous pressure loss in multiple tires.
- Accuracy is affected by factors such as wheel slip, vehicle load, and tire condition.
- The system only triggers a warning if pressure drops by at least 25–30%.

- Does not measure tire pressure before the vehicle starts moving.

In contrast, Direct TPMS systems rely on pressure sensors, a control unit, antennas, and a display screen to provide real-time pressure readings for each wheel. These systems measure the elasticity of the tire-air structure, which is directly related to the internal pressure. Because they monitor pressure continuously, they offer more accurate and timely information, significantly improving safety and tire management.

It is well established that tire pressure affects rolling resistance: higher pressure reduces the rolling resistance coefficient, while lower pressure increases it. Although this principle is widely acknowledged in tire literature, the exact relationship between pressure change and rolling resistance is often vaguely defined, and few reliable studies are available. Many sources cite varying figures—such as a 2–5% increase in rolling resistance for every 0.01 MPa (0.1 bar) pressure drop—without specifying the tire type, test conditions, or methodology.

One study that provides clear and detailed data is described in [1]. It involved coast-down testing of a Lada-112 (VAZ-2112) equipped with Kleber Viaxer 175/70 R13 82T tires. The test vehicle was loaded with a driver and a Racelogic VBOX operator. The VBOX system used GPS signals to track distance. The vehicle was tested at three different tire pressures:

1. 0.2 MPa (nominal): Average coast-down distance from 80 km/h – 1,175 m
2. 0.25 MPa (increased): Coast-down distance – 1,232 m, fuel consumption reduced by 1.6%
3. 0.15 MPa (decreased): Coast-down distance – 1,108 m, fuel consumption increased by 2%

Braking distances and subjective driving impressions were also evaluated. The findings indicated that although a slight increase in pressure resulted in minor fuel savings, it also caused a deterioration in ride comfort and handling. Therefore, the modest economic benefit does not outweigh the negative impact on vehicle performance and safety.

### *Aim and Tasks of the Research*

The objective of this article is to enhance the accuracy of vehicle motion calculations by establishing the relationship between rolling resistance coefficients and tire air pressure.

To achieve this, the following tasks are addressed:

- Refine the description of vehicle resistance during coasting, incorporating the effect of tire pressure;
- Solve the direct problem — calculate the coasting distance based on the improved resistance model;
- Solve the inverse problem — determine the rolling resistance coefficient using a known coasting distance.

### *Research Results*

The deceleration of a vehicle during coasting is caused by various resistance forces, primarily aerodynamic drag ($P_a$), rolling resistance ($P_r$), and the internal resistance of the transmission when idling. The latter is typically not treated as a separate component and is generally assumed to be implicitly accounted for within the other two resistance forces. Aerodynamic drag is only indirectly influenced by tire pressure, as changes in pressure affect the vehicle's ride height (clearance), which in turn alters the aerodynamic characteristics [2, 3].

$$C_x = C_{x0} \cdot (1 + 1{,}7 \cdot \Delta e) \,, \qquad (1)$$

where $C_{x0}$ is the value of $C_x$ at nominal clearance, $\Delta e$ is the change in clearance compared to nominal, m (taking into account the sign).

The clearance will change by the amount of change in tire deflection ($\Delta e = \Delta t$), and the tire deflection (m) is determined by the load on the wheel $G_k$ (N) and the tire stiffness Ct in N/m:

$$\Delta_t = \frac{G_k}{C_t} , \quad (2)$$

Rolling resistance can be effectively estimated using approximating polynomials, as suggested in [3]. For the purposes of this analysis, we assume that moderate variations in tire pressure do not alter the shape of the curve describing the dependence of the rolling resistance coefficient (f) on vehicle speed (v). Instead, only the values of the function (its ordinates) change, scaled by a proportionality factor denoted as $K_t$. Therefore...

$$f = K_t \cdot (A_v^2 + B_v + C), \quad (3)$$

where A, B, C are the coefficients of the approximating polynomial.

Next, we can formulate a differential equation

$$\frac{d_v}{d_t} = \frac{(P_w + P_f)}{m_{rm}} = \frac{(k_F \cdot v_2 + K_t \cdot (A_v^2 + B_v + C) \cdot G_a)}{m_{rm}} , \quad (4)$$

where the streamlining coefficient $k = \rho \cdot \frac{C_x}{2}$ (ρ – air density, kg/m$^3$; $C_x$ – aerodynamic drag coefficient); F – frontal area of the vehicle, m$^2$; mpr – reduced mass of the vehicle, kg; $G_a$ – vehicle weight, N.

Experience shows that it is more convenient to solve this equation numerically: select the step of change in speed $\Delta v$, for each i-th interval find the average speed $v_{av}$, assuming that on this interval the deceleration $j_i$ is constant; calculate the resistance forces at this average speed, from their sum find the average deceleration ji; then you need to calculate the duration of the i-th interval $\Delta ti = \Delta v / ji$ $\Delta t_i = \frac{\Delta_v}{J_i}$ and the path of the car on this interval $\Delta S_i = \Delta t_i \cdot v_{av}$; summing up the cumulative total, we obtain diagrams of the time and distance of the coasting from the initial speed to a complete stop. This algorithm is very easily implemented, for example, in the Microsoft Excel package. Now, by changing the coefficient $K_{sh}$, you can select a value for which the calculated path will be equal to the measured value. The minimum value of the coefficient of rolling resistance

$$f = C \cdot K_t , \quad (5)$$

***Discussion of the Research Results***

Let us apply the proposed method to the experimental data presented in [1].

The curb weight of the Lada-112 is 1060 kg. Adding the weight of the driver, the test operator, and the measuring equipment (assumed to be 180 kg), along with the equivalent (reduced) mass of the wheels and transmission components (37 kg), the total reduced mass of the vehicle becomes: $m_{mr} = 1060 + 180 + 37 = 1277$ kg.

This value will be used in subsequent calculations to determine the rolling resistance characteristics under varying tire pressure conditions.

According to [4], the frontal area is F = 1.944 m$^2$, the coefficient of aerodynamic drag is $C_x$ = 0.335; we will assume from [5] that on the road it will be 10% greater: $C_{xd}$ = 0.335 * 1.1 = 0.3685. The weather data are not specified in the article [1], we will assume the average air density to be 1.2 kg/m$^3$. Air resistance in nominal condition

$$P_w = 0{,}5 \cdot 1{,}2 \cdot 0{,}335 \cdot 1{,}1 \cdot \frac{1{,}944 v^2}{12{,}96} = 0{,}033165 v^2. \quad (6)$$

The dependence f(v) for SR, TR buses at the upper limit of the field of possible values is described by the expression [3]

$$f = 3{,}11238 \cdot 10^{-7} \cdot v^2 - 1{,}25429 \cdot 10^{-5} \cdot v + 0{,}013005 \quad (7)$$

The stiffness of 175/70R13 82T tires can be considered approximately 170 kN/m at a pressure of 0.2 MPa, 120 at 0.15 and 220 at 0.245 MPa [6, p. 260]. The corresponding tire deflections ($\Delta_t$), assuming a uniform distribution of load across the wheels, were calculated using Equation (2). Similarly, the aerodynamic drag coefficients ($C_x$) were determined using Equation (1). The outcomes of these calculations, employing the full method, are presented in Table 1 and visually depicted in Figure 1. In Figure 1, we can observe the graphical representation of the dependence of rolling resistance ($f(p_v)$) on tire pressure ($p_v$), as well as the linear and quadratic approximation curves derived from the experimental data.

Additionally, a simplified version of the calculation was conducted, which excluded the influence of tire pressure on aerodynamic drag. This version of the calculation assumes that aerodynamic resistance remains constant, regardless of the tire's inflation level. Interestingly, the results obtained from this simplified approach were found to be almost identical to those obtained from the full method, indicating that the effect of tire pressure on aerodynamic drag is minimal for the range of pressures tested. This suggests that, under the specific conditions of the experiment, the influence of tire pressure on rolling resistance dominates over its effect on aerodynamic resistance.

## 3. Conclusion:

It is important to note that the calculations presented here are based on the widely accepted mathematical model of vehicle motion resistance. While this model offers a reasonable approximation in most cases, the real-world situation diverges notably, particularly at lower speeds (below 20 km/h), as shown in Figure 2. At these lower speeds, additional factors—such as tire deformation and surface interaction—become more prominent, leading to deviations from the idealized model. However, incorporating these discrepancies would require a fundamental revision of the current rolling resistance model, which lies beyond the scope and objectives of this article.

Despite these differences, it can be concluded that the impact of variations in tire pressure on rolling resistance is relatively small. However, for high-precision calculations, especially in contexts requiring a high degree of accuracy, the influence of tire pressure must still be considered. Our analysis provides a useful reference for researchers who aim to refine existing models and incorporate the subtleties of tire dynamics into more sophisticated vehicle performance simulations.

**Table 1.** Results of Calculations for the Rolling Resistance Coefficient

| Pressure, MPa | 0,15 | 0,20 | 0,25 |
|---|---|---|---|
| $\Delta_t$, m | 0,0266 | 0,0188 | 0,0145 |
| $C_x$ | 0,3394 | 0,335 | 0,3325 |
| Run-out distance, m | 1108 | 1175 | 1232 |
| $K_t$ | 1,13882 | 1,0527 | 0,98589 |
| Taking into account changes in air resistance | | | |
| f | 0,015489 | 0,014317 | 0,013409 |
| Relative change f, %% | +1,64 | 0 | -1,27 |
| Without taking into account changes in air resistance | | | |
| f | 0,015563 | 0,014347 | 0,013369 |
| Relative change f, %% | +1,74 | 0 | -1,32 |

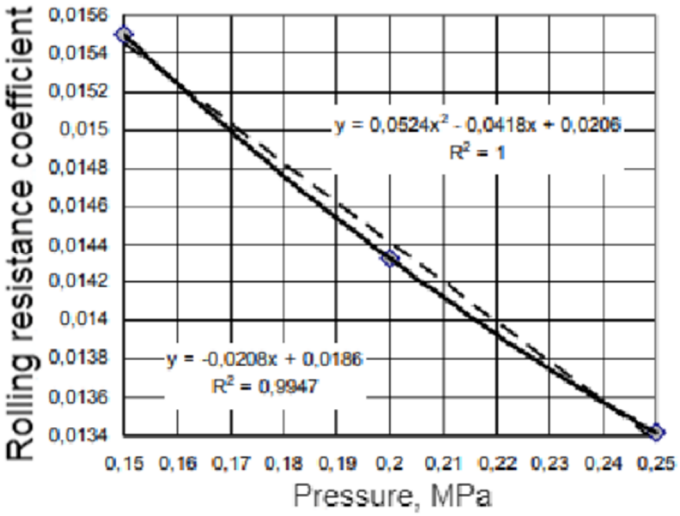



**Fig. 1.** Dependence of the rolling resistance coefficient of the tire 175/70R13 82T Kleber Viaxer on the internal pressure

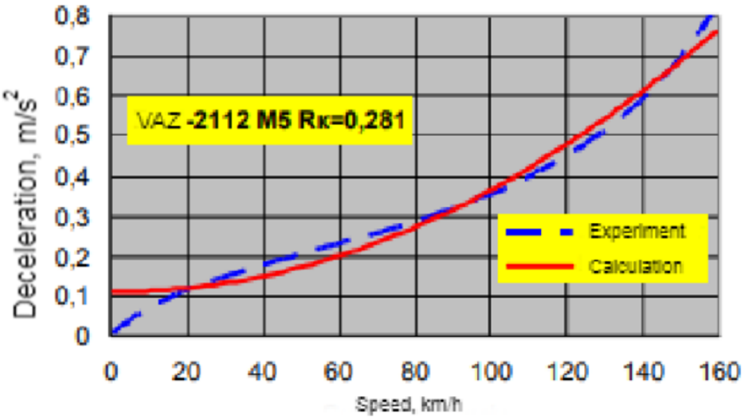



**Fig. 2.** Dependence j(V) of the Lada-112 (VAZ-2112) car (data processing by "Autoreview")

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За контакти:
[1] Zybtsev Yurij Vasiliyvich, Senior Lecturer, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(057)7073687, dandz2805@gmail.com.
[2] Voroshylov Pavlo, Student, Kharkov National Automobile and Highway University, Department “Technical operation and service of cars named after prof. Govorushchenko N.Ya.”, Yroslava Mudrogo str. 25, Kharkov, Ukraine, +38(057)7073687, voropasha01@gmail.com.

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# АНАЛИЗ НА УСУКВАЩАТА ПОДАТЛИВОСТ НА КОЛЯНО ОТ КОЛЯНОВ ВАЛ

# ANALYSIS OF THE TORSIONAL FLEXIBILITY OF A CRANKSHAFT WEB

**Daniel Ivanov[1], Rosen Hristov[2]**

**Abstract.** The study analyzes the results of an investigation aimed at determining the torsional compliance of a crankshaft web, performed using empirical formulas applied to various types and designs of internal combustion engines. The key formulas commonly used in the design of high-speed automotive, stationary, and marine engines are presented. The elastic characteristics of the crankshaft web elements are examined, taking into account the interrelations between them. A finite element model of the same component has been developed, and a comparative analysis is carried out between the results obtained through finite element analysis and those derived from the empirical formulas.

**Keywords:** Crankshaft, torsional compliance, internal combustion engine.

## 1. Въведение:

Общата ъглова деформация на едно коляно от колянов вал при усукващи колебания се осъществява за сметка усукването на мотовилковите и основните шийки и огъването на ramената в равнина, перпендикулярна към оста на вала. Определянето на податливостта като сума от податливостите на споменатите елементи не може да даде удовлетворителен резултат вследствие сложността на отчитане на влиянието на преходите (от шийка към рамо) и сложността на отчета на ефекта «запъване», който се състои в следното: ако към основните шийки на дадено коляно се приложат усукващи моменти с различен знак, то осите на основните шийки ще се разместят на някаква величина, допускана от хлабината в основните лагери. Ако това разместване на шийките се отстрани, т.е. да се възстанови тяхната съосност, то е необходимо да се приложи допълнителна сила. Следователно коравината на коляно със съосни основни шийки ще бъде по-голяма, а податливостта по-малка, отколкото на несъосно коляно. Практически податливостта на всяко коляно зависи от хлабината в лагерите и податливостта на последните. Тези причини характеризират аналитичното изчисляване на податливостта на колената като доста сложен процес, поради което тя се оценява по емпирични формули.

## 2. Изложение:

Приведените по-долу формули съдържат по три члена. Не е трудно да се забележи, че два от тях характеризират податливостта на основната и мотовилковата шийка на усукване и един – огъването на ramената.

**Формулата на Тимошенко** определя областта, в границите на която трябва да бъде действителното значение на податливостта на коляното. Тя има вида:

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left[ \frac{l_1 + 0.9 \cdot h}{x_1} + \frac{0.433 R}{h \cdot b0^3} + \left(1 - \frac{em}{k}\right) \cdot \left( \frac{l_2 + 0.9 \cdot h}{x_2} + \frac{0.433 R}{h \cdot b0^3} \right) \right] \quad (1)$$

където:

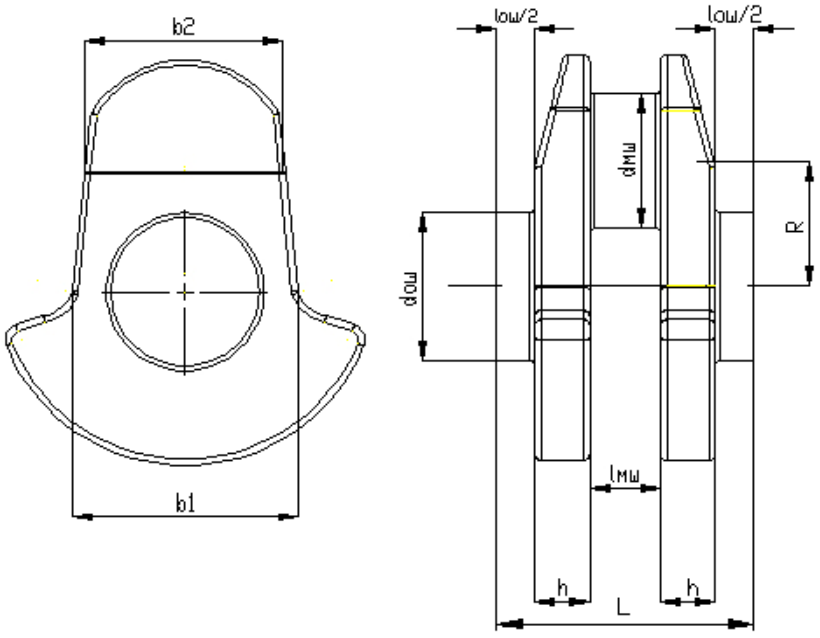
$$x_1 := \left(d_1\right)^4 - \left(\delta_1\right)^4$$

$$x_2 := \left(d_2\right)^4 - \left(\delta_2\right)^4$$

$$k_1 := \left(1.63 b0^2 - R^2\right) \cdot h^2 + 1.22 \left(l_2 + h\right)^2 \cdot \left(b0^2 + h^2\right)$$

$$k := 1 + \frac{0.44}{R^2} \cdot \frac{\dfrac{1.32 \cdot l_2}{\left(d_2\right)^2 - \left(\delta_2\right)^2} + \dfrac{R}{h^3 \cdot b0^3} \cdot k_1}{\dfrac{l_2}{\left(d_2\right)^4 - \left(\delta_2\right)^4} + \dfrac{0.433R}{h \cdot b0^3}}$$

em – коефициент, отчитащ хлабината в основните лагери, числовите значения на който лежат между нула и единица.




**Фиг.1.** Основни размери на коляно от колянов вал.

Неопределеността в числовото значение на m създава големи неудобства, поради което формулата на Тимошенко се използва обикновенно в два варианта. Първа формула на Тимошенко, когато участващия във формулата параметър em, отчитащ граничните условия на деформация, заема стойност em=0, т.е. при предпоставка за достатъчно големи хлабини между основните лагери и основните шийки на коляновия вал. Втора формула на Тимошенко, когато em=1, т.е. при предпоставка за нулеви хлабини в опорите. За реалните двигатели с определена хлабина в основните лагери, на стойностите, получени по тези две формули трябва да се гледа като на заградителни. Останалите използвани във формулите означения са посочени на фиг.1. Под ширина на рамото следва да се разбира така наречената ефективна ширина на рамото, която за рамена с по-сложна конфигурация се определя по графики.

**Формула на Коломенския машиностроителен завод** (формула на Урванцев). Тази формула е разработена за колянови валове на корабни дизелови двигатели със средна мощност и дава добри резултати при проектиране на колянови валове за подобни конструкции автомобилни двигатели.

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left[ \frac{l_1}{x_1} + \frac{l_2}{x_2} + \frac{1.8 \cdot k}{h} \cdot \left[ 1 + \frac{0.64}{R^2} \cdot \left( \frac{x_1 \cdot x_2}{R^2} \right)^{\frac{1}{3}} \right] \right] \quad (2)$$

където:

$$k := \frac{R}{2 \cdot b0^3}$$

Формулата дава възможност за отчитане на променливата ширина на рамото чрез коефициента k. Предвид на усложненията които се получават при изчисляване с променлива ширина, се препоръчва вместо нея да се използва ефективната ширина на раменатa.

**Формула на Картър.** Разработена е от анализа на колянови валове на бързоходни автомобилни и авиационни двигатели.

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left( \frac{l_1 + 0.8 \cdot h}{x_1} + \frac{0.75 \cdot l_2}{x_2} + \frac{1.5 \cdot R}{h \cdot b0^3} \right) \quad (3)$$

Формула на Зулцер. Получена въз основа анализа на колянови валове на корабни двигатели със средна и голяма мощност, в частност за нискочестотни двигатели със съставни валове.

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left( \frac{l_1 + 0.4 \cdot d_1}{x_1} + \frac{l_2 + 0.4 \cdot d_2}{x_2} + \frac{0.8 \cdot y}{h \cdot b0^3} \right) \quad (4)$$

където:

$$y := R - \frac{4}{3 \cdot \pi} \cdot \frac{\left(d_2\right)^3 - \left(\delta_2\right)^3}{\left(d_2\right)^2 - \left(\delta_2\right)^2}$$

**Формула на Зиманенко.** Получена е въз основа анализа на съществуващите теоретични и експериментални формули, а също така и опитно изследване на колянови валове съвременни двигатели от различен тип. По изследванията на автора дадената формула дава по-добро приближение към действителното значение на податливостта за колянови валове на съвременните двигатели с голямо припокриване на шийките и има вида:

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left( \frac{l_1 + 0.6 \cdot h \cdot \frac{d_1}{l_1}}{x_1} + \frac{0.8 \cdot l_2 + 0.2 \cdot b0 \cdot \frac{d_1}{R}}{x_2} + \frac{R \cdot \sqrt{R}}{h \cdot b0^3 \cdot \sqrt{d_2}} \right) \quad (5)$$

**Формула на Таплин.** Дава доста точни резултати, но е значително усложнена.

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left[ \frac{\left(l_1 + 0.15d_1\right) \cdot \left(d_1\right)^4}{\left(x_1\right)^2} + \frac{\left(l_2 + 0.15d_2\right) \cdot \left(d_2\right)^4}{\left(x_2\right)^2} + \frac{2 \cdot h - 0.15\left(d_1 + d_2\right)}{b0^4 - \left(\delta_1\right)^4} + \frac{0.016}{h^2 \cdot b0} + R \cdot \frac{0.58 + 0.065\left(\frac{d_1}{h}\right)}{h \cdot b0^3} \right] \quad (6)$$

**Формула на Гайгер.** Препоръчва се за тежки и бавноходни двигатели.

$$e_{i,j} := \frac{32}{\pi \cdot G} \cdot \left( \frac{l_1 + 0.4 \cdot h}{x_1} + \frac{l_2 + 0.4 \cdot h}{x_2} + \frac{0.91 \cdot R}{h \cdot b0^3} \right) \quad (7)$$

**Формула на Терских.** В тези случаи, когато не са известни всички размери на коляновия вал, за грубо ориентировъчно определяне на податливостта може да се използват следните формули:

За двигатели със самовъзпламеняване от компресия:

$$e_{i,j} := \frac{kt}{\left(\frac{d_1 + d_2}{2}\right)^4 - \left(\frac{\delta_1 + \delta_2}{2}\right)^4} \cdot (L + 0.5 \cdot R) \quad (8)$$

За леки двигатели, работещи по изохорен цикъл:

$$e_{i,j} := \frac{kt}{\left(\frac{d_1 + d_2}{2}\right)^4 - \left(\frac{\delta_1 + \delta_2}{2}\right)^4} \cdot (L + 2.2 \cdot R) \quad (9)$$

където:

$$kt := \frac{9.4}{G}$$

Формулата на Терских е получена при обработката на данни за 30 типа двигатели.

На практика обикновено се получават затруднения относно избора на най-подходящата формула за пресмятане. Поради тези причини се препоръчва метода на последователните приближения. От посочените формули се избират онези от тях, които се отнасят за подобен на изследвания вид колянов вал и се пресмятат податливостите. Получените резултати се осредняват аритметично и се отхвърля резултата от тази формула, чиято относителна погрешност относно средната податливост е най-голяма и надхвърля 10%. Останалите резултати отново се осредняват, извършва се горното сравнение и т.н. докато останат най-малко три резултата, от които определяме средната предполагаема податливост на дадения колянов вал.

Формули (1) до (8) се отнасят за пълноопорни колянови валове. В случай, когато трябва да се определи податливостта на непълноопорен колянов вал трябва да се има предвид, че изборът за съсредоточаване на масите на валопровода предопределя податливостта на съединенията между тях. Следователно в случай на непълноопорен

колянов вал под податливост на съединението между приведените маси на два съседни коляно-мотовилкови механизма, между които нямаме основна шийка, трябва да се разбира податливостта на така нареченото дълго рамо с двете половинки от мотовилковата шийка.

$$e = e_{д.р.} + e_{м}$$

където:

$e_{д.р.}$ - податливост на дългото рамо;

$e_{м}$ - податливост на мотовилковата шийка.

Както бе посочено в горните формули могат да се разграничат основно три члена, съответно отчитащи податливостта на основната шийка с влияние на преходите между шийките и рамото, податливостта на мотовилковата шийка, с отчитане влиянието между мотовилковата шийка и рамото, податливостта на рамената на огъване с отчитане влиянието на преходите и припокриването на мотовилкова и основна шийки. В такъв случай под податливостта трябва да се вземе предвид съответния член от гореспоменатите формули. Например за формула (5) (формула на Зиманенко), се получава:

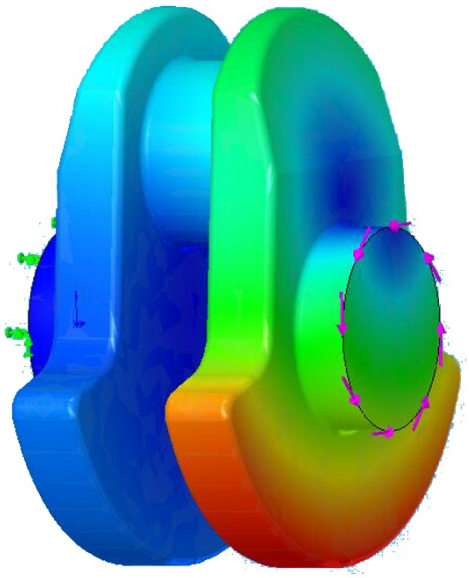
$$e_m := \frac{32}{\pi \cdot G} \cdot \left( \frac{0.8 \cdot l_2 + 0.2 \cdot b0 \cdot \frac{d_1}{R}}{x_2} \right) \tag{10}$$

Изхождайки от предположението, че дългото рамо се деформира подобно на две къси със същото сечение, за податливостта може да се запише

$$e_{dp} := \frac{32}{\pi \cdot G} \cdot \left( \frac{R \cdot \sqrt{R}}{h \cdot b0^3 \cdot \sqrt{d_2}} \right) \tag{11}$$

Сумирайки (10) и (11) получаваме търсената податливост. Чрез подобен анализ на всяка една от формули (1) до (8) ще се получат и съответните формули за податливост на коляно с дълго рамо. След това, използвайки така нареченото последователно осредняване, определяме предполагаемите податливости. Следва да се отбележи, че предложеният начин е силно приблизителен и трябва да се използва само ако не разполагаме с конкретни експериментални данни. Същото, но в много по-малка степен се отнася и за формули (1) до (8).

Резултатите, получени при пресмятанията за определяне на очакваната податливост на едно коляно по формули (1) до (8) са сравнени с тези от изследване по метода на крайните елементи. Симулацията тук е извършена с гранични условия, при които се допуска, че хлабините в основните лагери на двигателя са достатъчно големи. На фиг.2. е показано деформационното състояние на коляното при натоварване с усукващ момент по оста на коляновия вал, приложен в средното сечение на едната основна шийка, като в средата на другата основна шийка коляното е запънато. Получената податливост е по-малка от средната, пресметната по формули (1) до (8) като относителните отклонения са показани на фиг.2.

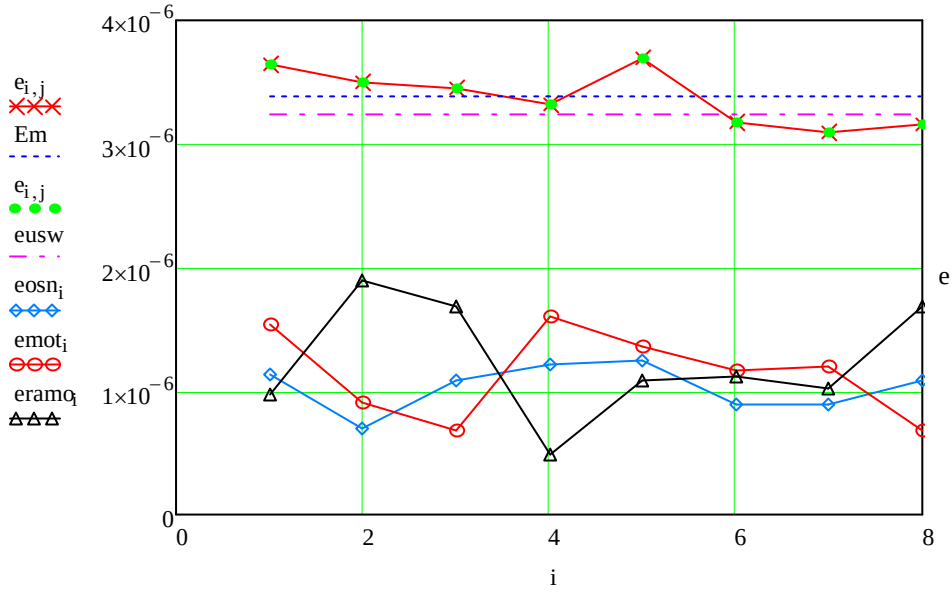


$$\frac{e_{i,j} - eusw}{eusw} = \cdot\%$$

| |
|---|
| 12.855 |
| 8.228 |
| 6.631 |
| 2.587 |
| 14.174 |
| -1.65 |
| -4.096 |
| -2.246 |

$$eusw = 3.231\times 10^{-6}\cdot\frac{1}{N\cdot m}$$

**Фиг.2.** Деформационно състояние на коляното от фиг.1 при действие на усукващ момент.




$$e = \begin{pmatrix} 0 & 0 \\ 3.647\times 10^{-6} & 3.426\times 10^{-6} \\ 3.497\times 10^{-6} & 0 \\ 3.446\times 10^{-6} & 0 \\ 3.315\times 10^{-6} & 0 \\ 3.689\times 10^{-6} & 0 \\ 3.178\times 10^{-6} & 0 \\ 3.099\times 10^{-6} & 0 \\ 3.159\times 10^{-6} & 5.263\times 10^{-6} \end{pmatrix}\cdot\frac{1}{N\cdot m}$$

**Фиг.3.** Податливост на основна (eosn) и мотовилкова (emot) шийка, рамената на коляното (eramo) и обща (ei,j)пресметнати по формули (1) до (8). Средна податливост Em и тези от пресмятане по метода на крайните елементи eusw.

На фиг.3 са показани резултатите от пресмятането по формули (1) до (8). За формулата на Тимошенко са получени две стойности, като първата се отнася за стойност на параметъра em=0, т.е. при предпоставка за достатъчно големи хлабини в основните лагери, а втората, когато em=1, т.е. при предпоставка за нулеви хлабини в основните лагери на двигателя. При формулата на Терских (8) стойността се отнася за двигател със самовъзпламеняване от компресия. Средно аритметичната стойност на податливостта и отклонението на резултатите, получени по отделните формили се определянт от изрази (12):

$$Em := \left(\frac{1}{n}\right)\cdot\sum_{i} e_{i,j} = 3.379\times 10^{-6}\,\frac{1}{N\cdot m} \qquad O_i := \left|\left(\frac{Em - e_{i,j}}{Em}\right)\cdot 100\%\right| \qquad O = \begin{pmatrix} 0 \\ 7.933 \\ 3.508 \\ 1.98 \\ 1.887 \\ 9.194 \\ 5.939 \\ 8.279 \\ 6.509 \end{pmatrix}\cdot\% \tag{12}$$

Изрази (12) показват абсолютните стойности и процентното разпределение на податливостите на основна и мотовилкова шийка и раменатата на коляното, пресметнати по формулите. Средната стойност на податливостта на основната шийка е около 30%, на мотовилковата е 35.6% и на двете рамена общо е 34.5% от общата податливост на коляното. Авторите на горните формули отдават различно значение на отделните елементи, като при едни и същи размери на коляното за тези елементи се получават различни стойности, а разликите между тях са значителни.

$$eosn_i = \begin{pmatrix} 1.132\cdot 10^{-6} \\ 6.911\cdot 10^{-7} \\ 1.083\cdot 10^{-6} \\ 1.221\cdot 10^{-6} \\ 1.254\cdot 10^{-6} \\ 8.898\cdot 10^{-7} \\ 8.869\cdot 10^{-7} \end{pmatrix}\cdot\frac{1}{N\cdot m} \quad emot_i = \begin{pmatrix} 1.546\cdot 10^{-6} \\ 9.116\cdot 10^{-7} \\ 6.837\cdot 10^{-7} \\ 1.608\cdot 10^{-6} \\ 1.357\cdot 10^{-6} \\ 1.173\cdot 10^{-6} \\ 1.193\cdot 10^{-6} \end{pmatrix}\cdot\frac{1}{N\cdot m} \quad eramo_i = \begin{pmatrix} 9.694\cdot 10^{-7} \\ 1.894\cdot 10^{-6} \\ 1.679\cdot 10^{-6} \\ 4.862\cdot 10^{-7} \\ 1.079\cdot 10^{-6} \\ 1.116\cdot 10^{-6} \\ 1.019\cdot 10^{-6} \end{pmatrix}\cdot\frac{1}{N\cdot m} \tag{13}$$

$$\frac{eosn_i}{e_{i,j}} = \begin{pmatrix} 31 \\ 19.8 \\ 31.4 \\ 36.8 \\ 34 \\ 28 \\ 28.6 \end{pmatrix}\cdot\% \quad \frac{emot_i}{e_{i,j}} = \begin{pmatrix} 42.4 \\ 26.1 \\ 19.8 \\ 48.5 \\ 36.8 \\ 36.9 \\ 38.5 \end{pmatrix}\cdot\% \quad \frac{eramo_i}{e_{i,j}} = \begin{pmatrix} 26.6 \\ 54.2 \\ 48.7 \\ 14.7 \\ 29.2 \\ 35.1 \\ 32.9 \end{pmatrix}\cdot\% \quad \frac{eosn_i}{e_{i,j}} + \frac{emot_i}{e_{i,j}} + \frac{eramo_i}{e_{i,j}} = \begin{pmatrix} 100 \\ 100 \\ 100 \\ 100 \\ 100 \\ 100 \\ 100 \end{pmatrix}\cdot\%$$

**3. Заключение**

Получените резултати за определяне на очакваната податливост на коляно от колянов вал показват различното разпределение на еластичността по отделните елементи на коляното. За отделните формули това разпределение е рзлично, което се дължи основно на приетата конструктивна конфигурация на колената, използвани при съставянето на формулите. Тези конструктивни различия водят до разлики в еластичните

характеристики на коляното по основните елементи. В изрази (13) се открояват резултатите, получени по формули (2) и (3), където податливостта на раменатa съставлява около половината от общата податливост на коляното. Формула (4) отдава по-голямо значение на характеристиките на мотовилковата и основната шийки. Разликите в стойностите на еластичността за един и същ елемент на коляното, получени по отделните формули, показва стремежа на авторите за отчитане на конкретното деформационно състояние и влиянието на сложната връзка между елементите на коляното върху общата податливост.

Посочените формули са разработени и се отнасят за колена с основни и мотовилкови шийки с или без концентричен отвор, отчитан по-горе чрез параметрите $x_1$ и $x_2$. Наличието на отвори от маслената система на двигателя в друго направление, различно от това по оста на коляновия вал или по оста на мотовилковата шийка, се счита, че оказва пренебрежимо малко влияние върху податливостта или е в рамките на допустимите грешки и не се отчита. Някои от посочените формули не отчитат и евентуалното наличие на отвори в раменатa.

Специфичната конфигурация на преходите между отделните елементи на коляното, за избягване на усложнаване на изразите, също не се отчита. Сложната форма на раменатa се приема твърде схематично, като размерите описващи рамото се свеждат до ширина в трите сечения, средна дебелина на рамото и радиус на коляното. Счита се, че двете рамена са еднакви, с еднаква дебелина по цялата височина. Наличието на противотежести и закръгления, които могат да повлияят на деформационното състояние също не се отчита.

Усложненатa конфигурация на коляновите валове на съвременните двигатели с вътрешно горене, сложната форма на раменатa, получена с цел оптимизиране на конструкцията и наличието на допълнителни отвори, изискват все по-широко използване на метода на крайните елементи за определяне на очакванатa податливост на колената и конкретизиране на началните условия за всяка конструкция.

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За контакти:
Ас. д-р инж. Даниел Иванов
Технически Университет - Варна
МТФ, Катедра: "Транспортна техника и технологии"
Варна, п.к. 9010, ул. "Студентска" №1
Тел: +359 886212821

# ПАРАМЕТРИЧЕН МЕТОД ЗА АНАЛИЗ НА УСУКВАЩА ПОДАТЛИВОСТ НА КОЛЯНО ОТ КОЛЯНОВ ВАЛ

# PARAMETRIC METHOD FOR ANALYZING THE TORSIONAL COMPLANCE OF A CRANKSHAFT CRANK

**Daniel Ivanov**

**Abstract.** To determine the torsional compliance of a crank in an engine crankshaft, formulas derived from the investigation of a large number of crankshafts are used. The coefficients embedded in their structure reflect the interrelations of the spatial beam and the complex deformation state under torsion. When improving the design of the crank, mainly due to the need to vary the elements of the system, modifications of the principal dimensions are required. The proposed method makes it possible to predict the compliance behavior of the crank when any of the main dimensions are varied independently. It has been established that the key factors exerting a decisive influence on the elastic characteristic are the diameters of the crankpin and the main journal, as well as the width of the crank web.

**Keywords:** Crankshaft, torsional compliance, internal combustion engine.

## 1. Въведение:

Определянето на точната стойност на усукващата податливост на коляно от колянов вал на бутален двигател представлява сериозно предизвикателство както в процеса на проектиране на нови конструкции или динамично оптимизиране на задвижващата система на автомобила, така и при експерименталните изследвания на съществуващи конструкции.

При експерименталното определяне на еластичните характеристики при усукване, основните затруднения са свързани с точността на резултатите по отношение на сложната деформация на коляното, представляващо конструкция на пространствената греда. Необходимо е да бъдат извършени прецизни измервания, отчитащи конкретните гранични условия при относителното преместване на две сечения, намиращи се в средата на две съседни основни шийки. Наличието на хлабини между основните и мотовилковите лагери на коляновия вал и огъването на рамената на коляното пораждат деформация, състояща се от пространствено преместване и две завъртания относно оста на коляновия вал и оста на мотовилковата шийка.

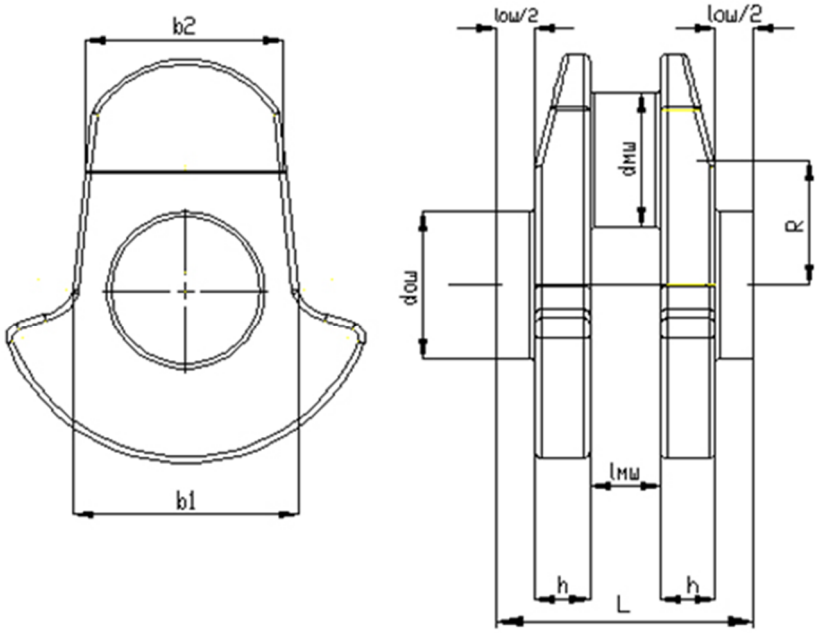
Аналитичните методи за определяне на усукващата податливост на коляно от колянов вал са основани на аналитични формули, които по своята същност са полуемперични. Разликите в конфигурацията на коляновите валове, основно във формата на рамената, размерите на рамото и отчитането на преходите между основните и мотовилковите шийки, водят до различни резултати получени за едно и също коляно пресметнати по различните формули. Поради тази причина е прието да се извършват пресмятания по разполагаемите формули за различни колянови валове и след това чрез методите на статистически анализ да се търси най-вероятната стойност на податливостта на бъдещата конструкция.

Процесите на проектиране на колянов вал на двигател са свързани с решаване на оптимизационни задачи. Не рядко се налага да се извършват промени в основните конструктивни размери на предварително проектираното коляно поради различни причини от термодинамичен, конструктивен или експлоатационен характер, с цел повишаване на надеждността на конструкцията. Промяната на който и да е конструктивен размер се отразява на масовите и еластичните характеристики на коляновия вал с последващ ефект върху параметрите на дискретния динамичен модел.

## 2. Изложение:

В настоящата разработка се предлага метод за изследване промяната в стойносттите на податливостта чрез анализ поведението на параметричните функции на коляно от колянов вал на двигател. Целта е да се създаде метод за прогнозиране

влиянието на изменение на основните конструктивни размери на коляното върху стойността на неговата усукваща податливост.




**Фиг.1.** Основни размери на коляно от колянов вал.

Същността на метода се илюстрира с анализ на първата формула на Тимошенко за определяне на прогнозната стойност на податливост на коляно, определена при гранични условия допущащи наличие на безкрайно големи хлабини в основните шийки на коляновия вал. Формулата има вида:

$$e = \frac{32}{\pi . G}\left[\frac{l_1 + 0.9h}{x_1} + \frac{0.433R}{h.bo^3} + \left(1 - \frac{em}{k}\right).\left(\frac{l_2 + 0.9h}{x_2} + \frac{0.433R}{h.bo^3}\right)\right] \quad (1)$$

където: em - коефициент, отчитащ хлабината в основните лагери, числовите значения на който лежат между нула и единица. За конкретния случай $em = 1$. С индекс 1 са означени размерите на основната шийка, а с индекс 2 тези на мотовилковата шийка. Останалите означения в (1) са както следва:

$$x_1 = (d_1)^4 - (\delta_1)^4$$

$$x_2 = (d_2)^4 - (\delta_2)^4$$

$$k_1 = (1.63.bo^2 - R^2).h^2 + 1.22(l_2 + h)^2.(bo^2 + h^2)$$

$$k = 1 + \frac{0.44}{R^2}\frac{\frac{1.32.l_2}{(d_2)^2 - (\delta_2)^2} + \frac{R}{h^3.bo^3}.k_1}{\frac{l_2}{(d_2)^4 - (\delta_2)^4} + \frac{0.433R}{h.bo^3}}$$

За целите на предложения метод формула (1) се представя в параметричен вид във функция на основните размери на коляното:

$$e\left(d_{\text{ош}}, d_{\text{мш}}, l_{\text{ош}}, l_{\text{мш}}, h_{\text{рамо}}, b_{\text{рамо}}, r\right) =$$

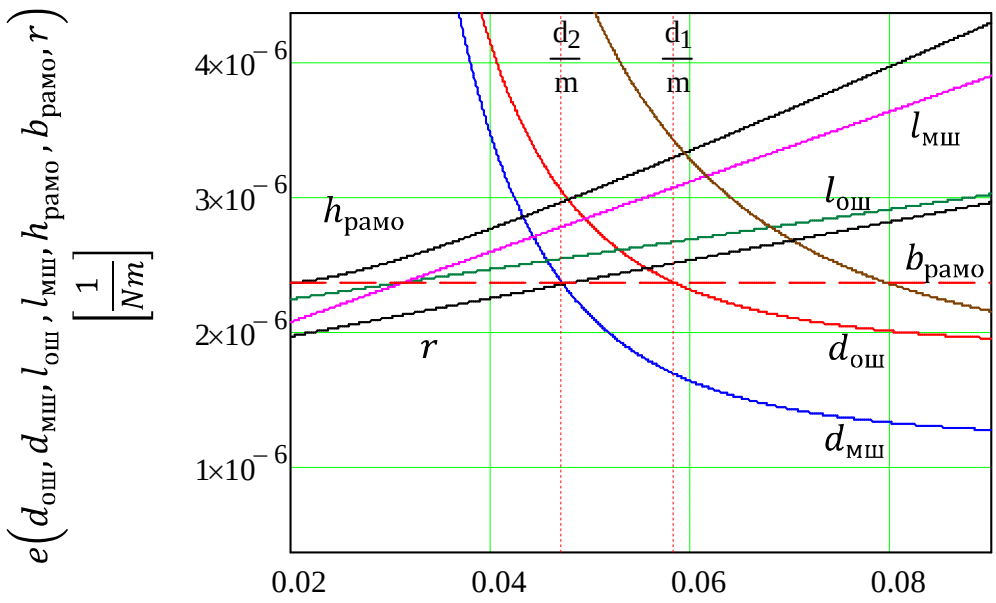
$$= \frac{32}{\pi . G}\left\{ \frac{l_{\text{ош}} + 0.9.h_{\text{рамо}}}{(d_{\text{ош}})^4 - (\delta_1)^4} + \frac{0.433r}{h_{\text{рамо}} . {b_{\text{рамо}}}^3} + \right.$$

$$\left. + \left[ 1 - \frac{em}{1 + \frac{0.44}{r^2}} \cdot \left( \frac{1.32.l_{\text{мш}}}{(d_{\text{мш}})^2 - (\delta_2)^2} + \frac{r}{{h_{\text{рамо}}}^3 . bo^3} \cdot \frac{\left(1.63.{b_{\text{рамо}}}^2 - R^2\right).{h_{\text{рамо}}}^2 + 1.22\left(l_{\text{мш}} + h_{\text{рамо}}\right)^2 . \left({b_{\text{рамо}}}^2 + h^2\right)}{\frac{l_2}{(d_{\text{мш}})^4 - (\delta_2)^4} + \frac{0.433r}{h_{\text{рамо}} . {b_{\text{рамо}}}^3}} \right) \right] \right.$$

$$\left. \cdot \left( \frac{l_{\text{мш}} + 0.9.h_{\text{рамо}}}{(d_{\text{мш}})^4 - (\delta_2)^4} + \frac{0.433r}{h_{\text{рамо}} . {b_{\text{рамо}}}^3} \right) \right\}$$

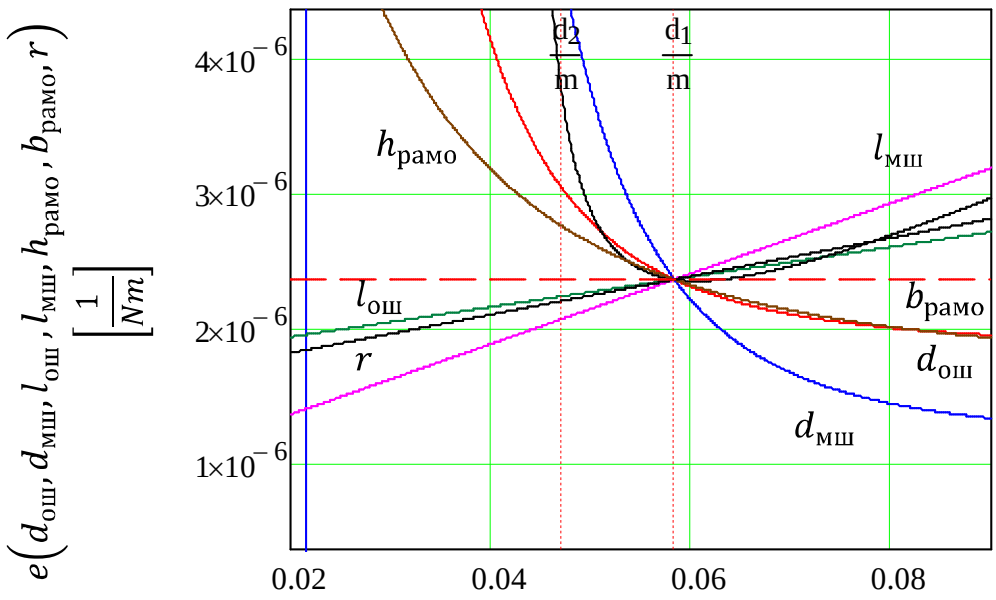
На фиг.2. са показани резултатите за влиянието от промяната на конструктивните размери върху прогнозната податливост на коляно от колянов вал на автомобилен високочестотен дизелов двигател. Стойността на податливостта получена от пресмятания по формула (1) е показана с хоризонтална пунктирана линия. От извършеното симулационно изследване се вижда, че при различните размери параметричната функция има различен характер, като за някои от тях, в затворения интервал на валидност на формулата, те са монотонно растящи, а за други са монотонно намалящи.

Промяната в който и да е от основните размери на коляното, при запазване стойностите на останалите, влияе по различен начин. Показател за това е различния наклон на линиите в доверителния интервал относно абцисната ос. За нелинейните функции, каквито са $e\left(d_{\text{ош}}, d_{\text{мш}}, b_{\text{рамо}}\right)$, се отчита тенденция за понижаване влиянието на размерите при тяхното повишаване и по-висок темп на нарастване на стойностите на податливостта при намаляне на същите размери. Изключение от това прави функцията $e\left(h_{\text{рамо}}\right)$, която е монотонно нарастваща.




**Фиг.2.** Параметрични функции на податливостта на коляното при вариране на основните размери.

За изследване на основните конструктивни фактори влияещи върху еластичната характеристика на коляното, параметричните функции са транслирани относно базовата стойност по начин, осигуряващ тяхното пресичане в една и съща точка, равна на стойността пресметнатата податливост, фиг.3. Получената графика показва различното влияние на отделните размери. Най-значим фактор за податливостта е стойността на диаметъра на мотовилковата шийка $d_{мш}$. Нарастването на диаметъра на мотовилкова шийка с 10% води до намаляне податливостта на коляното с 15.8%, неговото намаляване с 10% увеличава податливостта с 26.2%.

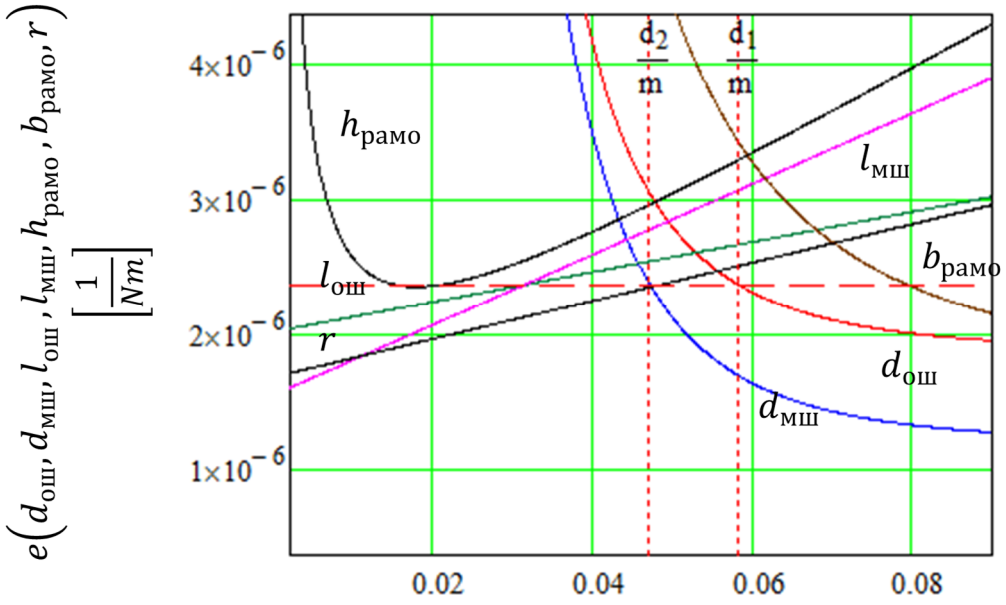



**Фиг.3.** Транслирани параметрични функции за податливостта на коляното при вариране на основните размери.

Диаметърът н основната шийка $d_{\text{ош}}$ е вторият значим фактор. Неговото нарастване с 10% води до намаляне податливостта на коляното с 6.7%, неговото намаляване с 10% увеличава податливостта с 11.1%. Тази последователност на влиянието на различните размери е валидна в околността на базовата точка $d_{\text{ош}}$. При отклонения в размерите от нея по-големи от 10% влиянието на ширината на рамото $b_{\text{рамо}}$ нараства значително и става определящ фактор за вариране на елементите на системата относно приведените еластични характеристики. Дебелината на рамото $h_{\text{рамо}}$ четвъртият значим параметър, като влиянието на този размер нараства при отклонения значително по-големи от 10%.

Разширяването на диапазона на изменение на размерите на коляното е необходимо да се извършва при внимателен анализ на граничните условия за валидност на използваната формула. Графиката за функцията $e\left(h_{\text{рамо}}\right)$, показана на фиг.4, показва, че конкретната формула е валидна и следва да се очакват устойчиви резултати единствено при незначително повишение на размера $h_{\text{рамо}}$ с не повече от 10%. При по-големи отклонения на $h_{\text{рамо}}$ формулата губи устойчивост което дава основание да се счита, че получените резултати ще бъдат с по-голямо отклонение от средните, получавани от пресмятания по други формули.

Комбинацията от останалите размери показва устойчивост на формулата. Видно от графиката нелинейните параметрични функции $e\left(d_{\text{ош}}, d_{\text{мш}}, b_{\text{рамо}}\right)$ притежават минимуми в далечни области, основно при значително увеличаване на размерите за $d_{\text{ош}}, d_{\text{мш}}, b_{\text{рамо}}$.




**Фиг.4.** Устойчивост на параметричните функции за податливостта на коляното при вариране на основните размери.

## 3. Заключение

Същността на предложеният метод се състои в трансформация на съществуващите формули за определяне на усукваща податливост на коляно от колянов вал и прдставянето им в параметричен вид. По тази начин се създават възможности за прогнозиране поведението на еластичната характеристика на коляното при промяна на даден параметър, продиктувана от необходимост за усъвършенстване на конструкцията или при оптимизационни задачи с цел вариране на елементите на системата за борба с високоамплитудни колебателни процеси.

От анализа на данните и получените резултати са определени основните конструктивни фактори, оказващи повишена чувствителност на вероятната податливост на коляното към тях. Промяната в стойностите на диаметрите на мотовилковата и основната шийка, както и на ширината на рамената се оказват решаващи. По този начин е възможно с минимални конструктивни изменения, без необходимост от промяна на междуцилиндровото разстояние, да се варира с елемнтите на системата за постигане на целеви стойности за оптимална податливост на колената.

Използваните за целите на проектиране формули за податливост на коляно са съставени при изследване на колена от различни двигатели от даден типоред и предназначени за използване в определена транспортна технология. Анализа на параметричните функции показва гранците на тяхната приложимост.

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За контакти:
Ас. д-р инж. Даниел Иванов
Технически Университет - Варна
МТФ, Катедра: "Транспортна техника и технологии"
Варна, п.к. 9010, ул. "Студентска" №1
Тел: +359 886212821

# ВЛИЯНИЕ НА ДОБАВКИТЕ В ГОРИВОТО НА ДВИГАТЕЛИ С ВЪТРЕШНО ГОРЕНЕ

# INFLUENCE OF FUEL ADDITIVES IN INTERNAL COMBUSTION ENGINES

**инж. Ренан Кыров**

**Abstract.** Vehicle emissions are a major source of air pollution, resulting from the combustion of fuel, therefore the use of high-quality fuel and optimization of the combustion process can reduce harmful emissions and improve fuel economy. The level of fuel quality is mainly determined by the petrochemical production process, and the optimization of the combustion process is due to the application of advanced engine technology. The use of appropriate fuel additives is a prerequisite for achieving a positive effect on combustion performance, thereby improving engine emission performance and energy saving.
**Keywords**: fuel, additives, efficiency, economy, emissions

## 1. Въведение:

През последните години все повече се увеличават проведените изследвания, свързани с влиянието на добавките в горивата на двигатели с вътрешно горене, за подобряване на производителността и емисиите на двигателите. Двигателят е съставен от множество компоненти и елементи, всеки от които има своята специфична роля. Основен компонент в горивото са въглеводородите, като съставът и свойствата им определят производителността и емисиите в процеса на горене. Двигателите с вътрешно горене непрекъснато се усъвършенстват и развиват по отношение на топлинната ефективност, плътността на мощността и надеждността и широко се използват в транспорта, машиностроенето, производството на електроенергия и др. Въпреки, че броят на електрическите превозни средства се увеличава, повечето от превозните средства все още са оборудвани с двигатели с вътрешно горене.

Поради широкото използване на превозни средства с двигатели с вътрешно горене, то те се определят като един от причинителите на значителни проблеми, сред които недостиг на енергия и замърсяване на околната среда [15]. Основните замърсители, емисионни от превозни средства, задвижвани с двигатели с вътрешно горене, са въглероден оксид (CO), въглеводороди (HC), азотни оксиди (NOx) и твърди частици (PM). Посочените замърсители могат да причинят екологични проблеми, които влияят на човешкото здраве [10]. Освен това, въглеродният диоксид ($CO_2$) е основният продукт от изгарянето на изкопаеми горива и се счита за основен парников газ, който допринася за глобалното затопляне. Бензиновите двигатели продължават да бъдат основен източник на енергия за лекотоварните превозни средства и заемат голям дял от пазара, особено за леките автомобили. Следователно, повишаването на топлинната ефективност и намаляването на емисиите на бензиновите двигатели са от голямо значение. От друга страна, отличната топлинна ефективност на дизеловите двигатели е основна причина за широкото им приложение. Дизеловите двигатели с компресионно запалване отделят огромни обеми замърсители (NOx, сажди, CO, UHC и твърди частици), което представлява сериозна опасност за здравето и околната среда. По-голямата част от тези замърсители са резултат от неидеални цикли на горене, като фрагментирано запалване на горивото, реакции на продукта при висока температура и смесване при пресоване, запалване на смазочно масло

и добавки към двигателя, както и изгаряне на невъглеводородни компоненти на дизеловото гориво, като серни съединения и добавени към горивото вещества. По отношение на околната среда, емисиите на дим, произвеждани от дизеловите двигатели, могат да причинят замърсяване както на водата, така и на въздуха, което значително допринася за глобалното изменение на климата. Дългосрочното излагане на посочените замърсители създава здравословни рискове при хората, включително по отношение на сърдечно-съдови и респираторни заболявания. Поради посочените факти емисиите от дизеловите двигатели са значително предизвикателство, което изисква постоянно прогнозиране, за да се ограничи до минимум негативното влияние и да предприемат мерки, като промяна в състава на горивото, добавки към горивото и други алтернативи за управление на емисиите.

**2. Изложение:**

Въвеждането на различните добавки за гориво е насочено към постигането на повече мощност, но при ограничаване на емисиите от двигателите с вътрешно горене. Алтернативни концепции за превозни средства, като електрически превозни средства и горивни клетки, са един от начините за намаляване на емисиите. По-малко радикалният вариант включва използването на двигател с вътрешно горене, но с алтернативни горива като биодизел, вместо чист дизел. Друга алтернатива е добавянето на добавки към горивото, което се използва в момента. Първото приложение на горивните добавки е било за елиминиране на детонацията в бензиновите двигатели в началото на XX век. Модификатори на горенето, антиоксиданти, инхибитори на корозията и детергенти за контрол на отлаганията са примери за горивни добавки. Освен това, бензиновите добавки могат да се използват за различни приложения, включително октанови усилватели, почистващи препарати за инжектори на гориво и антифризи за горивните тръбопроводи.

Ефективността на двигателите с вътрешно горене може да се увеличи чрез оптимизиране на дизайна на двигателя, както и подобряване на системите за управление на двигателя и използваното гориво [9]. Приложението на добавки в горивото се определя за рентабилен и лесен подход за подобряване на неговите свойства, който може да постигне по-висока ефективност и да намали вредните емисии на двигателите с вътрешно горене, без добавяне на устройства или промяна на структурата им. Добавките за бензин могат да бъдат разделени на три категории, според функциите им: детергентни добавки за бензин, бензинови добавки, които повишават октановото число, и комбинирани функционални бензинови добавки. Бензиновите добавки, които повишават октановото число, също се считат за антидетонационни добавки, защото основната им роля е да увеличат антидетонационния капацитет на горивото. Антидетонационните добавки за бензин включват главно етери (метил трет-бутилов етер, трет-амил метилов етер, диизопропилов етер и етил трет-бутилов етер), естери (диметилкарбонат и диметил малонат), органометални съединения и т.н. Тетраетил оловото е често срещано и ефективно средство за подобряване на антидетонационните свойства на бензина [21]. Отработените газове на оловния бензин обаче съдържат олово, което е токсичен и вреден тежък метал, който може да попадне в човешкото тяло през дихателните пътища, когато се разпространи в атмосферата. Оловният бензин може да повлияе на интелектуалното развитие на децата и може да причини отравяне на каталитичните конвертори. Поради това тетраетил оловото вече е забранено в

международен план като добавка към бензина. [26]. Като заместител на оловото, метил трет-бутилов етер (MTBE) се приема за обещаващ поради високото октаново число и пречистването на отработените газове [29]. MTBE обаче е вид етер, който е много разтворим във вода и дори ниски концентрации могат да причинят миризма на вода. Вдишването на малко количество MTBE може да причини възпаление на носа и гърлото. MTBE е труден за разграждане. Поради посочените причини различни щати в Съединените щати забраняват употребата на MTBE в бензина след 2000 г. [28].

Проведени са множество изследвания за анализиране ефективността на традиционните добавки в горивото при двигатели с вътрешно горене. Poulopoulos и Philippopoulos са изследвали ефекта от добавянето на 0%-11% MTBE в бензина върху емисиите на двигател с искрово запалване (IS). Техните експериментални резултати показват, че смесването на MTBE в бензина намалява емисиите на CO и HC само при високи натоварвания. Междувременно, по време на студен старт на двигателя, емисиите на CO и HC се увеличават с увеличаване на съотношението на смесване на MTBE [18]. Franklin et al. са установили, че смесването на MTBE с бензин намалява до известна степен емисиите на CO и общи въглеводороди (THC), но съдържанието на MTBE в неизгорелите въглеводороди (UHC) се увеличава значително при студен старт на двигателя или при условия на богато гориво (т.е. липса на кислород) [4]. Проучванията показват, че съществуващите кислородни съединения с високо октаново число не са в състояние да отговорят на изисквания за безопасност и опазване на околната среда, като например MTBE, тъй като MTBE е разтворим във вода и е устойчив на биоразграждане, което води до замърсяване на подпочвените води. Освен това, MTBE се абсорбира главно през дихателните пътища, както и през кожата и храносмилателния тракт, като високите концентрации на MTBE могат да бъдат канцерогенни [6].

Диметилкарбонатът (DMC) е безцветна течност, която се използва като зелен разтворител или метилираща добавка. Може да се използва и като добавка към бензина поради високите си антидетонационни свойства. Установено е, че смесването на DMC в бензин намалява, както емисиите на летливи органични съединения, така и емисиите на $CO_2$, но има малък ефект върху емисиите на NOx [28]. Междувременно, Abdullah et al. провеждат експеримент върху едноцилиндров двигател с впръскване на гориво, използващ смеси от етанол и бензин с 10%-30% добавка на етанол, които са обозначени съответно като E10, E20 и E30, при скорости от 2000, 2500 и 3000 об/мин. Резултатите показват, че най-ниският специфичен разход на гориво при спиране се постига чрез използване на E20, чрез което може да се постигне подобрение от около 41% в сравнение с базовия бензин. Тези резултати се дължат на по-добрата термична ефективност на смесите от етанол и бензин в сравнение с базовия бензин [1]. Su et al. изследват ефектите от смесите от етанол и бензин върху емисиите на PM в двигател с директно впръскване на гориво. Резултатите показват, че смесите етанол-бензин намаляват общите и натрупващите се прахови частици (PM) в сравнение с чистия бензин [23]. Изследвани са и ефектите на смесите етанол-бензин (съотношение на смесване 10%, 20%, 40% и 60% етанол) върху характеристиките на горене и емисии на двигател с въглероден дизел. Установено е, че емисиите на въглеводороди от смесите етанол-бензин са по-ниски от тези на базовото гориво, а максималните намаления на E40 (40% концентрация на етанол) и E60 (60% концентрация на етанол) са съответно 9,9% и 16,45% при обороти на двигателя от 5000 об/мин. Няколко причини допринасят за тези резултати, например етанолът

има по-висока латентна топлина на изпарение в сравнение с базовото гориво, а по-високото съдържание на кислород е допринесло за подобряване на процеса на горене [20]. Разгледаните изследвания са с основен фокус върху ефектите на конвенционалните бензинови добавки (напр. етанол, MTEB, DMC и др.) върху характеристиките на горенето и емисиите на двигателите с впръскване на запалване. Установено е, че има сравнително по-малко изследвания относно ефектите на неконвенционалните бензинови добавки върху производителността на превозните средства.

Wen et al. провеждат изследване на пет неконвенционални добавки, а именно изопропилов етер, анилин, диетиламин, диметил малонат и p-трет-бутилфенол. Ефектите на различните добавки върху разхода на гориво, мощността и емисионните характеристики са изследвани върху пътнически автомобил, оборудван с двигател с директно впръскване на бензин (GDI), чрез експеримент с въртящ се барабан, който симулира реални условия на шофиране по пътя. Експерименталните горива в посоченото проучване са базов бензин (G92), бензин, смесен с 15% (обемна фракция, същото е и за други горива) добавка изопропилов етер (наречен G92-1), бензин, смесен с 1,5% добавка анилина (G92-2), бензин, смесен с 1,5% добавка диетиламин (G92-3), бензин, смесен с 3% добавка диметил малонат (G92-4) и бензин, смесен с 3% добавка p-трет-бутилфенол (G92-5). Изследваните добавки имат отлична способност да подобряват антидетонационните характеристики на бензина поради по-високото октаново число, което допълнително влияе върху горивните и емисионните характеристики на превозното средство. Следователно е важно да се изследва ефектът на избраните добавки върху горивните и емисионните характеристики на превозното средство. Влиянието на различните добавки върху мощността на превозното средство в изследването на Wen et al. е оценено чрез експеримент за ускорение. Приложен е метод, който извършва измервания поотделно за всяка предавка, тъй като превозното средство е оборудвано с ръчна скоростна кутия. Резултатите от изследването показват, че за обемния разход на гориво на всеки 100 км, минималната стойност на разхода на гориво се получава чрез зареждане с G92-3, което показва, че смесването на диетиламин с бензин намалява разхода на гориво (0,17%). Максималната стойност на разхода на гориво се постига при използване на G92-2, което показва, че бензинът, смесен с анилин, увеличава разхода на гориво (2,4%). По отношение на ускорителните характеристики, всички добавки могат да съкратят времето за ускорение. Въздействието на петте неконвенционални горивни добавки върху ускорителните характеристики обаче е незначително – разликата е по-малка от 3%. По отношение на газовите емисии, двигателят получава най-ниските емисии на NOx и CO при използване съответно на G92-5 и G92-2. Това показва, че добавянето на p-трет-бутилфенол и анилин намалява съответно NOx (13%) и CO (3,1%). Двигателят получава най-ниските емисии на THC и $CO_2$ при използване на G92-3, което показва, че добавянето на диетиламин намалява емисиите на THC (8,1%) и $CO_2$ (0,12%). Двигателят показва най-високи емисии на NOx и $CO_2$ при използване на гориво съответно с G92-3 и G92-2, което предполага, че добавянето на диетиламин и анилин увеличава съответно емисиите на NOx (13%) и $CO_2$ (0,12%). Установено е, че най-високи емисии на CO и THC при използване на гориво с G92-4, което показва, че добавянето на диметил малонат увеличава емисиите на CO (5%) и THC (2,5%). По отношение на емисиите на PM, всички горива с добавки подобряват емисиите на PM в сравнение с базовото бензиново гориво. Разликата между максималните и минималните стойности на емисиите на PM е 54,6%, което се получава чрез

сравняване съответно на G92 (базов бензин) и G92-3 (добавяне на диетиламин). Изводът от посоченото изследване е, че най-ниският разход на гориво и емисии на THC, $CO_2$ и PM се постигат при използване на гориво с G92-3. Въпреки че емисиите на NOx са по-високи от тези на други тестови горива поради съдържанието на азот в диетиламин, газообразните емисии могат да бъдат решени чрез TWC (температурно пречистване на отпадъци). Следователно, сред всички избрани добавки, диетиламинът е обещаваща неконвенционална добавка за бензин [28].

В момента транспортният сектор разчита предимно на двигатели с вътрешно горене, като например дизелови и двигатели с искрово запалване. Двигателите с вътрешно горене вероятно ще останат най-важният двигател през следващите 30 години. Всяка година световният транспортен сектор консумира все повече енергия. Използването на изкопаеми горива е основен принос за този факт. Двигателите с вътрешно горене, които работят с изкопаеми горива, осигуряват много енергия за транспортния сектор. Въпреки напредъка в алтернативните горива, около 90% от хората все още използват традиционни изкопаеми горива, като само малък процент използват възобновяеми горива. Търсенето на транспортни, промишлени и изследователски услуги се увеличава всеки ден с нарастването на населението на света, което води до недостиг на петролни горива. Бързото изчерпване на петролните горива, както и въздействието на емисиите им върху околната среда, се превърнаха в основен проблем за хората по целия свят. В проведените изследвания са предложени някои популярни добавки, които се използват. Водород, CNG, LPG, ZnO, алкохоли, метилови естери, $Mn_2O_3$ , $Al_2O_3$, MWCNT, GO и GNP са най-новите допълнения към списъка с материали, използвани като добавки. Тези добавки могат да бъдат класифицирани (таблица 1).

**Таблица 1.** Класификация на използваните добавки в горивата

| Параметър | Видове |
|---|---|
| Газообразни добавки | Водород, CNG, LPG, HHO |
| Течни добавки | DME, метил ацетат, глицерол ацетат, алкохол |
| Твърди добавки | Метални – CuO, MgO, $AL_2O_3$, $TiO_2$<br>Неметални. |

Свойствата на основното гориво (дизел или биодизел) могат да бъдат обобщени в Таблица 2.

**Таблица 2.** Свойства на основното гориво (дизел и биодизел) [8]

| Свойство | CV [MJ/kg] | Плътност [кг/м³] | Кинематичен вискозитет [mm²/s] | Температура на възпламеняване [℃] |
|---|---|---|---|---|
| чист дизел | 44 | 825.96 | 3.96 | 72 |
| биодизел | 38.7 | 860 | 3.7 | 124 |

Свойствата на газообразните и течните добавки са представени в Таблица 3.

**Таблица 3.** Свойства на газообразните и течните добавки [22]

| Свойство | CV [MJ/kg] | Плътност [кг/м³] | Кинематичен вискозитет [mm²/s] | Температура на възпламеняване [℃] |
|---|---|---|---|---|
| водород | 119.93 | 0.0838 | 110 | - |
| метанол | 20.30 | 790 | 0.59 | 12 |
| етанол | 27 | 785 | 1.1 | 14 |
| CNG | 45.76 | 720 | - | 81.6 |

Използваните добавки на основата на въглерод са въглеродни нанотръби и графен. Свойствата на материалите са показани в таблица 4.

**Таблица 4.** Свойства на въглеродните добавки, използвани като добавки за гориво [22]

| Свойство | CV [MJ/kg] | Плътност [кг/м³] | Специфична повърхност ($m^2g$-1) | Топлопроводимост (kW/mK) |
|---|---|---|---|---|
| SWCNT | - | 1.3-1.4 | 1315 | 1750-3800 |
| Графен | 31.82 | 2.267 | 1598 | 5300 |

Важно е да се уточни, че различни параметри могат да се използват за измерване на производителността и емисиите на дизелов двигател. След проучване на проведени изследвания се установява, че стандартните параметри, използвани за оценка на производителността на двигателя, са спирачният момент, спирачната мощност, специфичният разход на гориво при спиране (BSFC) и термичната ефективност на спирачката (BTE). Освен това, наблюдаваните параметри на емисиите са въглероден оксид (CO), въглероден диоксид ($CO_2$), азотни оксиди (NOx) и неизгорели въглеводороди (HC).

Установени са изследвания, свързани с анализиране на влиянието на течните добавки върху производителността и емисиите на двигателя. Najafi провежда експеримент за оценка на производителността и емисиите на отработени газове на четирицилиндров двигател с принудително впръскване. Двигателят работи с различни съотношения на смесване на етанол и бензинови смеси. Използвана е смес от бензин и биоетанол, получен от картофени обелки. Използвани са 0%, 5%, 10%, 15% и 20%. Сместа е наречена E0, E5, E10, E15 и E20. Производителността на двигателя и емисиите от сместа са сравнени с производителността и емисиите от 100% бензин. Експериментът установява, че използването на етанолови смеси подобрява спирачната мощност, термичната ефективност на спирачките (BTE), въртящия момент на двигателя и обемната ефективност. От друга страна, специфичният разход на гориво при спиране (BSFC) намалява. BSFC се определя като консумираната енергия на единица произведена мощност, като се има предвид калорийността на горивото [12]. Nour et al. идентифицират ефектите на сместа пентанол/воден етанол/дизел и октанол/воден етанол/дизел върху двигателя с компресионно запалване. Установява се, че добавянето на октанол към смесите воден етанол/дизел постига по-ниска BSFC при всички натоварвания [13]. По-задълбочено проучване от Yesilyurt et al. е проведено, за да се сравнят производителността на двигателя, горенето и емисиите на дизелови двигатели с директно впръскване, работещи с дизел, със смес дизел-бутанол и смес дизел-пентанол. Установява се, че смесените горива произвеждат по-ниски EGT и $CO_2$. Въпреки това се произвежда повече O2. Причината за наблюдението е по-високото съдържание на кислород в

алкохола [30]. Бензинът, смесен с алкохол, произвежда по-ниски EGT в сравнение със 100% бензин. Това е така, защото бензинът има най-висока калоричност и най-ниска латентна топлина на изпаряване, образуване на бедна смес и разпространение на пламъка. Посоченото довежда до повишаване на температурата в цилиндъра и използване на повече бензин. Друг експеримент с алкохол е проведен от Phuangwongtraku et al., за да се изследва работата на двигателя. Изследвани са спирачният въртящ момент и специфичният разход на гориво при спиране, докато е използвано различно съотношение на смесване на етанол. Експериментът доказа, че правилното съотношение на смесване на етанол и бензин може да подобри въртящия момент на двигателя, като същевременно намали емисиите. Чрез добавяне на пентанол към биодизел се установява, че максималните стойности на BTE на дизеловото гориво и B20 и B20P5 са съответно 22,75%, 21,82% и 20,96% при натоварване на двигателя от 750 W [16].

Yesilyurt et al. установяват, че характеристиките на емисиите на отработени газове на еднокамерен дизелов двигател с директно впръскване, работещ със смеси от биодизел/дизел/1-бутанол и биодизел/дизел/n-пентанолнамаляват NOx с 0,56%–2,65%, CO с 6,90%-32,40% и дима с 10,47%-44,33%. Авторите изразяват мнение, че висшите алкохоли, особено n-пентанолът, могат да бъдат ефикасна добавка за намаляване на емисиите на NOx, като се вземат предвид получените резултати [30]. В друго голямо изследване се използват смеси от диетилов етер (DEE) с чист дизел, за да изследват характеристиките на емисиите на отработени газове на едноцилиндров дизелов двигател с директно впръскване и въздушно охлаждане. Проведен е експеримент при четири скорости на двигателя, вариращи от 1000 до 1600 об/мин с интервали от 200 об/мин и четири натоварвания на двигателя, които са халогенни лампи с мощност 150, 300, 500 и 1000 вата. Дизеловото гориво е смесено с DEE0, DEE2.5, DEE5, DEE7.5 и DEE10, които съдържат съответно 2,5%, 5%, 7,5% и 10% обемни процента DEE. Според изводите от изследването DEE10 позволява намаляване на емисиите на NOx с 56% [25]. Друг експеримент е проведен от Dogan et al. за идентифициране на необратими процеси, използвайки енергиен и ексергетичен анализ. Горивата са смесени в различни съотношения. 100% безоловен бензин се нарича E0, а бензин, смесен с 10% етанол, се нарича E10. 20% етанол се нарича E20, а 30% етанол се нарича E30. След това горивните смеси се прилагат в бензинов двигател с различни скорости, при различни натоварвания и при едни и същи условия за всеки вид гориво. Резултатът от експериментите и теоретичните изчисления показва намаляване на въглеродния оксид (CO) [3]. В същото изследване е проведен и друг експеримент, фокусиран върху идентифицирането на необратими процеси, използвайки енергиен и ексергетичен анализ. Горивата са смесени в различни пропорции. E0 се отнася до 100% безоловен бензин, докато E10 се отнася до бензин, смесен с 10% етанол. E20 е етанол с концентрация 20%, а E30 е етанол с концентрация 30%. След това горивните смеси се прилагат в бензинови двигатели с различни скорости, при различни натоварвания и при едни и същи условия за всеки вид гориво. Нивата на въглероден диоксид бяха намалени в резултат на експериментите и теоретичните изчисления ($CO_2$). По подобен начин експериментите на Pinzi et al. установяват, че сместа от дизелово гориво/алкохол е в състояние да намали образуването на сажди. Това явление може да се дължи на високото съдържание на кислород в алкохола, което помага за изгарянето на сажди по време на горене [17].

Добавките за твърдо гориво също са изследвани от гледна точка на производителността. Amirabedi et al. изследват влиянието на Mn 2 O3 в бензино-алкохолната смес, която използва бензин, разреден с 10% етанол, след което се добавят 10 ppm и 20 ppm Mn2 O3 като допълнителни проби. Резултатите показват, че по отношение на ефективността, производителността се подобрява [2]. Посоченото се подкрепя от анализите на Jayaraman et al., които изследват ефектите от добавянето на титанов оксид TiO2 към смес B20 в двигател с въглероден дизел. В резултат на това специфичният разход на гориво е намалял. При 25% натоварване, B20 + 50 произвежда най-ниската BSFC от 0,46 kg/kw-hr. При натоварване от 18,16 kg, максималната BTE за B20 + 50 + EGR е била 32,64%. BTE на B20 с TiO2 е по-висок от този на нормалния B20, защото TiO2 подобрява горенето и отделя висока скорост на топлина [7]. Проведени са и изследвания на емисиите от работа на двигател с въздушно загряване със смеси от дизел и метанол, с използване на алуминиев оксид Al 2 O3 като добавка. Основните изводи са свързани с намаленията на BTE и BSFC съответно с 3,6 и 3,7 процента. Добавянето на TiO2 към смеси от биодизел и бутанол увеличава въртящия момент и мощността на спирачния двигател съответно с 10,20 процента и 9,74 процента. BSFC, от друга страна, може да бъде намален с 27,73% [27]. Производителността по отношение на мощност и ефективност се подобрява, като добавянето на 50 ppm Al 2 O3 и CuO към дизеловото гориво води до увеличаване на мощността на двигателя [14]. В изследвания е установено, че CO и HC намаляват съответно с около 14,96% и 34,39% с добавянето на TiO2. Емисиите на $CO_2$ и NO обаче са се увеличили съответно с 5,75% и 3,94%. Доказано е постигнато 51,83% намаление на HC чрез използване на бензин с 10% етанол и 20 ppm Mn2O3 в сравнение с базовия бензин. Това се постига, когато двигателят работи с пълно натоварване и скоростта е настроена на 2800 об/мин. CO е намален с 24,09% спрямо базовия бензин. Емисиите на $CO_2$ обаче са се увеличили с 13,27% в този експеримент [14].

Проведени са редица изследвания за установяване ефективността на добавки за гориво на въглеродна основа върху производителността на двигателя. Установено е, че производителността може да се подобри от смеси от биодизел и биоетанол, като се добави въглеродни нанотръби (CNT) и се увеличи въртящия момент, като мощността и BTE съответно се увеличи с 15,52%, 15,52%, и 13,97%. BSFC, от друга страна, спадна с 11,73%. При използване на CNT като добавка в двигател с въглеродно впръскване, който се захранва от смес от дизел и биодизел, като експериментът се провежда при пълно натоварване с различни смеси и скорости се достига до извод, че добавянето на CNT произвежда по-голям въртящ момент от чистото дизелово гориво. В същото изследване се доказва, че мощността се е увеличила с 21,84% [5]. BTE намалява от 1800 до 2800 об/мин., което се дължи на намаляване на обемната ефективност. Добавянето на CNT също намали BSFC. При използване на въглеродни нанотръби и графенови нанолистове като горивни добавки в смеси B20, като CNT и графенови нанолистове се смесват с B20 в концентрации от 25, 50 и 100 ppm за създаване на горивни смеси, се установява, че термичната ефективност за B20CNT100 и B20CNS100 се подобрява съответно с 8% и 19% [19].

В експеримента на Hosseini et al. се установява, че при различни условия емисиите на горивна смес с добавки от въглеродни нанотрубки (CNT) са намалени с 40,38% в сравнение с чист дизел. В случая на $CO_2$, средните емисии се увеличават с 9,88%, когато всички горивни смеси с CNT са сравнени с чисто дизелово гориво. Емисиите на HC от горивна смес, съдържаща добавка от CNT,

са намалени като цяло [5]. Наблюдават се изключително големи намаления в плътността на дима, CO, NOx, HC и с B20CNT100, които са съответно 28%, 27%, 22% и 28%. За плътността на дима, CO, NOx и HC, B20CNS100 получава съответно 54%, 47%, 44% и 52%.

Tomar & Kumar провеждат подобно изследване, използвайки едноцилиндров четиритактов дизелов двигател (Kirloskar) и смеси от дизел и Schleichera Oleosa Biodiesel с алуминиеви наночастици и многостенни въглеродни нанотръби. Въз основа на своите открития, авторите смятат, че използването на алуминиев оксид и вещества с добавка на MWCNT може да бъде ефективна стратегия за преформулиране на горивото. Емисиите на NOx намаляват в резултат на наличието на добавени нановещества в горивото D80B20C100, поради удивителния гъбест наклон на MWCNT наночастиците [24].

Mei et al. изследват едноцилиндров четиритактов дизелов двигател с въздушно охлаждане и система за впръскване с common-rail, работещ при 3000 об/мин с променящи се натоварвания от 100%, 75%, 50% и 25%. Авторите са използвали две различни наночастици, въглеродни нанотрубки (CNT) и молибденов триоксид (MoO3), и са ги смесили с чист дизел при концентрации от 50 mg/L и 100 mg/L за всяка наночастица. Според авторите, CNT имат по-голям потенциал от MoO3 да намалят общите очаквани емисии на отработени газове. CO, HC, NOx и димните емисии от CNT100 са намалени съответно с 9,6%, 11,4%, 8,9% и 15,25% в сравнение с емисиите на отработени газове, произведени от Mo100, които са 6,8%, 7,5%, 5,2% и 8,3%. Авторите също така заявяват, че резултатите могат да се дължат на превъзходната топлопроводимост и повърхностния дефицит на CNT в сравнение с MoO3 [11].

## 3. Заключение:

Емисиите от автомобилите са важен източник на замърсяване на въздуха, като се получават от изгарянето на горивото, поради което използването на висококачествено гориво и оптимизирането на процеса на горене може да намали вредните емисии и да подобри разхода на гориво. Нивото на качество на горивото се определя главно от нефтохимическия производствен процес, а оптимизирането на процеса на горене се дължи на прилагането на усъвършенствана технология на двигателя. Използването на подходящи добавки за гориво е предпоставка за постигане на положителен ефект върху производителността на горенето, като по този начин подобри емисионните характеристики на двигателя, икономията на енергия и чистотата на цилиндрите. Процесът на горене на двигател с вътрешно горене определя емисиите на замърсители, а добавките за гориво могат да оптимизират процеса на горене, да намалят емисиите на отработени газове и да осигурят спазване на все по-строгите разпоредби за ограничаване на замърсяването.

В резултат на изследвания са разработени много различни видове горивни добавки. Значително количество добавки са налични в газообразна, течна и твърда форма. Много твърди материали се разглеждат като горивни добавки с напредването на нанотехнологиите. Наноматериалите на основата на въглерод показват многообещаващи резултати по отношение на подобрена производителност и по-ниски емисии. Нови графенови материали също са открити и добавени към списъка с добавки; дълбочината на изследванията обаче все още е недостатъчна.

В обобщение следва да се посочи, че проведените проучвания на ефекта на горивната добавка върху разхода на гориво и емисиите на двигателя показват, че

в сравнение с гориво без добавка, използването на добавка може да подобри мощността, разхода на гориво и емисиите на двигателя. Постигнатите резултати категорично доказват, че горивните добавки имат положителен ефект върху намаляването на емисиите и пестенето на енергия.

Научните изследвания, резултатите от които са представени в настоящата публикация, са извършени по проект в рамките на присъщата на ТУ-Варна научноизследователска дейност, финансирана целево от държавния бюджет

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За контакти: инж. Ренан Къров Технически университет гр. Варна
email: renan_karov@abv.bg

# АЛТЕРНАТИВНИ ЗАДВИЖВАНИЯ В АВТОМОБИЛНИЯ ТРАНСПОРТ – КОНСТРУКЦИЯ И ЕНЕРГИЙНА ЕФЕКТИВНОСТ НА ПОЛИМЕРНО-ЕЛЕКТРОЛИТНИ ГОРИВНИ КЛЕТКИ

# ALTERNATIVE PROPULSION SYSTEMS IN AUTOMOTIVE TRANSPORT – DESIGN AND ENERGY EFFICIENCY OF PROTON EXCHANGE MEMBRANE FUEL CELL

**Teodora Palazova**

**Abstract.** This report examines hydrogen fuel cell vehicles as a promising alternative to conventional systems. Hydrogen technologies offer high energy efficiency, zero harmful emissions, and rapid refueling times, positioning them as a key component in the transition toward sustainable and environmentally friendly mobility. This report analyzes the operating principle of fuel cell, including the electrochemical processes involved in converting hydrogen into electrical energy, as well as the system components. The main advantages and challenges of the technology are also presented.
**Keywords**: Hydrogen fuel cells, Hydrogen, Zero-emission transport, Green economy

## 1. Въведение:

Технологията на водородните горивни клетки представлява обещаващо решение за транспорт с нулеви емисии, като предлага висока енергийна ефективност, бързо зареждане и устойчива алтернатива на конвенционалните двигатели с вътрешно горене и електрическите превозни средства с батерии. За разлика от превозните средства, задвижвани с изкопаеми горива, горивните клетки на водород произвеждат само вода като страничен продукт, което води до значително намаляване на емисиите на парникови газове и замърсители на въздуха. Въпреки тези предимства, редица предизвикателства възпрепятстват широкото внедряване на технологията. Основни бариери са: високата производна цена на системите с горивни клетки, ограничената наличност на инфраструктура за зареждане с водород, както и сложността при съхранение и дистрибуция на водорода. Освен това, екологичното въздействие и енергийните изисквания на методите за производство на водород, като паров реформинг на метан и електролиза, остават ключови фактори, определящи общата устойчивост на водорода като енергиен носител.

## 2. Изложение:

Горивната клетка представлява електрическа клетка, която за разлика от акумулаторните клетки, може да бъде непрекъснато захранвана с гориво, така че електрическата ѝ мощност да се поддържа за неограничен период от време. Тя преобразува водород или водородо-съдържащи горива директно в електрическа енергия и топлина чрез електрохимична реакция между водорода и кислорода, при която се образува вода. По същество процесът представлява обратната реакция на електролизата:

$$2\,H_{2(gas)} + O_{2(gas)} \rightarrow 2\,H2O + \text{енергия} \qquad (1)$$

Тъй като водородът и кислородът се преобразуват електрохимично във вода, горивните клетки имат редица предимства пред двигателите с вътрешно горене. Сред тях са: висока ефективност, почти безшумна работа и липса на замърсяващи емисии, когато водородът се произвежда от възобновяеми енергийни източници, произведената електроенергия може да бъде напълно устойчива.

**Химични реакции, протичащи в горивните клетки с полимерно-елетролитна мембрана**

Полимерните горивни клетки са използвани за първи път от NASA в програмата GEMINI (1960 година). Те се отличават с компактност, гъвкавост и ниска температура на работа.

В тези горивни клетки протичат две реакции едновременно – окислителна (загуба на електрони) и редукционна (придобиване на електрони). Двете реакции съставят общата окислително-редукционна реакция на горивната клетка, при която се образува вода от водород и кислород. Както при електролизатора, анодът и катодът са разделени от електролит, който позволява пренос на йони между двете страни. Електролитът в горивната клетка представлява твърда киселина, вградена в мембраната.

Уравнение на анодната реакция:

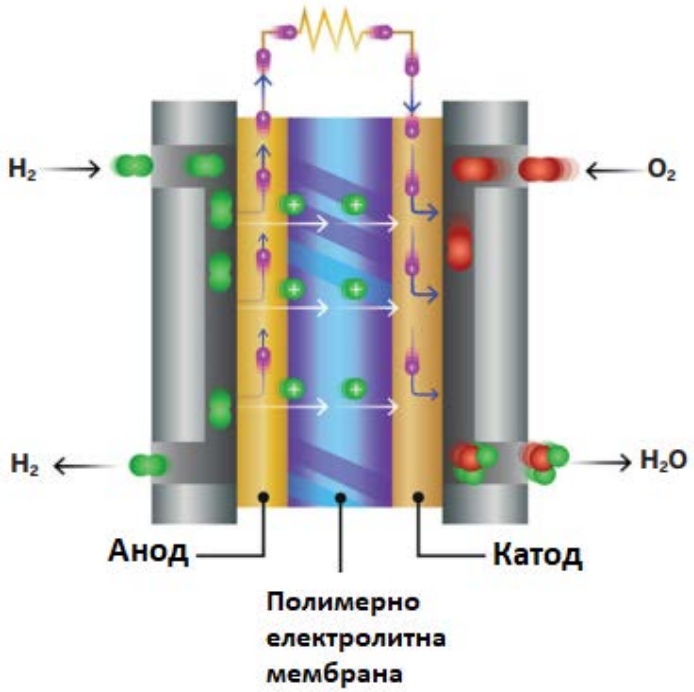
$$H_2 \rightarrow 2H^+ + 2e^- \qquad (2)$$

Уравнение на катодната реакция:

$$½O_2 + 2e^- + 2H^+ \rightarrow H_2O \qquad (3)$$

Обща реакция:

$$H_2 + ½O_2 \rightarrow H_2O \qquad (4)$$




**Фиг. 1.** Водородна клетка с полимерно елетролитна мембрана

При анода, водородните молекули първо влизат в контакт с платинов катализатор върху повърхността на електрода. Те се разпадат, образувайки слаби връзки. След това започва окислителната реакция, при която всеки водороден атом отделя електрон, който преминава през външната електрическа верига към катода – този поток на електрони представлява електрически ток. Останалият протон ($H^+$) се свързва с водна молекула върху повърхността на мембраната, образувайки хидрониев йон ($H_3O^+$). Той преминава през мембраната на катода, освобождавайки мястото на катализатора за следващата водородна молекула. Кислородните молекули на катода също се абсорбират върху платинения катализатор и се разделят на атоми (Фиг. 1). Всеки

кислороден атом реагира с два електрона и два протона като се образува една молекула вода. Така реакцията завършва, а катализаторът отново е свободен за нова молекула кислород.

**Компоненти на горивната клетка**

Полимерната горивна клетка принадлежи към групата на нискотемпературните горивни клетки. Поради ниската ѝ работна температура, е необходимо използването на високоефективни катализатори в електродите. Най-важният катализатор, използван в този тип клетка е платината. Един от най-ефективните методи за намаляване на количеството използвана платина е нанасянето на тънък слой катализатор с възможно най-голяма специфична повърхност. Електродите са порести, за да позволят дифузия на газовете до катализаторната повърхност. Платината и въглеродният субстрат са добри електропроводници, което позволява ефективен пренос на електрони.

Основният елемент на полимерната горивна клетка е протон-проводящата мембрана, която трябва да отговаря на редица изисквания, сред които – икономически целесъобразна, неразтворима във вода, непропусклива за реакционните газове, да притежава висока йонна проводимост при експлоатационни условия. Освен това мембраната трябва да бъде термично и химически устойчива до температури над 120 °C, както и устойчива на киселини, свободни радикали и окислители. Желателно е да осигурява експлоатационен живот от минимум 5000 часа при транспортни приложения и да има достатъчна механична якост.

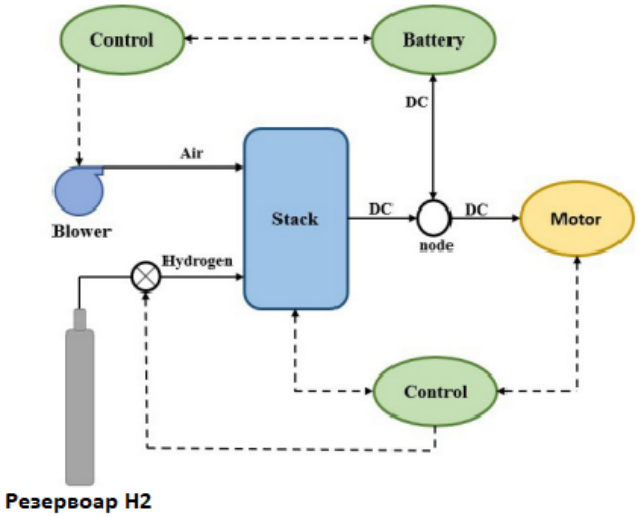
Най-често използваният материал за такива мембрани принадлежи към групата на флуорополимерите и е познат под търговското наименование „Nafion”. Този материал може да абсорбира големи количества вода, което повишава йонната му проводимост. Животът на тези мембрани може да достигне до 50 000 часа. Дебелината им обикновено е между 50 и 200 μm, като мембраната действа като ефективен разделител между анода и катода, предотвратявайки контакт между водорода и окислителя. Важно е да се отбележи, че въпреки високата си йонна проводимост, мембраната не е електропроводима, поради ограничената си структура, което я прави електрически изолатор.

Комбинацията от анод – мембрана – катод се нарича мембранно-електронен модул. Плътността на генерираната мощност в такива клетки е нараснала от 0,5A до 15A за всеки милиграм платина. Дебелината на катализаторните слоеве зависи от съдържанието на платината – при 0.15 g катализатор тя е около 10 μm, по-малко от половината дебелина на лист хартия.

Газоразпределителните слоеве са разположени около анода и катода. Обикновено са изработени от въглеродни порести плочи или тъкани, с дебелина между 100 и 300 μm. Те трябва да бъдат електропроводими и да позволяват дифузия и равномерно разпределение на реакционните газове върху повърхността на катализатора. Тези слоеве осигуряват ефективно управление на водата – подпомага преноса на вода от анода към мембраната и извеждането ѝ от катода, за да се избегне пренасищане с вода. За защита от влага, тези слоеве често се импрегнират с тефлон, което предотвратява запушването на порите от вода.

**Принцип на работа**

При водородо-въздушната система в полимерните горивни клетки (Фиг.2) водородът се подава от резервоар за съхранение към пакет от горивни клетки. Въздухът се осигурява чрез вентилатор или компресор. Електрическият ток, произведен от горивната клетка, е постоянен ток и се използва за захранване на електрическия двигател на превозното средство.

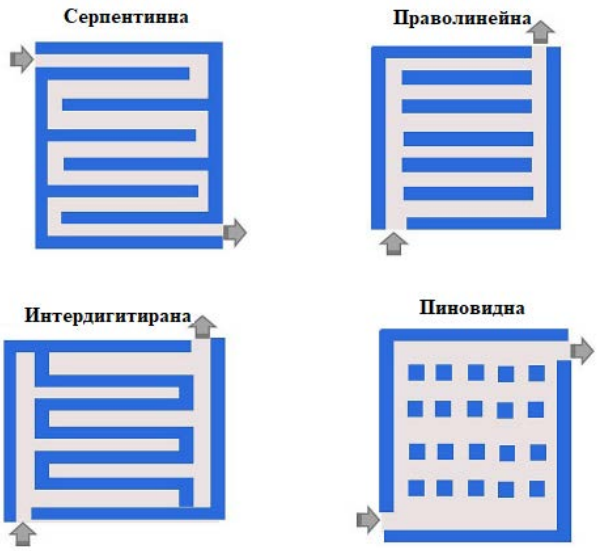



**Фиг. 2.** Принцип на работа на водородо-въздушна система с горивна клетка

За намаляване на размера и теглото на стека, системата може да включва акумулаторна батерия или суперкондензатор, които съхраняват и освобождават електрическата енергия според нуждите. Съхранението на водород обикновено се осъществява чрез метални хидриди (налягане около 1MPa) или бутилки под високо налягане (до 35MPa). Бутилките се изработват от неръждаема стомана, алуминий, въглеродни или стъклени влакна, армиращи алуминиев корпус. За повишаване на безопасността се използват предпазни клапани, отварящи се при свръхналягане и датчици за водород, които да откриват евентуални течове. Състоянието на горивния пакет и батерията се наблюдават от бордова система за управление, която регулира дебита на водород и въздух. При прегряване на стека или установяване на водороден теч, системата автоматично изключва горивната клетка за безопасност. Овлажняването на реагентите преди постъпване в стека подобрява ефективността и експлоатационната продължителност.

В един пакет от горивни клетки, реакционните газове се движат през канали на биполярните плочи, наричани газоразпределителни полета. Както е показано на Фиг.3, съществуват четири основни типа конфигурации:

- Праволинейна (Паралелна)
- Серпентинна (Змиевидна)
- Пиновидна (pin-type)
- Интердигитирана




**Фиг. 3.** Видове горивни клетки, според конфигурацията на газоразпределителните полета

**Производство на водород**

Проучване на Pembina Institute (Калгари, Канада) сравнява емисиите на въглероден диоксид при автомобили с горивни клетки в зависимост от метода на производство на водорода. Резултатите показват, че изборът на източник на водород е критично екологично решение. Ако водородът се произвежда чрез електролиза с електричество от въглищни централи, емисиите на въглероден диоксид са съпоставими, или дори по-високи отколкото при традиционните двигатели с вътрешно горене. Ако обаче електролизаторът се захранва от възобновяем източник, емисии на въглероден диоксид няма.

Реформирането на въглеводородни горива е икономически изгоден процес, но при него се отделя голямо количество въглероден диоксид, който допринася за парниковия ефект и глобалното затопляне.

Водород може да се произвежда устойчиво и без емисии, чрез възобновяеми източници от соларни панели, вятърни турбини и др. Електричеството от тези системи задвижва електролизатор, който разгражда водата на водород и кислород, където водородът се съхранява за бъдеща употреба в горивни клетки, а кислородът се освобождава в атмосферата. По този начин се създава затворен енергиен цикъл. Системата е чиста, ефективна и напълно устойчива.

Водород може да се произвежда и биологично – чрез водорасли и микроорганизми. Екипът на д-р Анис Мелис от Калифорнийския университет Бъркли открива метаболитен „превключвател” в зелените водорасли Chlamydomonas reinhardtii. При липса на сяра във водната среда, водораслите започват да окисляват водата и да отделят чист водороден газ. Тази технология все още е в етап на научно-развойни изследвания, но има потенциал да се превърне в допълнителен устойчив източник на водород в бъдеще.

**Напрежение и ефективност на горивната клетка**

Ако горивната клетка преобразуваше напълно химическата енергия в електрическа, термодинамичния обратим потенциал би бил 1,23V при 25 °C и 1 атмосфера. При достигане на работна температура около 80°C, идеалното напрежение спада до приблизително 1,18V.

На практика обаче, реалното напрежение е по-ниско поради редица загуби, което води до намаляване на електрическата ефективност – колкото по-ниско е напрежението, толкова по-голяма част от енергията се отделя под формата на топлина.

**Основни източници на загуби са:** *Активационните загуби* **–** възникват, заради енергията, необходима за иницииране на електрохимичната реакция (Редукцията на

кислорода е основният лимитиращ фактор за мощността, тъй като тя е доста по-бавна от тази на анода).

*Проникване на гориво и вътрешни токове* – част от водорода може да премине директно през електролита от анода към катода, без да отдаде електрони във външната верига. Това намалява ефективността и води до термични загуби.

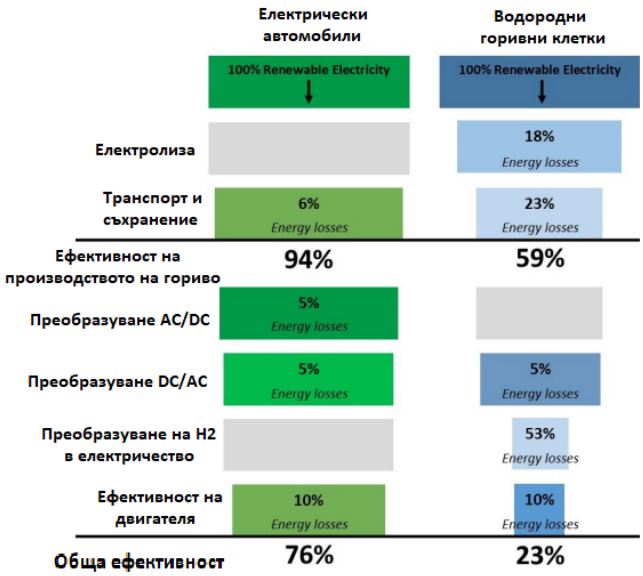
*Омични загуби* – те са резултат от съпротивлението на различните компоненти на клетката.

*Концентрационни загуби* – настъпват при намаляване на концентрацията на реагентите около електродите. При високи токове натрупаната вода на катода може да запуши катализаторните зони, ограничавайки достъпа на кислород.

**Сравнение между електрическите автомобили и тези с водородни горивни клетки**

Литиево-йонните батерии са обект на интензивно развитие през последните две десетилетия поради ръста на продажбите на електрически превозни средства. Когато електроенергията, използвана за зареждане на батериите идва от възобновяеми източници, трябва да се вземат предвид загубите при пренос по електрическата мрежа. За Европа средната стойност на загубите при пренос и разпределение е около 6%. Допълнително, инфраструктурата за зареждане има ефективност от приблизително 99%, т.е. загуби от около 1%.

При най-добрия сценарий, с високи нива на ефективност на всички етапи от процеса, електрическите автомобили с батерии остават най-ефективното решение за задвижване на превозни средства. Въпреки че автомобилите с водородни горивни клетки могат да изминат по-голям пробег с пълен резервоар в сравнение с тези с батериите, цената за пълно зареждане е значително по-висока поради енергийните загуби и неефективностите по веригата. Изчисленията показват, че разходът на енергия на километър при водородните автомобили е около три пъти по-висок, отколкото при електромобилите (Фиг. 4).




**Фиг. 4.** Сравнителни характеристики на електрическите автомобили с водородните горивни клетки

Допълнителни фактори като строителни разходи за водородна инфраструктура и печалбата на станциите за зареждане с водород, допълнително увеличават крайната цена на километър. Поради това, настоящите енергийни загуби и неефективности в системите за производство, съхранение и дистрибуция на водорода оформят пазара така, че основните инвестиции и изследвания се насочват към електрическите батерийни технологии.

**Предизвикателства и решения при полимерните горивни клетки**

Въпреки значителните предимства на протонно-обменните мембранни горивни клетки, тяхната дългосрочна експлоатационна пригодност зависи в голяма степен от издръжливостта на стека, особено от електролизаторите и газоразпределителния слой. Един от най-важните параметри, влияещи върху дълготрайността е работната температура. Прекомерно високата температура води до разрушаване на мембраната, намаляване на ефективността, както и наличие на дифузия на водород през електролитната мембрана към катода, което причинява вътрешни утечки и деградация.
От друга страна, работа при твърде ниски температури , дори под нулата, предизвиква замръзване на водата, увреждане на мембраната и газоразпределителните слоеве, повишаване на вътрешното налягане в клетката, което може да доведе до механичен пробив.

## *Управление на водата и топлината в горивните клетки*

Водата играе критично важна роля в процеса на работа на горивната клетка. Тя участва като реагент в анода, като овлажняващ агент на мембраната, повишаващ протонната проводимост и като реакционен продукт при катода. Едно от основните предизвикателства е явлението „водно наводняване”, при което прекомерното натрупване на вода в анода нарушава дифузията на газовете. За да се избегне това, е необходимо да се осигури баланс между хидратацията на мембраната и премахването на излишната вода.
Потокът на вода се определя от електроосмотичния коефициент, който представлява съотношението между броя на молекулите вода и броя на преминаващите протони. За мембраните тип “Nafion” този коефициент е приблизително 2.5. За да се предотврати водното наводняване, в катодната страна обикновено се прилага висок дебит на газовия поток, което улеснява изпарението и изнасянето на водните пари.

## *Управление на топлината*

Топлинният мениджмънт е друг ключов фактор за комерсиализацията на полимерните горивни клетки. Количеството топлинни загуби зависи от електрическата мощност, което на свой ред ограничава общата енергийна ефективност до около 50%. Този тип горивни клетки обикновено функционират в температурен диапазон 70–80°C, което предотвратява дехидрация на мембраната. Температури под 60°C водят до кондензация на водата, водно наводняване на електродите и пад на напрежението. Източниците на топлина включват реакционна топлина от електрохимични процеси, необратими електрохимични реакции, омично съпротивление и топлина от кондензацията на водата. При директните метанолови горивни клетки количеството отделяна топлина е по-голямо поради по-ниската им енергийна ефективност – око 20-25%. С нарастването на температурата скоростта на окисление на метанола се увеличава, но също така се повишава и степента на проникване на метанол през мембраната, което води до намалена ефективност и енергийна плътност.

**Текущи изследователски тенденции и перспективи за приложение**

Съвременните изследвания при полимерните горивни клетки са насочени към няколко ключови направления – разработка на катализатори с намалено съдържание на платина, които запазват висока каталитична активност при ниска цена. Усъвършенстват се газоразпределителните слоеве чрез въвеждане на наноразмерни порести структури за подобрен маслообмен и контрол на водата. Използват се флуорирани и сулфонирани полимери с по-добра механична устойчивост и термична стабилност над 100 °C.

Интегрират се хибридни системи за транспортни приложения, позволяваща оптимално използване на енергията при променливи натоварвания.

В краткосрочен план, тази технология ще намери приложение основно в електрическите превозни средства с удължен пробег, автобусите и товарните автомобили, както и в стационарни микромрежи и домашни системи за комбинирано производство на топлина и електричество. В дългосрочен план, с подобряване на ефективността на производство на зелен водород и намаляване на цената на компонентите, горивните клетки имат потенциал да се превърнат в основна технология за децентрализирано производство на енергия.

## III. ЗАКЛЮЧЕНИЕ:

Протонно-обменните мембранни горивни клетки представляват една от най-перспективните технологии за устойчиво енергийно преобразуване, благодарение на високата си енергийна ефективност, нулевите емисии на вредни газове и бързо стартиране при ниски температури. Техни основни предимства са високата плътност на мощността, компактната им конструкция, гъвкавостта им при мащабиране и възможността за интеграция с възобновяеми енергийни източници. Въпреки това, за широкомащабно внедряване в транспортния и енергийния сектор, все още съществуват редица технически и икономически предизвикателства. Едно от които е високата цена на катализаторите, които изработвайки се от платина остават скъпи и ограничават конкурентноспособността на горивните клетки. В последните години се изследват алтернативи на платината, включително метали от групата на преходните елементи и метал-оксидни наноструктури. Други основни предизвикателства са деградирането на мембраната, поради термично и химично стареене, управлението на водата и топлината и сложността на системата и инфраструктурата.

Протонно-обменните горивни клетки представляват ключова стъпка в прехода към водородна икономика. Тяхното бъдеще зависи от успешната комбинация между материалознание, инженерни решения и икономическа устойчивост. С непрекъснатия напредък в областта на нанотехнологиите, катализаторите и мембранните материали, полимерните горивни клетки ще продължат да бъдат централен обект на изследвания и развитие в посока устойчива и беземисионна енергетика.

Научните изследвания, резултатите от които са представени в настоящата публикация, са извършени по проект в рамките на присъщата на ТУ-Варна научноизследователска дейност, финансирана целево от държавния бюджет.

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За контакти: инж. Теодора Палазова Технически университет Варна
email: tedi_palazova@abv.bg

# ИЗСЛЕДВАНЕ ПОКАЗАТЕЛИТЕ НА ДВИГАТЕЛ С ВЪТРЕШНО ГОРЕНЕ ЗА ХИБРИДНО ЗАДВИЖВАНЕ ПРИ РАБОТА С АЛТЕРНАТИВНИ ГОРИВА

# INVESTIGATION OF THE PERFORMANCE OF AN INTERNAL COMBUSTION ENGINE FOR HYBRID PROPULSION WHEN OPERATING ON ALTERNATIVE FUELS

**Pavel Chalakov**

**Abstract.** Reducing the content of toxic components and carbon emissions in the exhaust gases of modern automotive engines is an extremely important part of the strategy for their future development. On a global scale, the possibilities and prospects for the practical implementation of internal combustion engines operating on various types of fuels are continuously being investigated. The advantages, disadvantages, and specific features of the working process when using alternative fuels are examined and discussed. The focus of scientific research is on the methods, design solutions, and necessary modifications for converting the engines of existing vehicles. The influence of fuels on the toxicity, power output, and economic performance of internal combustion engines is clarified. A major toxic component with pronounced carcinogenic effects is nitrogen oxide, whose permissible amount is regulated by the currently applicable EURO 6d-temp emission standard. The aim of the present research is to investigate the composition of the exhaust gases of an internal combustion engine for hybrid propulsion operating on alcohol fuel.
**Keywords:** ethanol, methanol, ICE, alternative fuels

## 1. Въведение:

Влиянието на транспортния сектор върху глобалните емисии нива е безспорен [1]. В резултат на това много се говори за алтернативни средства за задвижване, като използването на електрически превозни средства, които често погрешно се класифицират като превозни средства с нулеви емисии (ZEV). Това несъответствие в номенклатурата възниква, защото само се вземат предвид директните емисии в превозното средство, което всъщност не е така съществуват. Въпреки това, емисиите, генерирани от производството на електроенергия и ефектите от производството и изхвърлянето на батерии не се вземат предвид [2].

Електрификацията на превозните средства придобива все по-голяма популярност при намаляване на разхода на гориво и въглеродни емисии [1], с plug-in хибридни превозни средства (PHEVs) е осъществимо и практично решение за реализиране на електрификацията леки автомобили в краткосрочен/средносрочен план [2]. Ефективността на емисиите при хибридни електрически превозни средства (HEV) са сравними с и дори по-тежки отколкото конвенционалните превозни средства, задвижвани от двигатели с вътрешно горене, като доказано от статистическите данни от обширни тестове на превозни средства [3]. От друга страна, има данни, че PHEV могат да отделят по-високи PN и NOx емисии при режим на изчерпване на заряда (CD) въпреки по-малкото работа на двигателя.

Използването на възобновяеми нисковъглеродни горива влияе пряко върху емисиите на CO2 от транспортния сектор. Въпреки това, за да се постигне реално намаляване на всички емисии е необходимо технологично подобряване на горивния процес и ефективността на задвижването.

## 2. Изложение:

Намаляването на вредните емисии от автомобилния транспорт е един от основните приоритети в съвременното развитие на двигателите с вътрешно горене (ДВГ). Въвеждането на все по-строги екологични норми, регламентирани от стандартите EURO, налага прилагането на нови технологични решения както в конструкцията на двигателите, така и при избора на използваните горива. В този контекст хибридните задвижвания представляват ефективен преходен етап между конвенционалните двигатели и изцяло електрическите системи, тъй като позволяват значително намаляване на разхода на гориво и емисиите на вредни вещества чрез оптимизиране на режимите на работа на ДВГ.

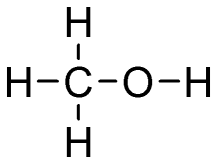
Хибридните силови установки съчетават двигател с вътрешно горене и електрическа машина, като в зависимост от конструктивното изпълнение ДВГ може да работи в най-икономичните и екологично благоприятни режими. Това създава благоприятни условия за използването на алтернативни горива, чиито физико-химични свойства често се различават от тези на традиционните нефтени горива. Алтернативните горива включват газови горива, биогорива, алкохоли, синтетични горива и водород, като особено широко приложение в практиката намират алкохолните горива поради своя възобновяем произход и добри експлоатационни показатели.

Метанолът, етанолът и бутанолът се отличават с високо октаново число, което позволява работа на двигателя при по-висока степен на сгъстяване и подобряване на термичния коефициент на полезно действие (таблица.1).

**Таблица 1.** Характеристики на алкохолите и на традиционните горива

| Параметър | Метанол | Етанол | Бензин |
|---|---|---|---|
| Молекулна маса | 32,04 | 46,07 | 102,5 - 107,0 |
| Плътност, g/cm$^3$ | 0,791 | 0,794 | 0,70-0,75 |
| Съдържание на кислород, масови % | 49,9 | 34,7 | 0 |
| Теоретично необходимо количество въздухза пълното изгаряне на 1 kg гориво, kg | 6,45 | 9 | 14,96 |
| Специфична топлина на изпарение, kJ/kg | 1189 | 921 | 377-502 |
| Специфична топлина на изгаряне, kJ/kg | 19900 | 27000 | 44000 |
| Октаново число:<br>а) по изследователски<br>методб) по моторен<br>метод | <br>112<br>91 | <br>111<br>92 | <br>94<br>84 |
| Температура на замръзване, К | 175 | 159 | 243-223 |
| Температура на кипене (0,1Mpa), К | 337,7 | 351,5 | 313-473 |
| Температура на самовъзпламеняване, К | 743 | 673-733 | 823 |

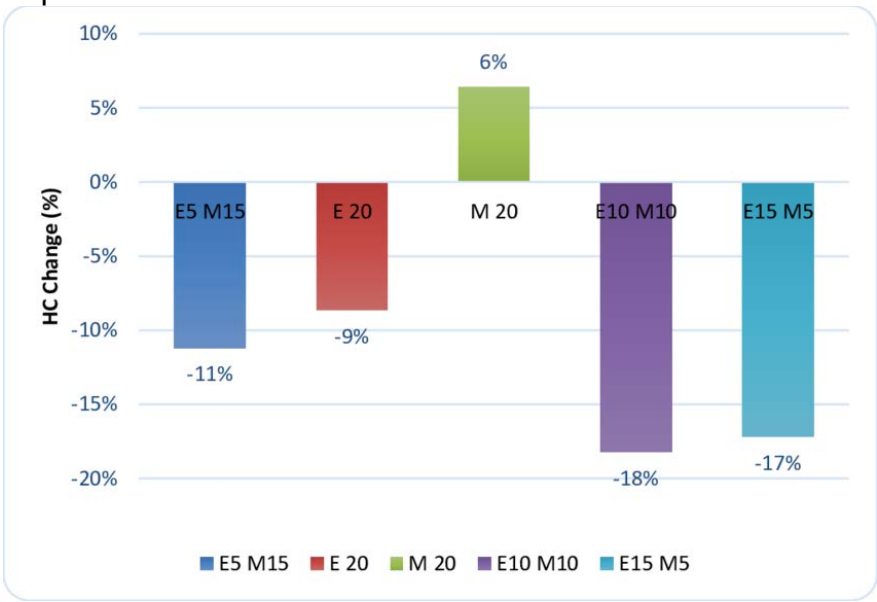
Метанолът притежава много добри антидетонационни свойства и висока степен на изпаряемост, но се характеризира с ниска калоричност и значителна токсичност, което изисква специални мерки при съхранението и експлоатацията му. Етанолът е най-разпространеното биогориво в световен мащаб и се използва както в чист вид, така и като добавка към бензина. Основното му предимство е възможността за значително намаляване на емисиите на въглероден оксид и неизгорели въглеводороди, както и по-ниският въглероден отпечатък. Бутанолът от своя страна се характеризира с по-висока енергийна плътност, по-ниска хигроскопичност и по-добра съвместимост със съществуващата горивна инфраструктура, което го прави особено перспективен за бъдещо приложение.




**Фиг.1.** Химична формула на метанол.

Ниските температури на горене на алкохолите позволяват да се поддържат значително по-ниски концентрации на NOx, отколкото при бензина, а пълното изгаряне води до намаляване на емисиите на CO и CH. Увеличено е съдържанието на алдехиди в отработилите газове. Известно намаляване може да бъде постигнато чрез увеличаване степента на сгъстяване. Използването на бензино-метанолова смес М-15 дава възможност за работа на двигателя с по-бедни гориво-въздушни смеси, отколкото само с бензин. Анализът на отработилите газове на двигателя показва, че при работа с бензино-метанолова смес М-15 концентрацията на токсични компоненти е значително по-малка. Това показва, че от екологична гледна точка работата на двигателя с бензино- метанолова смес е за предпочитане.

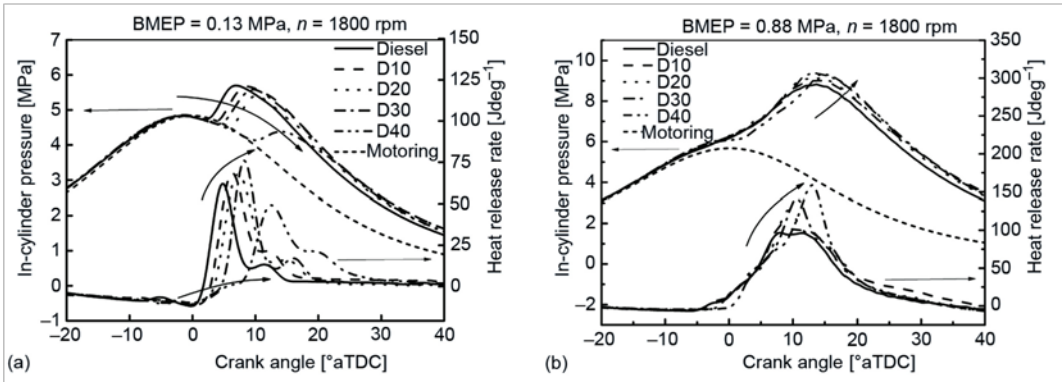
Вредните изпарения на алкохолите са с 15% по-малко от тези на бензина, в изгорелите газове се съдържат 40% по-малко CO, 20% по-малко NOX, а сулфатите са с цели 80% по-малко. Към тези предимства се прибавя и фактът, че производството на етанол е приблизително „CO2 неутрално” - т.е. отделеният от автомобилите въглероден двуокис се консумира при фотосинтезата на съответното количество биомаса, необходимо за производство на горивото.




**Фиг.2.** Сравнение на мисиите при различни смеси на етанол и метанол с бензин [20]

Освен алкохолните горива, научните изследвания са насочени и към развитието на ново поколение синтетични биогорива, какъвто е диметилфуранът. Той се получава от биомаса и има енергийна плътност, близка до тази на бензина, както и добри антидетонационни характеристики. Диметилфуранът не е разтворим във вода и има по-малка склонност към корозия в сравнение с алкохолите, което е съществено предимство от гледна точка на експлоатационната надеждност. Въпреки това, неговото практическо приложение все още е ограничено, поради необходимостта от допълнителни изследвания на влиянието му върху емисиите на азотни окиси, въглероден оксид и дълготрайността на материалите в горивната система. Диметилфуран е хетероциклично съединение с формула $C_6H_8O$. Въпреки че често се съкращава ДМФ, не трябва да се бърка с диметилформамид. Производно на фуран, това просто съединение е потенциално биогориво. Той има енергийна плътност с 40% по-голяма от тази на етанола, което го прави сравним с бензина. Освен това е химически стабилен и тъй като е неразтворим във вода, не абсорбира влага от атмосферата. Изпаряването на диметилфуран по време на производствения процес също изисква около една трета по-малко енергия от изпаряването на етанол, въпреки че има точка на кипене с около 14 °C по-висока, при 92 °C, в сравнение със 78 °C за етанола.

Способността за ефективно и бързо производство на диметилфуран от фруктоза, открита в плодовете и някои кореноплодни зеленчуци, или от глюкоза, която може да бъде получена от нишесте и целулоза - всички широко достъпни в природата - добавя към привлекателността на диметилфурана.




**Фиг.3.** Изменение на налягането в цилиндъра и топлоотделянето при различна концентрация на диметилфуран в горивото [9]

Наблюдава се, че пиковата скорост на отделяне на топлина се увеличава и се проявява по-далеч от горна мъртва точка, както при 10%, така и при 70% натоварване на двигателя, с увеличаване на масовата фракция на диметилфурана. Тези резултати показват забавено начало на горенето и значително удължено забавяне на запалването, което води до повече изгаряне на гориво в предварително смесената фаза, което води до по-висока пикова скорост на отделяне на топлина.

Използването на алтернативни горива в ДВГ за хибридно задвижване оказва съществено влияние върху основните експлоатационни показатели – мощност, икономичност и токсичност на отработилите газове. Високото октаново число на алкохолите позволява повишаване на степента на сгъстяване, което води до увеличаване на ефективната мощност и подобряване на термичния КПД на двигателя. От друга страна, по-ниската калоричност на алкохолните горива води до повишен специфичен разход на гориво, но този недостатък се компенсира в значителна степен при работа в хибриден режим, където ДВГ функционира при оптимални натоварвания.

От екологична гледна точка използването на алтернативни горива води до значително намаляване на емисиите на въглероден оксид, неизгорели въглеводороди и твърди частици. Основен токсичен компонент в отработилите газове на ДВГ са азотните окиси, които притежават силно изразено канцерогенно действие и са строго регламентирани от екологичните норми EURO 6d-temp. При работа с алкохолни горива в определени режими се наблюдава увеличение на NOx, което налага прилагането на ефективни системи за рециркулация на отработилите газове, селективна каталитична редукция и съвременни каталитични неутрализатори.

Производството на алтернативни горива от възобновяеми източници оказва положително въздействие и върху въглеродния баланс, тъй като при отглеждането на суровините за биогорива се поглъща значително количество въглероден диоксид. По този начин се формира частично затворен въглероден цикъл, който допринася за ограничаване на парниковия ефект. От икономическа гледна точка развитието на биогоривата създава предпоставки за енергийна независимост, диверсификация на енергийните източници и устойчиво развитие на селските райони.

Съществено предимство на алтернативните горива е възможността за тяхното използване в съществуващия автомобилен парк с относително малки конструктивни изменения на горивната система и системата за управление на двигателя. Това прави прилагането им икономически по-изгодно в сравнение с пълната подмяна на силовите установки. В условията на хибридно задвижване тези предимства се проявяват още по-

ясно, тъй като режимите на работа на ДВГ са по-стабилни и лесно подлежащи на оптимизация.

**3. Заключение**

Използването на алтернативни горива в двигатели с вътрешно горене за хибридно задвижване представлява ефективно решение за намаляване на вредните емисии и подобряване на енергийната ефективност на транспортните средства. Алкохолните и синтетичните биогорива притежават благоприятни експлоатационни и екологични характеристики, които ги правят реална алтернатива на традиционните горива. При съчетаването им с хибридни системи техните недостатъци се компенсират в значителна степен, което определя алтернативните горива като важен фактор за устойчивото развитие на автомобилния транспорт.

Научните изследвания, резултатите от които са представени в настоящата публикация, са извършени по проект в рамките на присъщата на ТУ-Варна научноизследователска дейност, финансирана целево от държавния бюджет.

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За контакти:
инж. Павел Чалъков
Технически Университет - Варна
МТФ, Катедра: "Транспортна техника и технологии"
Варна, п.к. 9010, ул. "Студентска" №1

# АЛТЕРНАТИВНИ ГОРИВА ЗА ДВИГАТЕЛИ С ВЪТРЕШНО ГОРЕНЕ

# ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES

**Nikolay Ivanov**

**Abstract.** Increasingly stringent legislative requirements regarding the content of toxic components contained in exhaust gases require the search for an alternative to fossil fuels. One of the alternative fuels that can provide the desired performance and emit minimal amounts of harmful emissions from gasoline engines is alcohol. Experimental studies have been studied in detail, showing changes in performance parameters, emissions such as hydrocarbons (HC), carbon monoxide (CO), carbon dioxide ($CO_2$) and nitrogen oxides (NOx), as well as combustion characteristics when using alcohol fuel in gasoline engines.
**Keywords**: alternative fuel, n-butanol, iso-propanol, internal combustion engine

## 1. Въведение:

Все по-строгите законодателни изисквания предявявани по отношение на съдържанието на токсични компоненти, съдържащи се в отработилите газове, налагат търсене на алтернатива на изкопаемите горива. Едно от алтернативните горива, което може да осигури желаната производителност и да отдели минимални количества вредни емисии от бензиновите двигатели, е алкохолът.

Подробно са изследвани експериментални проучвания, които показват промените в параметрите на производителността, емисиите като въглеводороди (HC), въглероден оксид (CO), въглероден диоксид ($CO_2$) и азотни оксиди (NOx), както и характеристиките на горенето при използване на алкохолно гориво в бензиновите двигатели.

За да бъдат предпочетени алтернативните горива пред конвенционалните, единичната им цена трябва да бъде ниска, да се използват с минимални промени в съществуващото горивно оборудване в превозните средства, да не водят до съществено намаляване на мощността на двигателя и емисиите на токсични компоненти в отработените им газове да са ниски.

Алкохолите, използвани като алтернативно гориво в бензиновите двигатели, са метанол, етанол, пропанол и бутанол. Предимството им се състои в това, че не се получават от суров петрол, а се произвеждат от отпадни продукти. Алкохолите имат високо октаново число, което увеличава устойчивостта на горивото срещу самовъзпламеняване. В този случай може да се подобри работата на двигателя чрез повишаване на степента на сгъстяване.

## 2. Изложение:

Химичната формула на алкохолите е $C_nH_{2n+1}OH$. Те се използват широко в хранителната, почистващата, козметичната и бояджийската индустрия, както и директно в двигатели с вътрешно горене или смесени с конвенционалните горива в определени пропорции. Макар че алкохолът и бензинът принадлежат към различни химични класове, химичните им формули са доста сходни. Бензинът е гориво, съставено от множество въглеводородни съединения. Въглеводороди е общото наименование за химични съединения, съставени от въглерод и водород. Алкохолите могат да се разглеждат като въглеводороди, при които един от водородните атоми е заместен от хидроксилна група – водороден атом, свързан с кислороден атом. Най-често използваните алкохолни горива в двигатели с вътрешно горене са метанол ($CH_3OH$), етанол ($C_2H_5OH$), пропанол ($C_3H_7OH$) и бутанол ($C_4H_9OH$). В таблица 1 са представени физикохимичните свойства на бензина и тези алкохоли.

**Таблица 1.** Физикохимични свойства на бензина и алкохолите

| Свойства | Бензин | Метанол | Етанол | Изопро-панол | н-бутанол |
|---|---|---|---|---|---|
| Химична формула | $C_8H_{15}$ | $CH_3OH$ | $C_2H_5OH$ | $C_3H_7OH$ | $C_4H_9OH$ |
| Октаново число по изсл. метод (RON) | 92 | 112 | 108 | 118 | 92 |

| | | | | | |
|---|---|---|---|---|---|
| Октаново число по моторен метод (MON) | 87.2 | 91 | 90 | 99 | 85 |
| Кислородно съдържание, [wt%] | 0 | 50 | 34.8 | 27 | 21.6 |
| Въглеродно съдържание, [wt%] | 86 | 38 | 52.1 | 60 | 65 |
| Водородно съдържание, [wt%] | 14 | 12 | 13.1 | 13 | 13.6 |
| Плътност при 298 K, [kg/m$^3$] | 715÷765 | 798 | 795 | 786 | 813 |
| Спец. топлина на изгаряне на горивото [MJ/kg] | 43.4 | 20.1 | 26.8 | 30 | 33.1 |
| Температура на кипене [$^o$C] | 38÷204 | 65 | 78 | 84 | 118 |
| Скрита топлина на изпарение, [KJ/kg] | 380-500 | 1170 | 904 | 758 | 582 |
| Въздушно отношение (AFR) | 14.7 | 6.43 | 9 | 10 | 11.2 |
| Температура на самовъзпламеняване [$^o$C] | 228-470 | 465 | 420 | 399 | 343 |
| Ламинарна скорост на пламъка [cm/s] | 33÷44 | 48 | 48 | 45 | 48 |
| Спец. топлина на изпарение при 25$^o$C [KJ/kg] | 351 | 1089 | 920 | 757 | 707.9 |
| Точка на възпламеняване, [$^o$C] | -45 | 12 | 17 | 12 | 36 |

Алкохолните горива могат да се използват в бензинови двигатели в чист вид или смесени с бензин. При използването на чист алкохол или смеси с високо съдържание на алкохол е необходимо да се направят определени промени в двигателя и горивната система. Въпреки това смеси с ниско съдържание на алкохол/бензин могат да се използват без модификации на двигателя. Те могат да бъдат смесени с горивата в определени пропорции, обемно или масово, както и да бъдат добавени в пълнителния колектор. Възможно е и съхранението им в два отделни резервоара, като подаването им към двигателя се извършва посредством смесител или се впръскват по отделно директно в цилиндъра. Последните методи изискват отделни системи за съхранение и подаване на горивото, което усложнява и оскъпява конструкцията, а също така прави процеса на управление по-сложен.

Метанол

Химичната формула на метанола е $CH_3OH$. Той е безцветна органична течност при стайна температура и налягане. Метанол може да бъде получен чрез дестилация на изкопаеми горива (като дървесина и въглища), съдържащи метилов алкохол, чрез прилагане на определени дестилационни процеси върху природен газ, или в резултат на синтез на CO и водород в каталитична среда. При използване на метанол като гориво трябва да се вземат необходимите предпазни мерки. Поради високата си летливост, метанолът може лесно да се възпламени на въздух. Метановите пари също могат да бъдат експлозивни в определени условия. Като токсично химично вещество метанолът може да причини трайна слепота или дори смърт при хора. Метанолът образува леснозапалима смес, която може да се комбинира с вода във всякакво съотношение.

Метанолът се разглежда като валидно „зелено гориво“ за двигатели с вътрешно горене благодарение на ниските си емисии и способността му да бъде неутрален по отношение на $CO_2$. При използване на метанол като гориво степента на сгъстяване на двигателя може значително да се увеличи, тъй като той има по-високото октаново число, както и по-високата топлина на изпарение, която увеличава коефициента на напълване.

При използване на метанолови смеси в диапазона 3–15% е необходимо материалите в горивната система, които са в директен контакт с метанола, да бъдат адаптирани. Чистият метанол първоначално е неподходящ за употреба в превозни средства, тъй като ниското му парно налягане предизвиква проблеми при студен старт. Затова към него се добавя 10–15% бензин по обем. За оптимално използване на горивните характеристики на сместа M85 (85% метанол и 15% бензин) са необходими промени в съществуващата конструкция на двигателя. [1]

Етанол

Това е вторият по простота алкохол с химична формула $C_2H_5OH$ – летлива, запалима и безцветна течност. Етанол, произведен от биомаса, може да бъде напълно биоразградим и възобновяем. В голям мащаб индустрията за производство на биоетанол използва най-често захарна тръстика или захарно цвекло, царевица или пшеница. Етанол се произвежда и търговски в целулозно-хартиената индустрия като страничен продукт. Смята се, че лигноцелулозната биомаса ще осигурява значителна част от суровините за производството на биоетанол в средносрочен и дългосрочен план поради ниската си цена и висока достъпност. Смеси от 5% етанол и 95% бензин (E5) и 10% етанол и 90% бензин (E10) се предлагат на пазара в целия свят и обикновено са съвместими със съществуващите бензинови двигатели. Наблюдаваните проблеми са свързани основно със стари превозни средства. Те включват корозия в горивопроводите, подуване и напукване на гумени или пластмасови части в горивната система, както и трудности при студен старт. [2]

Пропанол

Поради опасения относно изчерпването на изкопаемите ресурси са разработени няколко устойчиви начина за производство на този алкохол. Пропанол може да бъде произведен от суровини като биомаса или твърди битови отпадъци. Тези суровини се газифицират до синтезен газ (CO, $H_2$, $CO_2$). Осъществено е и микробиално производство на пропанол от различни видове Клостридиум, чрез трионинов катаболизъм или ферментация на бира от дрожди, но в много малки количества – под 70 mg/L. В природата няма микроорганизми, способни да произвеждат пропанол в големи количества от глюкоза. Затова изследователите се насочват към биосинтетични пътища за индустриално производство на пропанол чрез Ешерихия коли– микроорганизъм, който се поддава по-лесно на манипулация в сравнение с конвенционалните и по-сложни видове Клостридиум.

Алкохолите със същата молекулна формула, но с различна структура на отворената верига, се наричат изомерни алкохоли. Изомерът на пропанола е изопропанол. [3]

Бутанол

Бутанолът е безцветен и запалим алкохол с права верига от четири въглеродни атома. Той може да се смесва с метанол, етанол, етер и други органични разтворители. Бутанолът може да се използва като химически междинен продукт в козметиката, хидравлични течности, формули за почистващи препарати, лекарства, антибиотици, хормони и витамини, бутилакрилат и метакрилат, както и като допълнителен разтворител във фармацевтичното производство.

Бутанолът има 4-въглеродна структура, като въглеродните атоми могат да образуват права или разклонена верига с различни свойства. В зависимост от позицията на ОН-групата и структурата на въглеродната верига съществуват различни изомери (н-бутанол, 2-бутанол, изо-бутанол, трет-бутанол). Макар че свойствата на бутаноловите изомери се различават по октаново число, точка на кипене, вискозитет и др., основните им приложения са сходни в някои аспекти – използват се като разтворители, индустриални почистващи агенти или добавки към бензина. Всички тези изомери на бутанола могат да бъдат произведени по различни методи от изкопаеми горива. Изомерът на бутанола е изо-бутанол.

Производството на н-бутанол е по-ниско от това на етанол, а цената на н-бутанола е по-висока в сравнение с етанола. През последните години обаче са разработени ефективни и икономични технологии за производство на био-бутанол. Така, с увеличаване на производството на н-бутанол, се очаква цената му да стане по-конкурентоспособна. Бутанолът може да бъде произведен от биомаса и да се смесва с бензин или да се използва самостоятелно в бензинови двигатели. [2]

Използването на алтернативни горива като етанол, метанол, изо-бутанол и пропанол, оказва влияние на характеристиките на работа, емисиите на отработени газове

и горивният процес на бензинови двигатели. В литературата са изследвани редица проучвания, при които тези алкохоли се използват в чист вид или като смеси.

Извършено е подробно експериментално изследване на влиянието на смеси от изопропанол и бензин върху работните показатели и емисиите на бензинов двигател с директно впръскване (GDI). Изопропанолът, като кислородсъдържащо гориво с високо октаново число и по-висока енергийна плътност спрямо метанола и етанола, се разглежда като перспективна добавка за намаляване на вредните емисии и зависимостта от изкопаеми горива.

Изследването е проведено върху четирицилиндров бензинов двигател с директно впръскване, работещ при средни натоварвания и обороти от 1400 до 5400 rpm. Използвани са смеси с 0%, 10%, 20%, 30%, 40% и 50% изопропанол по обем. Измерени са основни експлоатационни параметри (спирачна мощност и специфичен разход на гориво), емисии на въглероден оксид (CO), въглероден диоксид ($CO_2$), въглеводороди (HC), азотни оксиди (Nox) и температура на отработилите газове.

Резултатите показват, че с увеличаване на съдържанието на изопропанол в горивото мощността на двигателя нараства, като ефектът е най-изразен при ниски и средни обороти. Това се обяснява с високото кислородно съдържание и голямата латентна топлина на изпарение на изопропанола, които подобряват пълнотата на горенето и охлаждането на заряда. Специфичният разход на гориво намалява с увеличаване на дела на изопропанола, като намалението е значително по-голямо при ниски натоварвания в сравнение с високите.

По отношение на емисиите се установява, че увеличаването на изопропанола води до съществено намаляване на емисиите на въглероден оксид (CO) и въглеводороди (HC) при всички режими на работа. Това се дължи на по-пълното и ефективно горене, осигурено от допълнителния кислород в горивото и по-благоприятното стехиометрично съотношение. За разлика от тях, емисиите на въглероден диоксид ($CO_2$) и азотни оксиди (NOx) нарастват с увеличаване на дела на изопропанола, което е свързано с по-високите температури в горивната камера и по-интензивния процес на горене. Наблюдава се също повишаване на температурата на отработилите газове при по-високи концентрации на изопропанол.

Използването на изопропанол–бензинови смеси до 50% по обемен способ в двигател с директно впръскване без конструктивни промени води до подобрени работни показатели и значително намаляване емисиите на въглеродния оксид (CO) и въглеводороди (HC), но е съпроводено с увеличение на въглеродния диоксид ($CO_2$) и азотните оксиди (NOx) и температурата на изгорелите газове. Резултатите потвърждават потенциала на изопропанола като алтернативно гориво за бензинови двигатели, като същевременно подчертават необходимостта от компромис между ефективност и определени видове емисии. [4]

В изследване на C. Sayin и колектив, се разглежда влиянието на степента на сгъстяване върху емисиите в отработилите газове, работните показатели и горивния процес на бензинов двигател, работещ с бензин, смесен с изо-бутанол в обемни дялове 10%, 30% и 50%. Изпитванията са проведени при три степени на сгъстяване (9:1, 10:1 и 11:1), постоянни обороти 2600 rpm и пълно натоварване. Анализирани са разходът на гориво, термичния КПД, вредните емисии и параметри на горенето като налягане в цилиндъра и скорост на топлоотделяне.

Резултатите показват, че с увеличаване на съдържанието на изо-бутанол в горивната смес при всички степени на сгъстяване се наблюдава увеличение на специфичния разход на гориво, термичния КПД и на емисиите на въглероден диоксид ($CO_2$), докато емисиите на въглеродния оксид (CO) и въглеводородите (HC) намаляват. Оптималните стойности за специфичния разход на гориво, термичния КПД и най-ниските емисии на въглероден оксид (CO) и въглеводороди (HC) са отчетени при по-високи степени на сгъстяване, тъй като горивния процес се подобрява, поради по-високите температури и налягания в края на такта сгъстяване.

Анализът на емисиите показва, че увеличаването на дела на изо-бутанол води до значително намаляване на въглероден оксид (CO) и въглеводородите (HC), което се обяснява с по-високото кислородно съдържание на изо-бутанола и по-пълното изгаряне на горивото. За разлика от тях, емисиите на въглероден диоксид ($CO_2$) нарастват, както с увеличаването на съдържанието на изо-бутанол, така и с повишаването на степента на сгъстяване, което е резултат от по-ефективното окисление по време на горенето.

По отношение на работните показатели е установено, че специфичния разход на гориво нараства с увеличаване на изо-бутанола поради по-ниската му калоричност в сравнение с бензина. Въпреки това, повишаването на степента на сгъстяване компенсира този ефект и води до значително намаляване на специфичния разход, особено при по-високи концентрации на изо-бутанол. Термичния КПД се увеличава както с по-високото съдържание на изо-бутанол, така и с увеличаването на степента на сгъстяване, благодарение на по-високото октаново число, кислородното съдържание и подобреното смесообразуване.

Изследването на горивните характеристики показва, че налягането в цилиндъра и скоростта на топлоотделяне се увеличават с увеличаване на дела на изо-бутанол при всички степени на сгъстяване, като максималните стойности се достигат по-рано в сравнение с чистия бензин. При най-високата степен на сгъстяване са наблюдавани признаци на по-ранно запалване и детонация при някои смеси. Като цяло, резултатите показват, че използването на изо-бутанол в бензинови двигатели, в комбинация с по-висока степен на сгъстяване, води до подобрена ефективност и по-ниски емисии на въглероден оксид (CO) и въглеводороди (HC), но емисиите на въглероден диоксид ($CO_2$) се увеличават. [5]

По време на експериментите проведени при пълно натоварване на едноцилиндров двигател, работещ с чист бензин и със смес бензин–бутанол с 35% обемен дял бутанол, са измерени работни, експлоатационни и емисионни параметри, като е установено, че добавянето на бутанол позволява изпреварване на запалването без поява на детонации, което води до по-висока ефективност на горенето. Двигателят показва подобрени показатели по отношение на мощност, разход на гориво, както и по-ниски емисии на въглероден оксид (CO) и въглеводороди (HC), но значително влошаване на емисиите на азотните оксиди (0).

Използването на бутанол–бензинови смеси изисква оптимизация на запалването и газоразпределението, както и пренастройка на електронния блок за управление на двигателя. [6]

Екип изследва поведението на смеси: н-бутанол–био-етанол–бензин (nBE) и изо-бутанол–био-метанол–бензин (iBM), при проведени изпитвания на едноцилиндров, четиритактов бензинов двигател без конструктивни промени. Използвани са три обемни концентрации на алкохолните компоненти (3%, 7% и 10%), като са анализирани основни работни показатели (въртящ момент, мощност, обемна ефективност, налягане в цилиндъра и температура на изгорелите газове) и емисии на въглероден оксид (CO), въглероден диоксид ($CO_2$) и въглеводороди (HC) при обороти от 2600 до 3400 $min^{-1}$.

Резултатите показват, че и двата вида смеси водят до леко понижение на работните показатели спрямо чистия бензин, когато двигателят не е пренастроен. Въпреки това, повечето параметри остават близки до тези на бензина, а промените в характеристиките са слабо чувствителни към увеличаването на дела на алкохолите от 3% до 10%. Смесите iBM показват малко по-добри работни показатели в сравнение с nBE, като налягането в цилиндъра при iBM дори превишава това при бензина.

По отношение на емисиите, всички горивни смеси водят до значително намаляване на въглеродния оксид (CO) и въглеводородите (HC) спрямо бензина, като най-ниски стойности се постигат при най-високия дял на алкохолите. Максималните емисии на въглеродния оксид (CO) и въглеводородите (HC) се наблюдават при средни обороти (около 3000 $min^{-1}$), а при по-ниски и по-високи обороти те намаляват. Смесите iBM показват по-ниски емисии на въглеродния оксид (CO) и въглеводородите (HC) и по-високи

на въглероден диоксид ($CO_2$) спрямо nBE, което се обяснява с по-пълно горене и по-високото кислородно съдържание.

Двата типа горивни смеси представляват обещаващи алтернативи на конвенционалния бензин. Особено изо-бутанол–био-метанол–бензин смесите се открояват с по-добър баланс между работни показатели и намалени вредни емисии. Резултатите показват, че чрез допълнителна оптимизация на запалването, впръскването и степента на сгъстяване е възможно тези горива да постигнат или дори да надминат характеристиките на бензина, допринасяйки за по-устойчив и екологичен транспорт. [7]

В друго изследване на същия екип се разглежда смесване на два изомера – н-бутанол и изо-бутанол – в комбинация с бензин. Въпреки че в предишни изследвания са се фокусирали основно, върху единични смеси на бутаноли с бензин, настоящото изследване въвежда концепцията за двойни смеси, които комбинират и двата изомера.

Експериментът е проведен с едноцилиндров четиритактов двигател без каталитичен конвертор, като са тествани три различни смеси – niB3 (1,5% н-бутанол + 1,5% изо-бутанол), niB7 (3,5% н-бутанол + 3,5% изо-бутанол) и niB10 (5% н-бутанол + 5% изо-бутанол) – и чист бензин. Двигателят е тестван при обхват от 2600 до 3400 rpm без допълнителни модификации. Измервани са емисиите в отработилите газове, мощност, въртящият момент, налягане и температура.

Резултатите показват, че двойните смеси водят до по-нисък коефициент на напълване при ниски концентрации (niB3 и niB7) поради по-ниското налягане на наситените пари на бутанолите. При по-висока концентрация (niB10) обаче коефициента на напълване се увеличава, тъй като високата топлина на изпарение на бутанолите подобрява охлаждането на въздуха и увеличава ефективността на сместа. Мощността и въртящият момент на двигателя леко намаляват при ниски концентрации, но при niB10 се наблюдава увеличение поради по-високата обемна ефективност и налягането в цилиндъра.

Емисиите на въглероден оксид (CO) и въглеводороди (HC) намаляват значително с нарастване на концентрацията на бутаноли, като най-голямо намаление се наблюдава при niB10. Емисиите на въглеродния диоксид ($CO_2$) също са по-ниски в сравнение с тези при чист бензин, но при niB10 се наблюдава леко увеличение, което се дължи на по-пълното изгаряне на горивото благодарение на по-високото съдържание на кислород. Сравнението с единичните смеси показва, че двойните смеси осигуряват по-ниски емисии и по-добра производителност при концентрации ≥10%, докато при ниски концентрации (3–7%) резултатите са по-лоши.

Авторите отбелязват, че двойните смеси имат по-висока ламинарна скорост на горене и по-малка продължителност на горене, което води до по-пълно изгаряне и по-ниски емисии. Те могат да се използват без модификации на двигателя при 10% концентрация или повече и имат по-високо октаново число, по-ниска корозивност и са по-безопасни в сравнение с етанола и метанола.

Смесите н-бутанол, изо-бутанол и бензин представляват алтернативно гориво, което може да намали емисиите на въглеродния оксид (CO), въглеродния диоксид ($CO_2$) и въглеводородите (HC), като същевременно запази и дори подобри производителността на двигателя при високи концентрации. Те се очертават като перспективна опция за използване в съществуващи двигатели с минимални конструктивни промени и биха могли да играят значителна роля в намаляването на зависимостта от изкопаеми горива и в ограничаването на глобалното затопляне. [8]

В Таблица 2 е показано влиянието на добавените алкохоли, към конвенционалното гориво, върху мощностно-икономическите показатели на двигателите с принудително възпламеняване и компонентите на отделяните от тях емисии в околната среда.

**Таблица 2.** Влияние на алкохолите, върху показателите и емисиите на двигателите

| източник | гориво | мощност | спец. разход | CO | $CO_2$ | HC | NOx | T о.г. |
|---|---|---|---|---|---|---|---|---|
| [4] | изопропанол - бензин | ↗ | ↗ | ↙ | ↗ | ↙ | ↗ | ↗ |
| [5] | изобутанол - бензин | x | ↗ | ↙ | ↗ | ↙ | x | x |
| [6] | бутанол - бензин | ↗ | ↙ | ↙ | x | ↙ | ↗ | x |
| [7] | н-бутанол - био-етанол - бензин, изо-бутанол - био-метанол - бензин | ↙ | x | ↙ | ↙ | ↙ | x | x |
| [8] | н-бутанол - изо-бутанол - бензин | ↙ | x | ↙ | ↙ | ↙ | x | x |

## 3. Заключение:

Добавянето на биоалкохоли като метанол, етанол, н-бутанол и изо-бутанол в бензиновите смеси се оказва ефективен подход за подобряване на екологичните показатели на двигателите с вътрешно горене. Малки до умерени концентрации на тези алкохоли водят до значително намаляване на емисиите на въглероден оксид (CO), въглероден диоксид ($CO_2$) и въглеводороди (HC), като същевременно подобряват горивната ефективност. Високите концентрации на единични алкохоли могат да доведат до леко намаляване на мощността и увеличаване на разхода на гориво, докато комбинираните смеси (например н-бутанол с изо-бутанол) демонстрират синергичен ефект, като осигуряват по-пълно изгаряне, по-висока скорост на горене и по-кратко време на запалване. Особено ефективни са смеси с около 10% съдържание на алкохоли, при които се постига баланс между подобрена производителност и намалени емисии, без необходимост от значителни модификации на двигателя. Също така, тези биоалкохоли имат по-високо октаново число, по-ниска корозивност и по-ниска летливост в сравнение с етанола и метанола, което ги прави безопасни и практически приложими като добавки или заместители на част от бензина в съществуващите транспортни системи. Като цяло, използването на биоалкохоли представлява обещаваща стратегия за намаляване на вредните емисии и постигане на по-устойчиви алтернативни горива за транспорта.

Научните изследвания, резултатите от които са представени в настоящата публикация, са извършени по проект в рамките на присъщата на ТУ-Варна научноизследователска дейност, финансирана целево от държавния бюджет.

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За контакти: ас. инж. Николай Иванов, Технически университет – Варна, МТФ, Катедра: „Транспортна техника и технологии“, гр. Варна, ул. „Студентска“ №1, e-mail: Nikolay.Ivanov@tu-varna.bg

# ВЛИЯНИЕ НА ДИЗЕЛОВО ГОРИВО BLUE DIESEL ВЪРХУ ХИДРАВЛИЧНИТЕ ХАРАКТЕРИСТИКИ НА ЕЛЕМЕНТИТЕ ОТ ГОРИВНА СИСТЕМА COMMON RAIL

# INFLUENCE OF DIESEL FUEL BLUE DIESEL ON HYDRAULIC CHARACTERISTICS OF COMMON RAIL FUEL SYSTEM ELEMENTS

**Sergej Belchev, Pavel Uzuntonev**

**Abstract:** The scientific article examines and analyzes the influence of Blue diesel R33 diesel fuel with reduced CO2 emissions on the operation of a Common Rail fuel system. As a result of the different physicochemical properties of the new type of fuel, doubts about a possible influence on the individual portions of fuel forming the dynamically changing differential law of fuel supply have been verified and rejected. The tests of specific nozzles with standard fuel and Blue diesel R33 have been carried out on a modern bench with high accuracy and good repeatability of the reported results.

**Keywords:** blue diesel R33, HV100 diesel, carbon neutrality, common rail injector

## 1. Въведение:

Приетото и силно оспорвано в момента решение за спиране на продажбите на нови автомобили, задвижвани с двигатели с вътрешно горене (ДВГ) в рамките на ЕС след 2035 г. предизвиква редица дискусии относно това до каква степен електрическите автомобили, явяващи се алтернативата на конвенционалните автомобили, задвижвани с ДВГ са „екологични“? Редица изследвания показват, че количеството на отделяния в атмосферата $CO_2$ в етапа на производство на батерията е еквивалентно на отделения $CO_2$ при изминаването на над 150 000 км. Освен това няма нормативна база и яснота относно съхраняването и утилизацията на излезлите от употреба акумулаторни батерии.

Приетото законодателство използва изрази като „въглеродно неутрални“ или „автомобили с нулеви емисии на $CO_2$ “. Това автоматично насочва вниманието към автомобилите, задвижвани с ДВГ, тъй като $CO_2$ като типичен продукт на пълното горене означава, че ако този компонент отсъства в състава на отработилите газове, то всъщност няма работен процес в цилиндъра на двигателя, т.е. няма двигател с вътрешно горене.

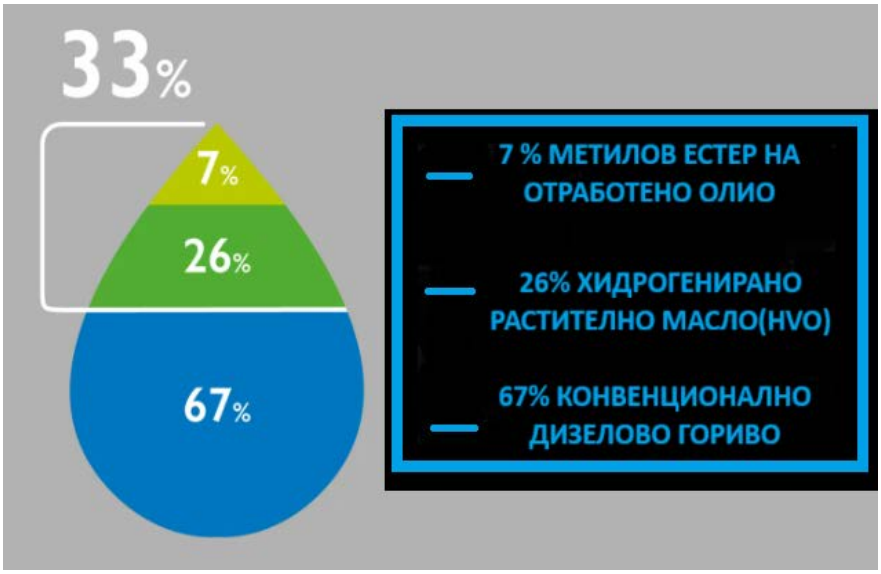
По-внимателното вникване в смисъла на използваните понятия дава възможност за тяхното тълкование. Използването на алтернативни горива, които при своето производство абсорбират $CO_2$ от атмосферата и го използват като изходна суровина при производството на синтетично гориво е реалистичен и перспективен начин за решаване на проблема с въглеродната неутралност. Разбира се при реализирането на работен процес в ДВГ се отделя съответното количество $CO_2$ ,но ако се постигне равенство на абсорбираното и отделеното количества на този продукт, това означавана на практика, че е постигната въглеродна неутралност. Решаването на проблема с емисиите на $CO_2$ отделяни от транспортните средства с помощта на използването на нов тип горива е от съществено значение за развитието на транспортния сектор и производството на автомобили в рамките на ЕС. Този подход ще запази технологичното предимство, изграждано в продължени е на десетки години което имат традиционните европейски производители на автомобили с ДВГ пред азиатските нови автомобилни гиганти, мощно спонсорирани от своите правителства. Използването на нов тип горива освен всичко друго ще запази вече съществуващата инфраструктура на зарядни станции за течни горива, създадена и съществуваща от години.

Освен предимствата от използването на нови горива възникват и допълнителни въпроси като този как ще бъде добивана електрическата енергия, необходима за реализирането на процеса на тяхното производство. Ако за това се използват изкопаеми горива или енергия от ТЕЦ това не компрометира ли идеята за въглеродна неутралност?

Основният проблем който е и обект на настоящата публикация е какво ще бъде поведението на серийно вградената горивна система при работата и с друг вид гориво, за което тя не е била предназначена при първоначалното вграждане в автомобила.

## 2. Изложение:

Обект на конкретните изследвания, представени в настоящата разработка е специален тип гориво което се намира в мрежата от бензиностанции на редица страни от ЕС. Търговското му наименование е Blue Diesei R33. Blue Diesel се състои от 33 процента биогенни суровини, като останалата част е висококачествено дизелово гориво, добито от изкопаеми петролни продукти.




**Фиг. 1.** Структура на горивото Blue Diesel R33

Това процентно съотношение на съставните компоненти дава търговското наименование на предлагания продукт.

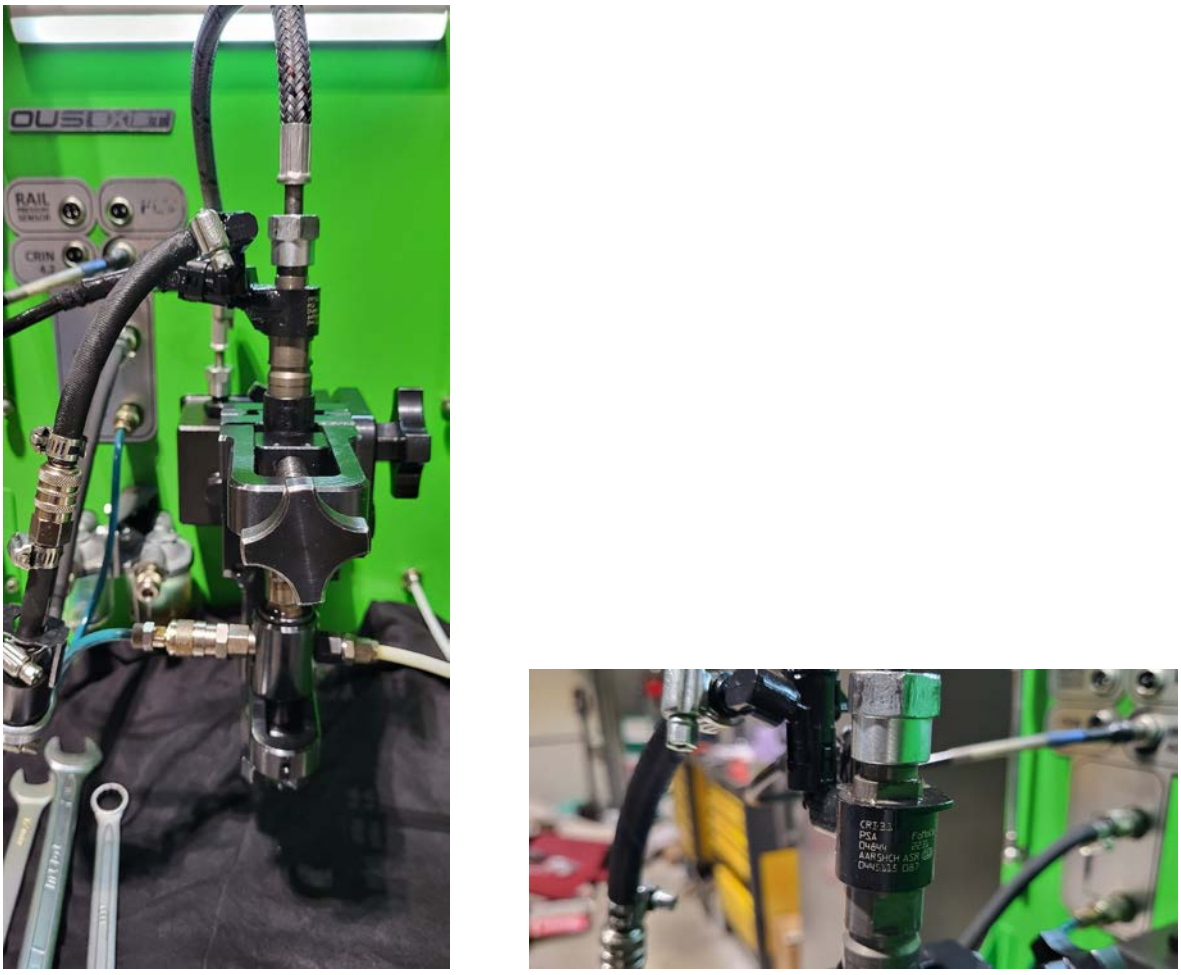
Новият тип гориво гарантира намаляване на емисиите на $CO_2$ до 20% . Този ефект се постига благодарение на състава му, който както вече беше уточнено е 67% извлечен от изкопаеми горива и 33% от рециклирани материали. Тези рециклирани материали са 26% хидрогенирано растително масло (HVO), получено от парафини, извлечени от отпадъчни материали и 7% метилов естер на използвано олио за готвене, което може да се рециклира за тази употреба и по този начин да се предотврати замърсяването на околната среда. По този начин новият тип дизелово гориво Blue Diesel R33 има две много добри характеристики: рециклира материали, които са силно замърсяващи и които при други обстоятелства биха попаднали в сметищата и същевременно постига значително намаляване на замърсяващия ефект на отработилите газове, отделяни от дизеловите автомобили. Остава отворен въпроса дали горивото Blue Diesel R33 може да се използва във всички горивни системи.

Същевременно трябва да се отбележи, че горивото Blue Diesel R33 според производителите напълно отговаря на действащия стандарт DIN EN 590. Това автоматично означава, че безпроблемно може да се използва във вече намиращите се в експлоатация дизелови автомобили. Това е вярно що се отнася до неговия химичен

състав. Съществува обаче опасение, че неговите хидравлични характеристики могат да повлияят на впръскваните количества гориво особено при реализирането на малки порции гориво от 1 до 4 мм$^3$. Това са типични порции при реализирането на предварително впръскване или последващи впръсквания след основното за доизгаряне на финитe прахови частици или късно последващо впръскване за рециклирана DPF филтъра. Това са режими на празен ход или малки до средни натоварвания, които до голяма степен формират изпитвателния цикъл за установяване на принадлежността към съответни евростандарт.

За установяването на толкова малки разлики в количествата впръснато горива е необходимо използването на прецизен изпитвателен стенд. За тази цел са проведени редица безмоторни изпитвания за различни видове дюзи, както и на различни производители на специализиран стенд за изпитване на дюзи от системата Common Rail OUS EXIST+. Изпитвателният стенд е запълнен последователно със стандартно дизелово гориво, със 7% биосъставка, закупено от стандартна бензиностанция в България и след това с гориво Blue Diesel R33, закупено от Германия. За да се гарантират еднаквите условия на експеримента по време на изпитанията стендът OUS EXIST+ автоматично поддържа температура от 40$^0$ C.

На фиг.2 е показана експерименталната установка на която е монтирана пиезо електрична дюза Bosch 0 445 115 087, използвана в автомобил Peugeot 508 , Citroen, Ford, Jaguar, доколкото всички те работят с един и същ двигател. Целта в случая е да се изследва поведението не на конкретната дюза, а на конкретния тип прецизен впръскващ елемент.

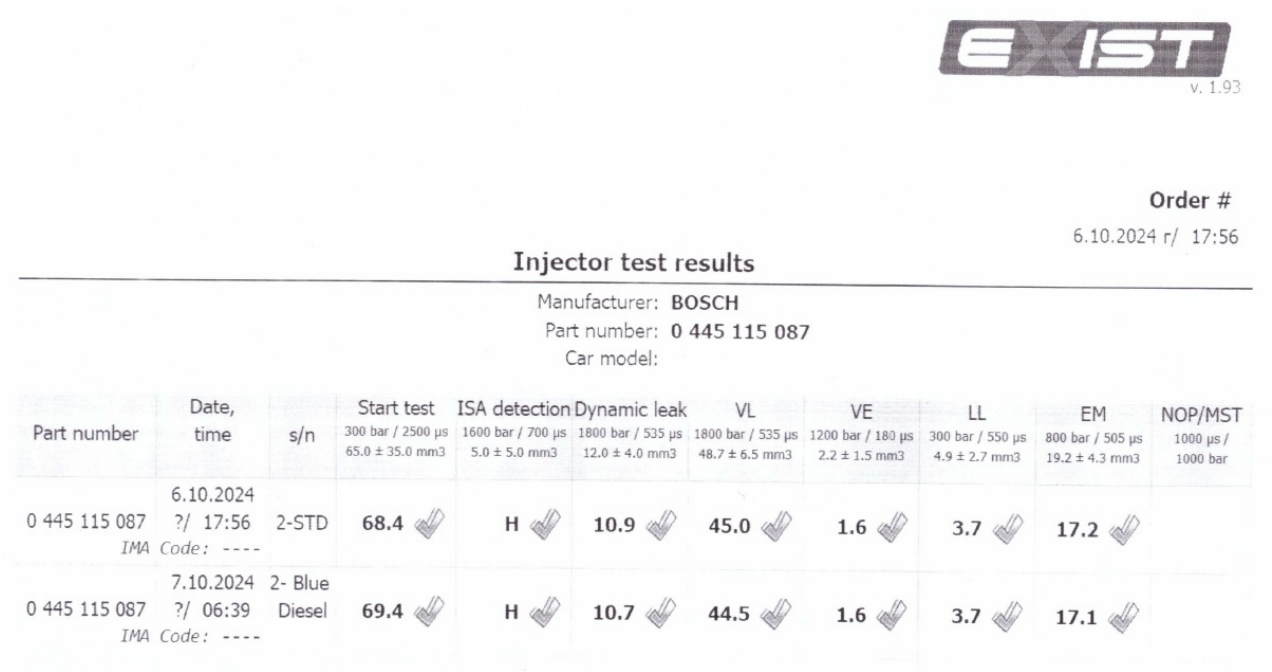


**Фиг. 2.** Експериментална установка (стенд за изпитване на дюзи от системата Common Rail)

С цел гарантиране на достоверността на представените резултати е направено няколкократно изпитание за всяка дюза при работа със стандартно гориво и новия продукт Blue Diesei R33. Получените резултати под формата на циклово количество гориво за отделните режими от плана за изпитване на дюзата са разгледани като случайна величина. Пресметнато е математическото очакване и дисперсията на отделните измервания при шесткратно повторение на експеримента. Оценена е еднородността на дисперсиите по метода на Фишер и по този начин е доказана точността на и повторяемостта на експерименталните изследвания.

В конкретния случай като обект на изпитанията е използвана пиезо електрична дюза, която е с ускорено бързодействие и се използва за широка гама автомобили на възраст, съответстваща на средната възраст на автомобилния парк в РБългария. Това дава възможност получените резултати да се мултиплицират върху по-голяма гама дюзи от същия вид и съответния експлоатационен период.

На фиг.3 е представена разпечатка на протокол от изпитанията на дюзата, съгласно плана, заложен в базата данни на изпитвателния стенд. В случая са взети пред вид типични експлоатационни режими като: работа на двигателя на празен ход (LL), предварителна порция впръснато гориво (VE), работа при пълно натоварване (VL), работа при максимален въртящ момент, която съвпада с максималната емисия на токсични компоненти (EM) и количеството на излишното гориво, съответно без подаване на управляващ импулс и в динамичен режим на работа (Start test и Dynamic leak).



EXIST v. 1.93

Order #

6.10.2024 г/ 17:56

**Injector test results**

Manufacturer: **BOSCH**

Part number: **0 445 115 087**

Car model:

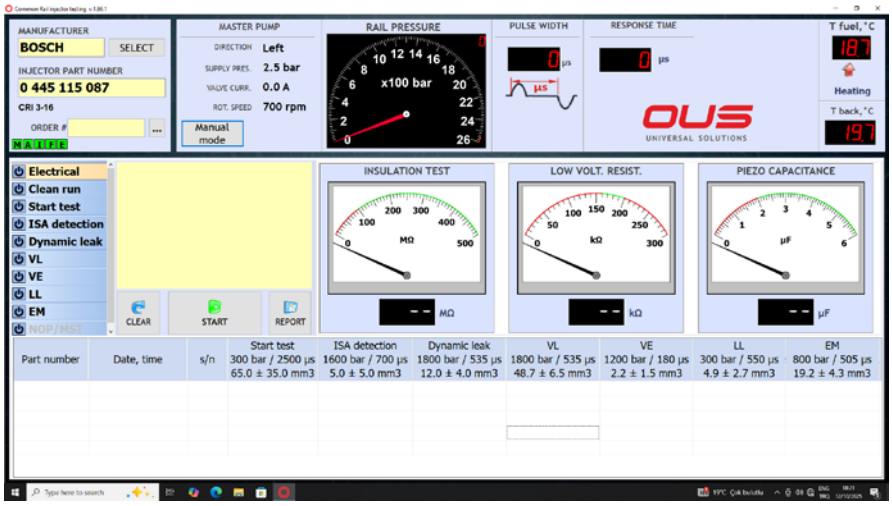
| Part number | Date, time | s/n | Start test 300 bar / 2500 µs 65.0 ± 35.0 mm3 | ISA detection 1600 bar / 700 µs 5.0 ± 5.0 mm3 | Dynamic leak 1800 bar / 535 µs 12.0 ± 4.0 mm3 | VL 1800 bar / 535 µs 48.7 ± 6.5 mm3 | VE 1200 bar / 180 µs 2.2 ± 1.5 mm3 | LL 300 bar / 550 µs 4.9 ± 2.7 mm3 | EM 800 bar / 505 µs 19.2 ± 4.3 mm3 | NOP/MST 1000 µs / 1000 bar |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 445 115 087 | 6.10.2024 ?/ 17:56 | 2-STD | 68.4 | H | 10.9 | 45.0 | 1.6 | 3.7 | 17.2 | |
| | IMA Code: ---- | | | | | | | | | |
| 0 445 115 087 | 7.10.2024 ?/ 06:39 | 2- Blue Diesel | 69.4 | H | 10.7 | 44.5 | 1.6 | 3.7 | 17.1 | |
| | IMA Code: ---- | | | | | | | | | |

**Фиг. 3.** Протокол от проведените изпитания на пиезо електрична дюзи о 445 115 087 при работа със стандартно гориво и Blue Diesel R33

Освен дебита на впръскваното количество гориво, допълнително е измерено времето за реакция на дюзата (response time). Това е промеждутъка от време от момента на подаване на управляващ импулс към дюзата до действителното начало на впръскване на горивото. Измерването на този важен параметър на горивоподаване е възможен благодарение на вграден пиезоелектричен датчик във впръскващата камера на изпитвателния стенд. Той е от голямо значение за поведението на горивната система при

работа с алтернативни горива, защото е възможно благодарение на различните физико-химични свойства на използваните горива да се получават близки циклови порции, но да се получи дефазиране на отделните впръсквания в рамките на един и същ диференциален закон на подаване на горивото. Подобни отклонения могат да окажат косвено влияние върху екологичните характеристики на отработилите газове, отделяни от автомобила. В конкретния случай времето за реакция е между 345μs и 351 μs. То е в рамките на статистическата грешка и по време на измерването не бяха констатиране тенденция в промените на този параметър за различните опити. Разликите са единствено резултат на случайния характер на проявление на измерваната непрекъсната случайна величина.

Преди провеждането на същинските изпитания са направени предварителни електрически измервания на дюзата, обект на настоящите изследвания. Това се извършва автоматично и е една от функциите на изпитвателния стенд. На фиг.4 е представен момента преди извършването на измерванията.




**Фиг. 4.** Извършване на първоначални електрически измервания на експерименталната дюза

Обект на анализ са тест за изолация на електрическата част спрямо корпуса на дюзата, ниско волтово съпротивление и капацитет в управляващия пиезо блок на изпиваната дюза. Промени в тези параметри особено в зависимост от температурното състояние могат да доведат до въздействие върху характеристиките на горивоподаване съизмерими с разликите от използването на различни горива. В конкретния случай не са установени отклонения в електрическите показания при измерванията. Това доказва верността на резултатите и изключва въздействието върху тях на странични фактори.

## 3. Изводи:

От направения анализ и проведените практически изпитвания могат да бъдат направени следните изводи:

3.1 Използването на алтернативното гориво Blue Diesel R33 в горивни системи на водещи световни производители и използвани в съвременните дизелови автомобили не оказва влияние върху диференциалната характеристика на горивоподаване, особено що се отнася до впръскването на по-малките порции гориво, формиращи до голяма степен екологичните характеристики на автомобила.

3.2 Новият тип гориво Blue Diesel R33 спомага за намаляване на негативното влияние на отработилите газове върху природата и намалява тяхното влияние върху климатичните промени. То е стъпка към постигането на въглеродна неутралVladimir Marност без радикални промени в конструкцията на автомобилите и инфраструктурата на тяхното зареждане.

3.3 Необходимо е да се направят надеждностни изпитания за установяване влиянието на новия тип гориво върху елементите на горивната система след продължителна експлоатация и в горивни системи на аварийно включващи се след продължителен престой дизел-генератори.

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# ДОСТИГАНЕ НА ВЪГЛЕРОДНА НЕУТРАЛНОСТ ПРИ РАБОТА НА ДИЗЕЛОВ ДВИГАТЕЛ С ГОРИВО HVO100

# ACHIEVING CARBON NEUTRALITY WHEN OPERATING A DIESEL ENGINE WITH HVO100 FUEL

**Pavel Uzuntonev**

**Abstract:** The scientific article examines and analyzes the influence of Blue diesel R33 diesel fuel with reduced CO2 emissions on the operation of a Common Rail fuel system. As a result of the different physicochemical properties of the new type of fuel, doubts about a possible influence on the individual portions of fuel forming the dynamically changing differential law of fuel supply have been verified and rejected. The tests of specific nozzles with standard fuel and Blue diesel R33 have been carried out on a modern bench with high accuracy and good repeatability of the reported results.

**Keywords:** blue diesel R33, HV100 diesel, carbon neutrality, common rail injector

## 1. Въведение:

Политически даденият краен срок до 2035г. всички продавани автомобили на територията на Европейския съюз да бъдат въглеродно неутрални навежда над мисълта, че става въпрос за спиране на продажбите на нови автомобили, задвижвани с двигатели с вътрешно горене (ДВГ) от този дата. В същото време очевиден факт е, че в света се намират в експлоатация над един милиард автомобили с ДВГ и тяхното преждевременно игнориране е стратегическа грешка. Стремежът към дефосилизация (намаляване на използването на изкопаеми горива) с цел намаляване на отделяния в атмосферата въглероден двуокис ($CO_2$) е безсмислено ако производството на електрическа енергия с която се зареждат батериите на електрическите превозни средства е свързано с отделянето на въглерод. По подобен начин стои и въпросът с производството на самите електрически батерии, който процес по мнението на редица изследователи съответства на отделянето на $CO_2$ в атмосферата, аналогичен на пробег от около 150 000 км. за конвенционален автомобил, задвижван с ДВГ. Ако към целия жизнен цикъл на експлоатация на автомобила се прибави и процеса на съхранение и утилизация на излезлите от употреба акумулаторни батерии, екологичната чистота на електрическите превозни средства може да бъде поставена под сериозен въпрос.

В този смисъл търсенето на вариант за захранване на автомобилите, задвижвани с ДВГ с горива, които са получавани от възстановими енергийни източници или разработването на синтетични горива, които трансформират зелен водород и уловен $CO_2$ в газообразно или течно гориво става все по-актуално. Друго важно предимство на този подход е запазване на съществуващата инфраструктура от бензиностанции и времето за зареждане на автомобила. Според доминиращата риторика през последните години относно електрификацията на автомобилния транспорт, най-важният технически параметър на електроавтомобила е пробега с едно зареждане. Това е доста имагинерно понятие защото този параметър е измерен съобразно условията на действащия екостандарт и наподобява повече на лабораторни условия отколкото реалната експлоатация. Значително по-важният фактор е времето за зареждане. Трудно е да си представим предимството на опашка от три, четири автомобила пред единична зарядна станция, чакащи за „бързо“ зареждане от по 30-40 минути.

Всички тези аргументи поставят въпроса за достигане на въглеродна неутралност чрез използването на синтетични горива или такива от растителни или отпадъчни

животински мазнини като алтернатива на бързата и пълна електрификация на автомобилния транспорт, без особена гаранция за екологичност и отсъствие на $CO_2$ през периода на тяхното производство и експлоатация.

В най-напредна етап в тази посока е възможността за масово производството и използване на дизелово гориво HV100 в качеството си на възстановяем енергиен източник.

## 2. Изложение:

Наименованието на този вид гориво **HVO100** (Hydrotreated Vegetable Oil 100) или хидро третирано растително масло 100 произтича от химическия подход за неговото получаване. Химическото получаване на HVO100 се осъществява чрез процес на хидрогениране на растителни масла или животински мазнини. Този процес представлява химична реакция между молекулен водород ($H_2$) и друго съединение или елемент, обикновено в присъствието на катализатор като никел, паладий или платина. Процесът се използва често за редуциране или насищане на органични съединения и обикновено включва добавянето на двойки водородни атоми към дадена молекула.

Хидрогенирането се използва широко за получаване на органични вещества както в лабораторни условия, така и в промишлен мащаб.

Този процес води до получаване на биогориво с характеристики на традиционно дизелово гориво, получавано от преработката на суров петрол. В процеса на неговата преработка се отстранява кислорода от органичните мазнини и същите се преобразуват в парафинови въглеводороди. Това води до голяма чистота на продукта, който може да се използва в дизеловите двигатели.

Основните етапи на химичното получаване на HVO 100 са следните:

**Избор на суровини (растителни масла или животински мазнини)**:

- Суровините за производството на HVO 100 могат да бъдат растителни масла (например, рапично, соево, палмово или слънчогледово масло) или животински мазнини.
- Тези мазнини съдържат молекули **триглицериди** — съединения, съставени от една молекула глицерол, свързана с три молекули мастни киселини.

Трифглицеридите са неподходящ компонент в състава на новите алтернативни горива и следва да бъдат редуцирани.

**Хидрогениране на триглицеридите:**

- Триглицеридите (основните съставки в растителните масла) се подлагат на процес на хидрогениране, при който към тях се добавя водород ($H_2$).
- Процесът се извършва в **реактор** при високо налягане (обикновено между 40-150 атм) и висока температура (около 300-400°C), в присъствието на **катализатор** (обикновено никел или платина).

Основната химическа реакция за хидрогениране на триглицериди е:
Триглицерид+3H2→Парафинови въглеводороди+3H2O
При хидрогенирането водородът се комбинира с кислорода, който се намира в състава на триглицеридите (във вид на хидроксилни и карбоксилни групи), и го премахва. Това води до образуването на **парафинови въглеводороди** — молекули, които имат по-чиста и стабилна структура и са близки до тези в традиционното дизелово гориво.

**Отстраняване на кислород**:

- В процеса на хидрогениране кислородът, който присъства в растителните масла (във вид на -OH групи и карбоксилни групи), се отстранява чрез химична реакция с водорода.
- Тази стъпка е ключова, тъй като тя премахва възможността за образуване на сажди и други вредни емисии при изгарянето на горивото.

**Преработка на продукта (рафиниране и отделяне на примеси)**:

- След хидрогенирането се получава смес от **парафинови въглеводороди** с различни молекулни размери.
- За да се постигне качествено гориво, преминава през допълнителни етапи на пречистване. Това включва **филтриране**, **дестилация** и други методи за премахване на неразтворени примеси, както и коригиране на вискозитета на горивото.

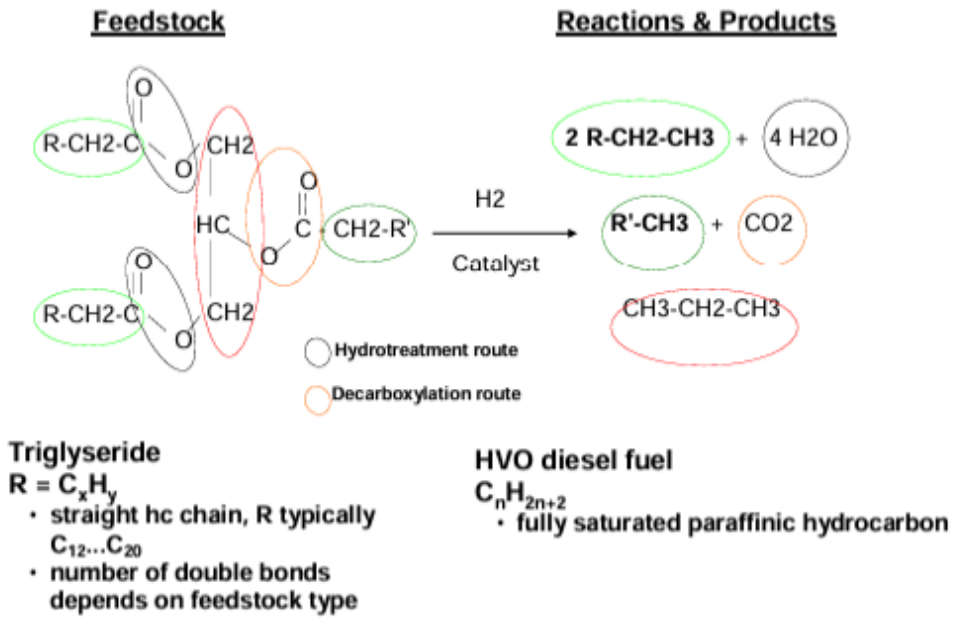
**Подобряване на характеристиките на горивото**:

- Продуктът се стабилизира и се обработва, за да отговори на изискванията за дизелово гориво. Това включва регулиране на:
  - Температура на замръзване,
  - Вискозитет,
  - Състав на въглеродните молекули и други важни параметри.
- HVO 100 се характеризира с много ниски нива на сяра, азот и сажди в сравнение с традиционното дизелово гориво.

След преработката дизеловото гориво HV100 преминава през редица тестове, които да докажат неговата съвместимост със стандартите за дизелови горива ASTM D975 и EN 15940.

На фиг.1 са представени в схематичен план процесът на химическа преработка на изходната суровина до получаването на изходния продукт-дизелово гориво, годно за употреба в дизелови двигатели и отговарящо на изискването за произход от възстановяем енергиен източник.

Същността на подхода за намален въглероден отпечатък върху околната среда или пълна въглеродна неутралност се заключава в използването на растителни масла или отпадъчни мазнини при получаването на нови горива. При този процес, произходът на тези горива може да се приеме, че е от възобновяеми енергийни източници. Смисълът на това твърдение се заключава във факта, че при получаването на изходната суровина (от растителен произход) растенията абсорбират от въздуха необходимото им количество $CO_2$ за осъществяване процеса на фотосинтеза. В случая $CO_2$ се явява „храна“ за растенията.




**Фиг.1.** Процес на преработка (хидрогениране) на изходната суровина с цел подобряване качеството на получения продукт

При използването на горива, получени по този начин, по подобие на изкопаемите горива в цилиндъра на двигателя с вътрешно горене се реализира работен процес. При това неминуемо се отделя $CO_2$ като продукт на пълното горене. Ако се осъществи равенство между абсорбираното количество $CO_2$ по време на получаване на изходната суровина и отделеното количество от този продукт при работата на двигателя, това означава, че е постигната въглеродна неутралност.

На дневен ред остават въпросите за необходимите количества суровина за задоволяване на нуждите на транспорта , цената на това гориво и неговото автоматично приложение във вече съществуващите автомобили с дизелови двигатели. Не на последно място стои и въпросът за морала на действие, свързано с използването на хранителен продукт (при добиването на HVO 100 от слънчогледово масло) в условията на съществуващ глад в редица страни от третия свят и Африка.

Отговорът на тези въпроси е широката възможност за получаването на изходните масла от технически култури като рапица, соя, палмово масло и др. Количествата не са проблем, тъй като и в момента рафинериите не работят с пълния си капацитет и често в обществото стои проблемът за евтин внос на суровини от трети страни.

Освен всичко друго за производството на HVO 100 е необходим водород. Досега обаче водородът в Европа все още се произвежда предимно от изкопаеми горива и това едва ли ще се промени скоро. Проучване на консултантската компания PwC сочи, че Германия и Европейският съюз вероятно няма да успеят да постигнат собствените си цели за "зелен водород" от възобновяеми енергийни източници. А това от своя страна поставя под съмнение твърденията за високата екосъобразност на горивото HVO100. Но подобни дори не съмнения са валидни и за „чистотата“ на електрическата енергия използвана в автомобилите с електрическо задвижване.

На фиг.2 е показано сравнение на три вида дизелови горива. Две от тях, а



**Фиг.2.** Сравнение на вида на три основни дизелови горива

именно дизелово гориво B7(със 7% биосъставка) и дизелово гориво без биосъставка могат да бъдат намерени в търговската мрежа от бензиностанции, докато горивото HVO100 може да бъде закупено за сега само от ограничен брой бензиностанции в различни страни от Европейския съюз. На фиг.3 е показна такава станция в Германия от където е закупена показаната мостра, предназначена за последващи стендови изпитания на дюзи.




**Фиг.3.** Гориво HVO100 в търговската мрежа в страните от ЕС

## 3. Изводи:

В резултат от направения анализ относно възможността за използване на новия тип дизелово гориво HV100, могат да бъдат направени следните изводи:

3.1 Използването на алтернативното гориво HVO 100 в качеството му на „въглеродно неутрално“ ще запази технологичното предимство, изграждано в продължение на десетки години от страна на традиционните европейски производители на автомобили с ДВГ пред новите азиатските автомобилни гиганти, мощно спонсорирани от своите правителства.

3.2 Използването на нов тип горива освен всичко друго ще запази вече съществуващата инфраструктура на зарядни станции за течни горива, създадена и съществуваща от години.

3.3 Разградимостта на новия вид гориво HVO 100 в почвата и водата е 3 месеца с пълно усвояване от бактериите на околната среда.

3.4 Няма вреда за животните, почвата, растенията, водните басейни и хората.

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