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Systematic integrated approach to quantifying preventive diagnostics in a “smart” transport system

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Abstract

One of the main tasks facing all European countries for the next few years is the creation of the most dynamically organized transport sector. The constant passenger and freight traffic lead to congestions and pollutions at the transport highways, having negative impact on a person. Thus, introduction of new technologies, addressing the interrelated problems of optimizing transport flows and improving the environmental footprint of transport, is an overriding priority. In this respect, approaches that allow analyzing the reliability of a vehicle as an object characteristic, reflecting the ability of a product to operate without sudden changes in its quality in real time, are of considerable interest. This is reflected in the development of preventive diagnostic systems (warning the driver of a possible failure of the systems and the car as a whole). The concept for formation of normative and methodological support for research in the field of reliability of complex systems (including vehicles), which can be adopted as a basis for the development of a database of a preventive diagnostic system, is proposed.

Keywords ITS · Preventive diagnostics · Reliability · System approach

Introduction

One of the main tasks facing the European countries for the next few years is the creation of the most dynamically organized transport sector. The constant growth of passenger and freight traffic leads to congestion and pollution of transport highways and has a negative impact on people. Thus, the delay in freight vehicles only because of the overload of the main roads causes a damage, which is estimated as 1% of the EU’s GDP each year.

So the introduction of new technologies in order to solve the interrelated problems of increasing the efficiency of transportation and improving its environmental footprint is of an overriding priority.

The existing research projects in addressing this issue are mainly focused on the widespread introduction of communication technologies. The work in this direction is primarily aimed at the development and application of intelligent road transport systems (IATS), which are the result of the integration of information and communication technologies

(ICT) in transport infrastructures and vehicles. The usage of electronic communication technologies in the transport sector is actively expanding. According to various estimates, the costs of automating driving processes increase by 8–10% each year. Independent estimates show that dynamic traffic information and navigation services (in percentages) for all road vehicles will increase from 1.5% in 2005 (about 9% in 2010) to 43% in 2020 (European Commission 2009).

The main technological components of the IATS are:

- various forms of wireless communication (UHF, VHF, WiMAX, GSM, etc.);
- computing technologies—they are developed taking into account the current tendency to reduce the number and cost of microprocessors, which allows us to develop more complex competitive applications, for example, based on the process control model and artificial intelligence;
- sensor technologies—they are based on the usage of sensor data for primary information for various vehicle monitoring systems (radar, camera of various types, etc.) (Honda 2017 and Volvo 2017) and infrastructure data (from similar devices—both inductive sensors and pressure sensors, installed or built in or near the road).

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However, the main problem is that all these components and methodologies are not integrated and, therefore, can not provide information to the user in real time. A centralized database for an “intelligent” large-scale traffic management system is too slow to provide real-time results. In addition, GPS navigators (TomTom, Garmin) have basically unidirectional communication channels. Vehicles that are equipped with vehicle data transfer technologies in the transport stream are rare, and they cannot provide a central communications station database on a sufficient scale. In this case, it is easy to predict a situation in which the traffic intensity will increase to a level where any barrier on the way (e.g., a small damage or failure of the vehicle) can cause large traffic jams. All this will lead to losses of time and money, reduce the efficiency of cargo transportation and worsen the ecological situation. The latter is especially important for large cities, since in the places of traffic jams the concentration of exhaust gases increases several times.

The solution for ensuring of the continuity of the traffic flows can be implemented in a communication system with a high-quality and reliable warning of the driver both about the technical state of his car, and driving conditions, other cars and other road users in order to warn the driver about emerging potentially dangerous situations on the road. Obviously, a solution can be obtained through the development of a service platform, including, among other things, a system for helping drivers (monitoring driving conditions—external and technical characteristics of the vehicle) in real time. At the same time, this question, being extremely topical, but very difficult for analysis, has not yet been solved.

That is why increasing the safety of vehicle operation is one of the priority tasks not only for today, but also for the near future (Wallace et al. 2012). Despite the fact that the level of safety of vehicle operation is increasing every day, the issues related to taking into account external conditions (including the human factor), the reliability of the systems of vehicles (subsystems, parts) that affect the occurrence of dangerous situations, have not been completely resolved for yet.

Proposed method

It is difficult to estimate too high the target value of vehicle safety settings, provided only by using modern electronic diagnostic and control tools. So, it is considered that the issue of the nomenclature of sensors used in the car is already quite well developed. In this respect, approaches that allow analyzing the reliability of a vehicle as a characteristic of an object, reflecting the ability of a product to operate without sudden changes in quality in real time, are of considerable interest (McPherson 2013). This is reflected in the development of preventive diagnostic systems (warning

the driver of a possible failure of the systems and the car as a whole).

The development of artificial intelligence systems for a vehicle is based on the creation of an appropriate neural network. The main feature of such networks is the high speed of information processing and decision making. This is why neural networks can be used to process real-time data from the built-in car diagnostics in order to predict its possible failures. The real problems arising from the operation of any machine-building structure are very complex and multifaceted, and sometimes they cannot be laid in the Procrustean bed of highly formalized mathematical models. The usually used expert specification of the requirements for the reliability of parts of complex technical systems, based only on engineering practice and operational experience, is not the simplest, but also the most common approach (Bolotin et al. 1993, 1996; Yankevich 2012).

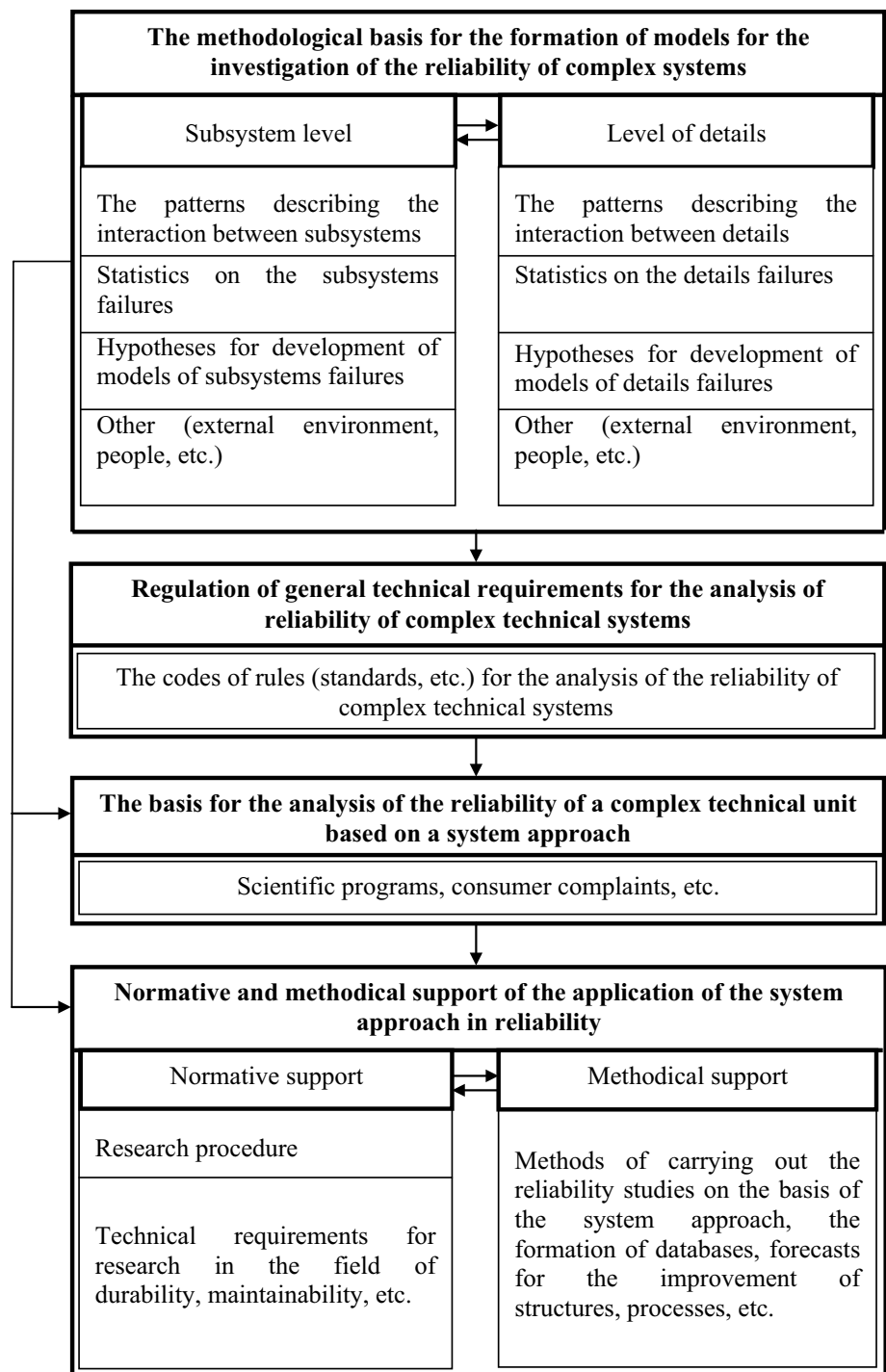
Despite the fact that such an approach has found a wide application in solving a number of issues (Bolotin et al. 1993), the conceptual and normative bases for its usage in the analysis of reliability problems (and, consequently, the creation of a real-time system of preventive diagnostics) have not yet been formulated. At the same time, the existence of clear provisions that determine the validity of certain decisions will significantly improve the effectiveness of the application of the method, not only focusing on the most important aspects, but also fully taking into account the most significant limitations. Figure 1 shows the proposed concept of the formation of regulatory and methodological support for research in the field of reliability of complex systems (including vehicles), which can be taken as a basis for the development of the database of the vehicle’s preventive diagnostic system, which can be an integral part of the IATS.

Increasing requirements for operating conditions, environmental safety and the whole ideology of technical development of transport, combined with the introduction of ICT, lead to the fact that modern vehicles and their components (engines) are transformed into complex integrated systems, a symbiosis of precision mechanics, electronics and computer programs (Wallace et al. 2012).

Therefore, to maintain operational characteristics at the modern level, more and more complicated diagnostic control and the preventive measures (adjustment of systems, cleaning and restoration of the surfaces of friction pairs, etc.) are applied. However, for the implementation of these measures, the usual functions of self-diagnosis or diagnostics with the help of a traditional instrumental set are, as a rule, insufficient.

It is obvious that the representation of a vehicle as a complex system—a set of interacting subsystems consisting of parts, which interact according to the relevant laws (rules), is justified by the practice of exploitation.

Fig. 1 Concept of forming the normative and methodological support for research in the field of reliability of complex systems



During numerous studies, the common approaches and limitations used in predicting the reliability of vehicles represented as complex technical systems have been established (Bolotin et al. 1993, 1996; Yankevich 2012). The information base of the developed models, as a rule, is formed from the condition of system closure, which means that the behavior and state of the modeled system are caused by the structure of interaction of its component processes. In this

case, the presence of a closed border does not exclude the impact of external factors on it. However, this approach is contrary to practice. As a rule, not only the boundary of a complex system, but also the interaction between structural units (subsystems) is not the deterministic quantities. In this regard, when developing a methodology for analyzing the reliability of a complex system, it seems to be necessary to introduce uncertainty (probabilistic evaluation).

The importance of this becomes obvious if we recall that the explanation of the mechanisms of the behavior of a vehicle, represented as a complex technical system and its states, is primarily related to the need to ascertain by what properties, to what extent and under what conditions this system possesses. It is believed that at the first stage, the structure and properties of the object under study are refined with the help of ensembles of models, various in their organization. This way of concretizing of an abstract system is effective in case of difficulties when clarifying knowledge about the properties of an object by using the details of special structures that represent these properties.

To solve this type of problems, models are usually developed in the form of graphs (failure networks) (Bolotin et al. 1993, 1996). Each branch of such graphs displays the failure states of the individual elements that cause the failure of the vehicle as a whole. In this case, the parameter values are often set on the basis of expert assessments and an analysis of the functioning of the vehicle in question is carried out for them, finding a conditionally optimal value of any of its characteristics (e.g., the number of failures of each subsystem or the vehicle as a whole). The value of this approach is questioned by a number of researchers, since it would be prudent to speak not about a conditionally optimal, but about a compromise solution that, while not being optimal, is still acceptable in the range of solutions. However, the theory of compromises has not yet been sufficiently developed. Therefore, the method of peer review remains the most applicable, despite the fact that it can lead to an unjustified overestimation of the risk assessment and, as a result, unjustified expenses for preventing unlikely failures or failures that do not lead to serious consequences.

There is another approach, consisting in the development of quantitative models supposing a more accurate determination of the average risk as a function of the probability of failure of a vehicle and the severity of its consequences. For each of the failures, a quantitative assessment of the contribution (weight) of failure to the formation of the overall risk can be obtained. The application of such quantitative models is focused on usage of the concept of probability to describe uncertainties of a different nature, including technics.

To construct the probabilistic models and to select their parameters, as a rule, one use the certain a priori information, as well as the results of observations, measurements over a single situation or a single object. On this basis, probabilistic estimates are calculated that relate to a particular situation or to a specific object.

As a methodological basis for computational algorithms constructing of the of preventive diagnostics system, a system approach has been chosen. It was applied, in particular, to the analysis of the reliability of an internal combustion engine, which is a complex multi-level system. Representation of the engine as a complex system allows taking into

account the existing connections between the subsystems that determine the engine's performance. Obviously, the internal combustion engine is a complex system, the development of an appropriate information model of which is possible on the basis of a comprehensive analysis of cause–effect relationships between subsystems, taking into account probabilistic estimates. At the same time, excessive detailing and concretization can only significantly hamper such an analysis and make it almost impossible. Therefore, it can be stated that when modeling such a system it is inappropriate to create one universal model that could reproduce both the operation of the system as a whole and its individual subsystems. When predicting the reliability of an engine as a whole, it is expedient to obtain a set of probability models describing each of these subsystems (Yankevich 2012), as well as a model that determines their interaction.

Development of the model of engine operation can be conducted in two directions, determined by the hierarchical level of consideration of the elements of the system:

- the level of engine systems (fuel supply, gas distribution, start-up, etc.) with further analysis (if necessary) of each of the subsystems in the same manner;
- the level of engine parts (crankshaft, connecting rod, etc.).

In general, the sequence of system analysis and synthesis of the reliability of an internal combustion engine can be described by the following steps (Fig. 2):

- as the vertices of the graph, the engine subsystems are considered, the connections—the interaction between them, the flow values along the sections—the probability

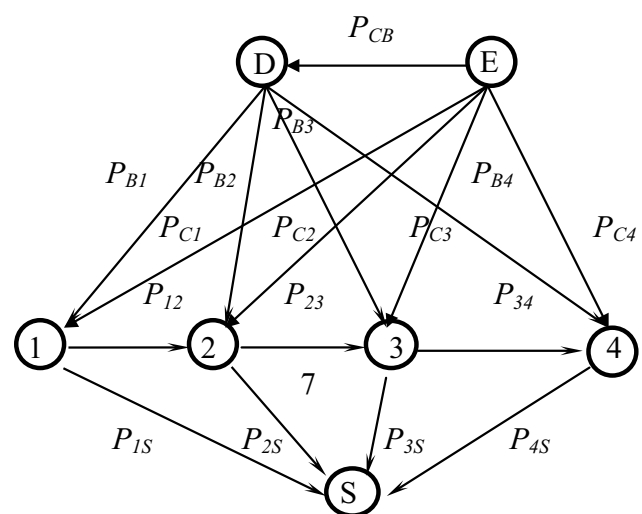


Fig. 2 Graph of states for analysis of reliability of an engine (system approach)

of failures caused by the cause–effect interaction between its subsystems;

- each of its subsystems is treated in the form of a similar network. Then, the details of the internal combustion engines entering the system are considered as the vertices of the graph; the connections between them are the probability of failures that arise during their interaction within each subsystem.

At this stage, the analysis of the internal combustion engine as a complex system can be considered as complete. Synthesis occurs when these steps are performed in the direction from bottom to up.

It should be noted that the commonly used expert specification of the requirements for the reliability of a complex technical system and its subsystems and parts, based only on engineering practice and operational experience, is not only the simplest, but also the most common approach (Bolotin et al. 1993, 1996; Yankevich 2012). The set of reliability indicators for a complex technical system, used in a number of cases, based on the analysis of available statistical information on already existing objects that are close in terms of indicators to the existing model, is largely a prediction in the direction of technical improvement of the design under study. However, such a forecast is based on the data obtained during operation. Similar approaches can be applied to analyze the reliability of subsystems and parts of an engine. In this case, it is expedient to carry out research on a generalized mathematical model, which can be understood as a system of “external environment—a person—a technical system (vehicle, engine)”.

In this case, the calculation of the failure probability related to the technical system as a whole is carried out according to the usual calculation rules for oriented probability graphs (Kornienko 2010). Thus, as a sequence of actions in the development of a mathematical apparatus for

the system of preventive diagnostics, the following algorithm can be adopted:

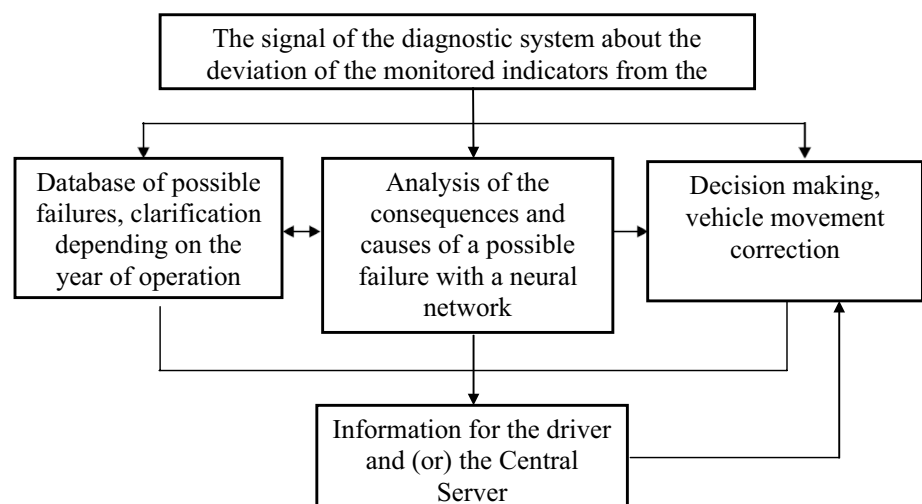
- in the case where the sensors indicate the excess of the controlled parameters of some admissible values, a state graph is constructed that includes all possible causes and consequences of current situation;
- as the probability of failure of the element (i) due to the effect of the element (j) (P_{ij}), expert judgments obtained on the base of operating data of the car (prototype) are accepted;
- the minimum path is calculated and the corresponding probability of failure of the system as a whole;
- if the probability of failure of the system as a whole approaches (exceeds) the threshold value (expert judgment), an automatic signal is given to the central service center indicating the possible cause of the failure, and the car is automatically taken to the extreme band or service center (in correspondence with predicted failure and way to be gone semiautomatically/automatically).

Developed approach can be the basis for creating and implementing on the basis of the developed methods and units [the model of the vehicle diagnostic system, the methodology for investigating the reliability of complex technical systems based on the system approach (Yankevich 2012)] of the basic scheme for the preventive diagnosis of vehicles (Fig. 3).

Results

The model sample of the proposed diagnostic system of an engine has been developed. (The data obtained with it are the basis for the functioning of the vehicle failure prediction system—the part of the preventive diagnostics system.)

Fig. 3 Schematic diagram of the preventive vehicle diagnostic system



All functions for converting data from sensors, providing interaction between the user and the system, the interaction between various modules of the system itself are entrusted to specially developed software algorithms.

When debugging the software and hardware of the diagnostic system, a Microchip debug kit consisting of the dsPICDEM 1.1 General Purpose Development Board (DM300014) and the MPLAB[®] ICD 2 in-circuit programmer/debugger was used.

During debugging, all sensors were connected to the board, and further adjustment was carried out on real signals.

In accordance with the algorithm of the main program, the processor was initialized first: The bits configuration and the frequency of the clock generator were set; a watchdog timer was switched off. Then, external interrupts for the buttons used to select the layout mode were assigned. After that, the initialization of the timers necessary to organize the exchange of information via the RS-232 interface was carried out. Next, the variables were initialized, and the device was ready for use.

The developed model of the engine diagnostic system performs the following functions:

- (1) storage of “technical passport” of the vehicle (state number of the vehicle, model of the vehicle, chassis number, engine number, injection pump number, gearbox number);
- (2) registration of engine start-up (time bound);
- (3) calculation of the total running time of the engine (in hours);
- (4) interrogating the oil pressure sensor in the engine lubrication system and registering the parameter output beyond the permissible limits in non-volatile memory (time bound);
- (5) interrogation of the oil pressure sensor in the transmission and registration of the parameter output beyond the permissible limits in non-volatile memory (time bound);
- (6) interrogating the coolant temperature sensor and recording the parameter output beyond the permissible limits in the non-volatile memory (time bound);
- (7) interrogation of the voltage of the onboard network and registration of the parameter output beyond permissible limits in non-volatile memory (time bound);
- (8) interrogation of the engine speed sensor and registration of the parameter output beyond permissible limits in non-volatile memory (time bound);
- (9) continuous registration (period from 5 to 60 s) of the pre-selected parameters (voltage of the onboard network, coolant temperature, oil pressure in the lubrication and transmission system) with writing to non-volatile memory;
- (10) interrogation of the ambient temperature sensor;
- (11) transmission of data on the sensors status to external devices (when receiving a request);
- (12) transmission of data on the output of the measured parameters beyond the permissible limits in the interface unit;
- (13) the transfer of statistical data to the PC on its demand (or when the observed parameters are outside the permissible limits).

The list of functions can be extended in the future.

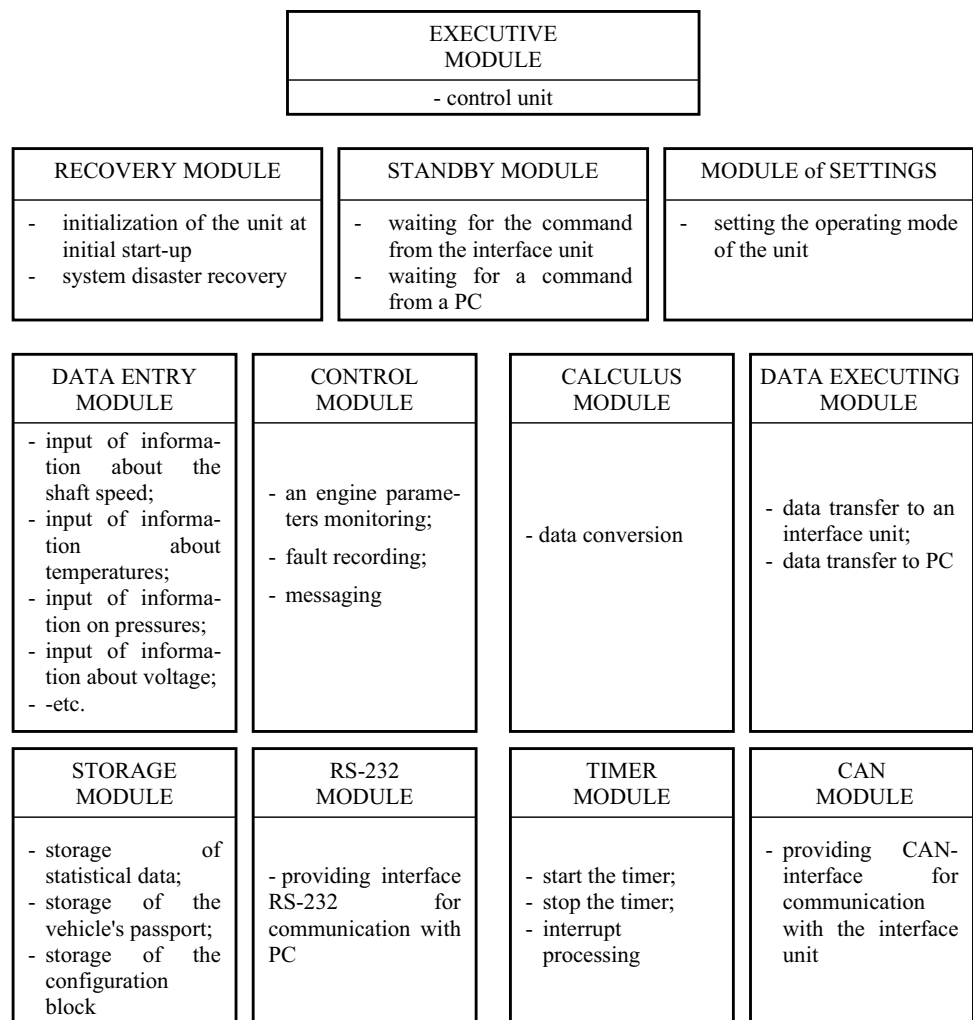
An important issue during the development of a functional specification is the implementation of an interface between the user and the system. The interaction is carried out using command registers, data and status (communication with PC), analog-to-digital converters.

Basing on the functional specification, a set of modules is defined that implements the functions performed by the system.

Modules perform the following functions (Fig. 4):

- (1) RESTORATION module performs initialization of the unit (hardware and software) at the initial power-up, system recovery after a failure;
- (2) STANDBY module checks the status of the command register and waits for the command from the PC or interface unit;
- (3) DATA INPUT module performs input of the measured values;
- (4) DATA OUTPUT module transfers data to the interface unit and PC;
- (5) SIGNALING module performs light signaling (in emergency cases);
- (6) CONTROL module checks the parameters of the engine and, if they exceed the permissible limits, transmits the message to an external device with simultaneous registration in non-volatile memory;
- (7) SETTINGS module provides setting and setting of the basic modes of the block operation;
- (8) TIMER module performs timer control: starts and stops the timer, sets the timer period and processes interrupts from it;
- (9) STORAGE module stores statistical data, passport of motor vehicle, as well as other service information;
- (10) CALCULATION module processes data received from sensors;
- (11) RS-232 module communicates with a PC using the RS-232 interface;
- (12) CAN module communicates with the interface unit via the CAN bus;
- (13) EXECUTIVE module performs management of the diagnostic system.

Fig. 4 Functional–modular structure of the engine diagnostic system, including the functions for each module



As a result of the analysis of the functions performed by the system, and on the basis of the modular structure, the system is divided into hardware and software modules.

In accordance with the structural scheme, a schematic electric circuit diagram and an electronic board for the engine diagnostic system have been developed, and a model of the diagnostic system has been made (Fig. 5).

A key requirement of real-time traffic control systems for generating meaningful contextual information obtained from the analysis of incoming data is their high quality. In this case, “quality” is determined by three criteria:

- accuracy;
- completeness;
- timeliness.

Traditionally, there is not much attention, devoted to the parameter “relevance,” as the analysis is focused primarily on processing static data with low temporal deviations. With the advent of various real-time data sources (cameras, GPS

sensors, mobile phones, traffic light controllers, etc.) and with the creation of new paradigms of the sensor applications in real time (situational awareness), the relevance of the database is currently rapidly gaining significance. Thus, a mechanism should be created for integration of sensors measurements and other data in real time, which combines various data sources, obtained using standard interfaces.

Nevertheless, the proposed technology will provide citizens with new services and will ensure monitoring of traffic management in real time, making an important contribution to increasing environmental safety. In addition to the obvious benefits for transport operators and customers, the application of such approaches for the logistics system will ensure the online management of traffic flows, providing the necessary information about the infrastructure and service capabilities. All this will not only improve driving comfort, but also increase safety, while ensuring the solution of issues in the interests of the environmental component.

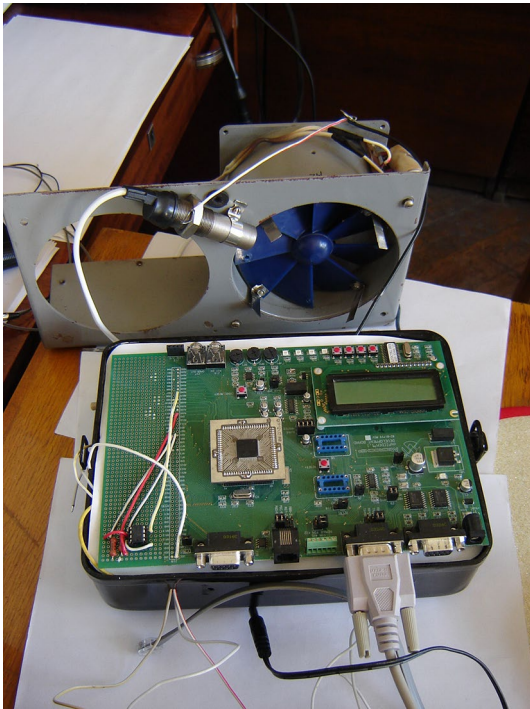


Fig. 5 Tests of the prototype of the engine diagnostic system

Conclusions and results

1. The concept for formation of normative and methodological support for research and development in the field of reliability of complex systems (including vehicles), which can be taken as a basis for the development of the vehicle's preventive diagnostic system, which is an integral part of the IATS, is proposed.
2. It is inappropriate to create one universal model that could reproduce both the operation of the system as a whole and its individual subsystems. When predicting the reliability of an engine as a whole, it is expedient

to obtain a set of probability models describing each of these subsystems, as well as a model that determines their interaction.

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