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SETTING PERIODIC MAINTENANCE INTERVALS FOR DIESEL ENGINES OPERATED UNDER DIFFICULT CONDITIONS

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Abstract:

Afghan highlands, landscape and altitude above the sea level, and geographical situation influence on the climate. Engines' operation are very different from their work in European plains. Mountainous terrain variability has a significant impact on operation mode of the car's chassis and transmission, and climate change determines the engine performance parameters. Mentioned factors result in technical performance characteristics and their costs. Defining requirements to preventive measures for technical failure would reduce technical repair costs and rational technical maintenance frequency would save funds for maintenance.

Keywords:

engine, reliability, maintance

INTRODUCTION

Automotive engine reliability represents an important feature of engine performance while determining the use of a vehicle in an ever globalizing world. Cars are often adapted to be capable of driving on different roads and to operate under various conditions. For this reason, when designing and producing land motor vehicles, automotive manufacturers focus not only on their design and comfort level but also on their operating reliability. Given the currently prevailing worldwide trend to develop automotive road systems with rigid pavements, automotive manufacturers tend to develop cars intended for operation on this type of roads. However, in some cases a need emerges for vehicles operable off-road under complicated climatic conditions, for example, for the purpose of exploratory works or to be used on international missions. For the purpose of tasks completion different vehicles are often used effectiveness of which depends on their reliability. As the need for such vehicles is limited, there is a lack of their research, and furthermore, findings and results of not all studies are reported and published, all of which leads to the lack of recommendations on vehicle operation under difficult conditions. Afghan highlands, landscape and altitude above sea level, and geographical situation influence on the climate. Engine operation can be very different from its work in European plains. Mountainous terrain variability has a significant impact on the operation mode of the car chassis and transmission, and climate change determines engine performance parameters. The above mentioned factors result in technical performance characteristics and their costs. Defining requirements to preventive measures for technical failure would reduce technical repair costs and rational technical maintenance frequency would save funds for maintenance.

Experience gained through vehicle operation in Afghanistan revealed the following three main reasons behind the inoperability of vehicles: combat damages; scheduled repairs after the established amount of motor hours or kilometers run by engine; car accidents and failures in the course of vehicle operation (operating failures) [1]. Failures of engines used in vehicles are also grouped into the following three groups: catastrophic, parametric and combined failures.

Taking into account high numbers of ICE failures, an engine as a repairable part of a vehicle is described using a particular law of distribution [9]. ICE failure flow must be known when setting ICE reliability criteria based on the values which determine the adjustment of periodic maintenance intervals, need for repairs, and amounts of spare parts stored and available for repairs can be accomplished. When studying ICE operating reliability, the distribution law of ICE failures must be determined.

Object of the research – diesel engines operating under difficult conditions, and fuel and oil used in them.

Research material. The article analyzes the performance of twenty nine diesel engines operating under difficult conditions: sixteen Toyota Land Cruiser 100 (LC) vehicles with diesel engines 1HD-FTE, and thirteen high-mobility multipurpose wheeled vehicles M998A2 (HMMWV) with diesel engines GM6.5L. Fuel and engine oil SAE 15W-30 (API CF-4) used for these engines are investigated as well.

The objective of the study was to set periodic maintenance intervals for diesel engines (ICE) operating under difficult conditions and suggest means for the extension thereof.

Research involves diesel engines 1HD–FTE, GM 6.5L of twenty nine Toyota Land Cruiser 100 cars, M998A2 operated under conditions of mountainous desert in Ghor, a province in Afghanistan and their consumed fuel and engine oils. The majority of vehicles and their engines were operated under conditions of a mountainous desert from the very beginning, i.e. from the beginning of summer in 2005 to December 31, 2011.

1. INVESTIGATION INTO ICE RELIABILITY

The reliability investigation was performed following the methodology suggested by Mickūnaitis [11] (2006) and a statistical series of initial data was composed based on the available statistical data.

As a result of the calculations the coefficients of variation for engine 1HD–FTE of 0.04 and for engine GM6.5L – 0.05 were determined. Both coefficients show that failure distribution density may belong to the normal distribution, consequently the hypothesis regarding the inclusion of failure distribution density into the normal distribution was formulated. Proving the hypothesis to be true would mean that engines under operation follow all the laws and rules of the normal distribution.

Research into the reliability of engines operating under difficult conditions and establishing reliability improvement involves the analysis of the influence of the fuel on the working process of an internal combustion engine in the highlands, setting the parameters of the distribution law of the engine failure flow, periodicity of engine technical maintenance and service, and weak points in engine systems.

Random variables distribution law depends on the origin of failure occurrence, it is characterized by individual features that are difficult to determine. Thus, having the hypothesis derived and parameters of the distribution law set, it is absolutely necessary to verify if the hypothesis matches experimental findings. The assessment of the conformity with the distribution law for engines GM6.5L and 1HD–FTE was carried out using χ^2-Pearson's goodness of fit measure. Based on the available data, $P_c(\chi^2>u)$=0.001 for both engines was calculated and a low probability was found, thus function *F(x)* was rejected as unfit and unacceptable. Based on the selected lengths of engine operation – i.e., 15,000 km for the GM6.5L engine and 32,000 km for the 1HD-FTE engine – histograms of random variable distribution and their polygon graphs were obtained. In summary of the obtained findings, statistical distributions (normal, Weibull's, exponential) typically used in engine reliability theory are suitable.

Based on the statistical data series, the following histogram and polygon as well as an integral curve of failure distribution were obtained (Figure 1).

The law of the distribution of random variables depends on the origin of failure occurrence and it is characterized by individual features that are difficult to determine. Thus, having the parameters of distribution law set, it is absolutely necessary to verify if the hypothesis matches the experimental findings. The assessment of the conformity with the distribution law was carried out using χ^2-Pearson's goodness of fit measure. Based on the research data, $P_c(\chi^2>u)$=0.001 was calculated, and after finding the probability to be low, function *F(x)* was rejected as unfit and unacceptable. Based on the selected total distance run by engine (15,000 km), histograms of random variable distribution for the GM6.5L engine and their polygon graphs, none of the statistical methods– normal, log-normal, Weibull's, exponential– typically used in engine reliability theory were suitable. The same research procedure was performed for the 1HD–FTE engine. The graphs of the random variable distribution histogram, polygon and differential function were drawn (Figure 2).

Similarly as with the GM6.5L engine, the assessment of the conformity with the failure distribution law was carried out using χ^2-Pearson's goodness of fit measure. Based on the research data, $P_c(\chi^2>u)$=0.001 was calculated and, after finding the probability to be low, function *F(x)* was rejected as unfit and unacceptable. Based on the selected total distance run by the engine (32,000 km), histograms of random variable distribution for the 1HD–FTE engine and their polygon graphs, none of the statistical methods typically used in the engine reliability theory – normal, log-normal, Weibull's, exponential distribution– were suitable.

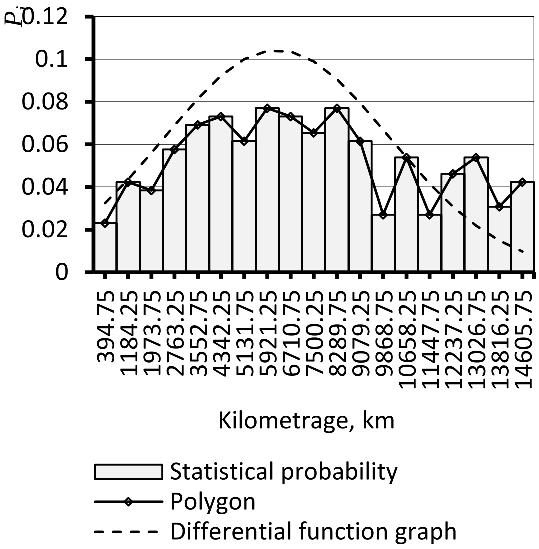

Fig.1. Histogram, polygon and differential function of the distribution of random variable of the GM6.5L engine

Source: own work

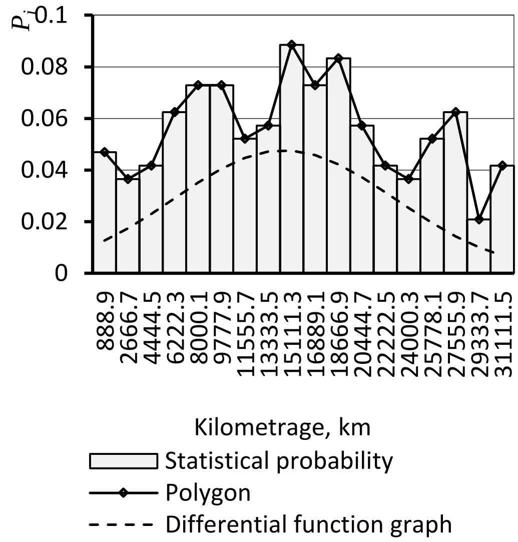

Fig.2. Graphs for histogram, polygon and differ- ential function of distribution of random vari- able of the 1HD–FTE engine

Source: own work

The reliability of engines operated in the mountains of Afghanistan is determined by a variety of climatic and geographic factors that are independent of each other. This means that probabilistic research techniques cannot be used for the determination of the laws of engine incorruptibility under these particular conditions of operation. For the purpose of studying the overall engine reliability, the structural scheme comprised of components linked in series is used, whereas the effect of climatic factors on failures of individual engine components must be evaluated individually. The incorruptibility of cold-resistant components under low temperatures is similar to the probability of incorruptibility under high temperatures. The same principle can be used in the opposite way: the probability of incorruptibility of heat-resistant engine components under high temperatures is similar to the probability of incorruptibility under negative temperatures.

Given the previously reviewed circumstances, the probability of engine incorruptibility in the period of climatic action is found as a product of the probabilities of the incorruptibility of individual components comprising the overall engine system.

The technical maintenance experience in Afghanistan reveals three main reasons for technical incapacity: fighting damages; scheduled repair after reaching a set number of working hours; accidents and failures during the operation of equipment (operational failures) [1]. Technical failures of engines are divided into three main categories: catastrophic, parametric and combined one.

When calculating the overall engine reliability $P_0(t)$, each type of the failure is expected to be an independent event with the following mathematical expression [10]:

$$P_0(t) = P_m(t) \cdot P_{pm}(t) \cdot P_{kl}(t) \cdot P_{km}(t), \quad (1)$$

where:

- $P_m(t)$– reliability of incorruptibility of ICE at sudden failures;
- $P_{pr}(t)$ – reliability of incorruptibility of ICE at parametric failures;
- $P_{kl}(t)$ – reliability of incorruptibility of ICE at failures dependent on climatic factors;
- $P_{km}(t)$ – reliability of incorruptibility of ICE at combined failures.

The probability of engine efficiency at combined failures depends on many factors. It is difficult to determine the number of failures because of their instability, consequently this rate is determined experimentally, and for calculations it is considered that $P_{km}(t)=1$.

For the assessment of engine reliability, the system based on engine incorruptibility is often used, however, it does not fully meet the requirements set for the operation of an engine as this system does not take into consideration functional and parametric failures. The engine can be operable despite the fact that it shows the above-mentioned failures. The determination of functional and parametric failures is best accomplished when the following, easy to use parameters are taken into account: engine power, torque, oil and air pressure as well as ecological emission rates. When assessing engine reliability the main task is to discover the engine operation law before the failure, which is usually expressed in deferential $f(t)$ (probability density) or integral (distribution function) form. Distribution law $F(t)$ refers to the engine reliability characteristic and allows to find engine incorruptibility work $P(t)=1–F(t)$ as well as other indicators of incorruptibility. The comprehensive analysis of engine reliability leads to the need of developing numerical models of engine reliability capable of revealing the variation of engine operating characteristics. According to the empirical tests of diesel engine reliability performed in Afghanistan, the specifics of forming distribution law emerges as it is necessary to take into consideration parameter fluctuation rather than ageing laws, thus extra phenomena occur which determine errors. A random process $X(t)$, dependent on any ageing process, occurs also due to the fact that its arguments are random values independent of time. The parameter fluctuation can have the determined part and the random part, consequently the ageing process varies following the non-linear law and acquires features characteristic for a mixed process, it can also show monotonous or non-monotonous features. Such random features of a process have the effect on the parameters of distribution law $f_{pr}(t)$ and on the evaluation of engine operating reliability $P_{pr}(t)$. The probability of climatic ICE incorruptibility $P_{kl}(t)$ is dependent on climatic factors and is closely related to the parametric failures which have influence on their occurrence and disappearance.

In reality, the failure flow parameter does not remain stable during engine operation and the failures of multiple engine systems occur due to exceeded terms and conditions as well as standard guidelines of operation.

Randomly varied operating conditions and non-accidental reasons change the engine failure flow parameter, however, these changes do not happen instantly; instead, they demonstrate a particular tendency over a particular period of time. Non-accidental reasons include poor repairs and maintenance, as well as the worsening of some engine system performance due to a failure or a defect of any other component (for example, a failure in the lubrication system). For this reason, failures sometimes result in irreversible outcomes.

The most frequent failures and faults of GM6.5L and 1HD–FTE engines, faced during our study, are discussed later in this work. Fig.3 shows the relative number of failures of the GM6.5L engines systems, and Fig. 4 – of the 1HD–FTE engine systems. In the case under consideration, the failure flow parameter depends on the following three factors: climatic adversity, road conditions and operating intensity. Given research findings and the equation (2 and 3) of the proposed hypothesis, a system of linear equations can be constructed which is further expressed in a matrix form.

To find out coefficients of polynomial approximation, the system of linear equations was solved in the matrix form. When solving the system of equations, the coefficients of mathematical simulation of the approximation are calculated, they encompass, e.g. the relationship between the engine failure flow, weather adversity for ICE operation, rolling resistance coefficient and operating intensity. As a result the following regression function is obtained.

According to the research, the failure flow of ICE operated in Afghanistan increases in winter and summer. It is obvious that the engine failure flow depends on climatic adversity of the region as regards the operation of vehicles. The GM6.5L engine of M998A2 is more dependent on climatic adversity when compared to 1HD–FTE engine of Toyota Land Cruiser 100, meaning that the 1HD–FTE engine offers better possibilities of adaption for such conditions of operation.

The approximation equation for engine failure flow ω of 1HD–FTE diesel engines used in Toyota Land Cruiser 100 cars is defined through the following dependency [2]:

$$\omega = 0{,}026 + 0{,}06K_N^2 + 0{,}6f_r + 0{,}002l_{ei}\,, \tag{2}$$

The regression model is considered suitable, as the coefficient of determination R^2=0.96.

The approximation equation for engine failure flow ω of GM6.5L diesel engines used in high-mobility multipurpose wheeled vehicles M998A2 (HMMWV) is defined through the following dependency [2]:

$$\omega = 0{,}01 + 0{,}28 K_N^2 + 2{,}4 f_r + 0{,}005 l_{ei} \, , \qquad (3)$$

The regression model is considered suitable, as the coefficient of determination R^2=0.97.

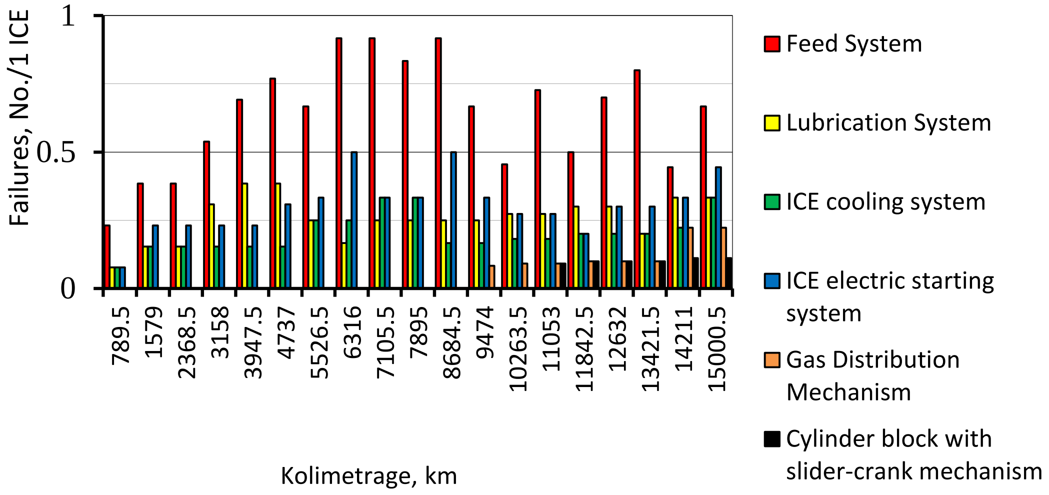

Fig.3. Relative number of failures of engine GM6.5L by ICE systems in period of 2005–2011

Source: own work

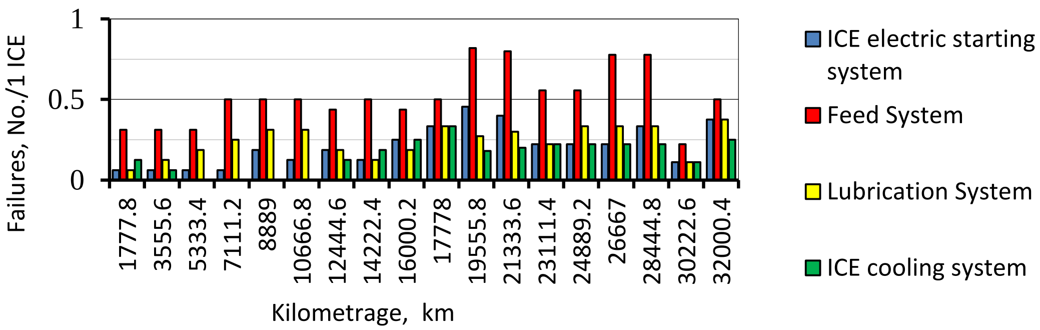

Fig.4. Relative number of failures of engine 1HD–FTE by ICE systems in the period of 2005–2011

Source: own work

Fig.5 presents calculations of the failure flow parameter for each ICE model respectively.

The analysis of the failure flow parameters of different models of engines operated in Ghor Province leads to a suggestion that engines show different dependencies on climatic adversity as regards ICE operation according to the engine failure flow parameter. Different ICE adaption possibilities were also observed under variable ICE operating conditions for over a year. The higher the coefficients in the equation the worse the adaptation potential of an engine.

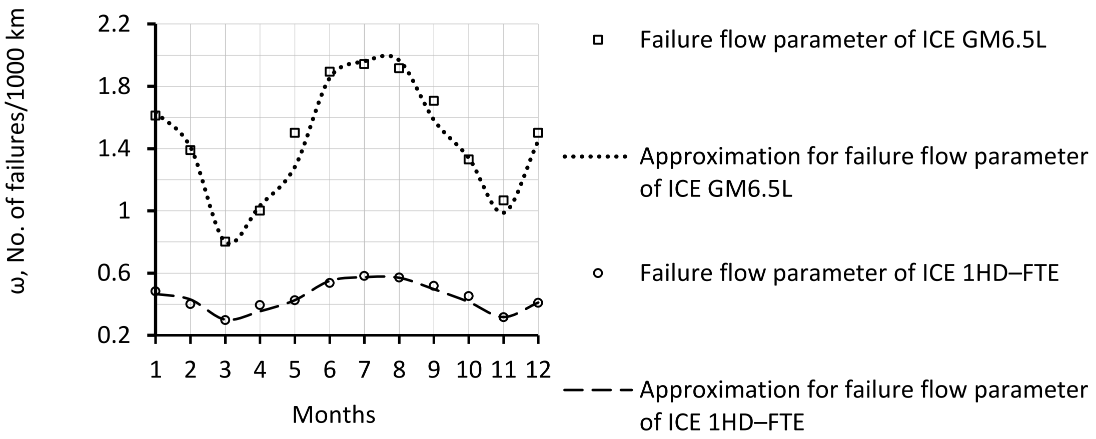

Fig.5. Failure flow parameters of the GM6.5L engine used in M998A2, and the 1HD–FTE engine used in LC and approximations thereof in the period of 2005–2011, depicted monthly

Source: own work

2. SETTING PERIODIC MAINTENANCE AND SERVICE INTERVALS FOR AUTOMOTIVE ENGINES.

From the structural point of view, an engine is a consistent system comprised of structural components which function independently of each other, and in the case of any component failure, it is replaced immediately. In the course of engine operation, the times of some failure events happen to coincide; B. Kanarchiuk [8], B. Bolotin [7] and L. Jonaitis [3] report that failure events of individual components of a system can be consequently described by the Poisson distribution, thus the processes of the entire system can be described by the Poisson distribution, too. Using this particular distribution, probability *m* of the number of failures in length *L* can be expressed as follows:

$$P_n = \frac{(\omega L)^{m_n}}{m_n!} \exp^{-\omega L}, \tag{4}$$

where:

– ω – ICE failure flow parameter; m_n – number of failures; L – length of engine operation.

As the research shows, the failure flow parameter is variable not constant, whereas the reliability function differs from the exponent. Thus assessing engine reliability requires taking into account the deviation of the distribution of the number of failures from the Poisson distribution.

Determining engine reliability encompasses the calculation of the function $R_n(L,u)$ which is treated as the probability of the engine failure comprised of K_{se} components for *m* times in the range under investigation [8]:

$$R_n(L,\omega) = \frac{(\overline{\omega}L)^{m_n}}{m_n!} exp^{-\omega L} + \varepsilon\delta^2 \frac{(\overline{\omega}L)^{m_n}}{m_n!} exp^{-\omega L}, \quad (5)$$

where:

- $\overline{\omega}$ – the average failure flow parameter;
- m_n – number of failures in the length under investigation;
- $\varepsilon\delta^2$ – offset (deviation) from the approximation typical for the Poisson distribution;
- ε – deviation of the dispersion of number of failures from the Poisson flow dispersion; ω – ICE failure flow parameter;
- m_n – number of failures;
- L – length of engine operation.

$$\varepsilon = \frac{1}{2}(m_D - m_v), \quad (6)$$

where:

- m_D – dispersion of the number of failures in the interval; m_V– average number of failures in the interval.

Having established the value of parameter $R_n(L,\omega)$, which ensures the continuous completion of tasks, and using equation (5), the intervals of periodic maintenance and service L can be estimated ensuring prevention against ICE failure.

The calculations resulted in the following technical service intervals of automotive engines operating in Ghor Province in Afghanistan: Toyota Land Cruiser 100 diesel engines 1HD-FTE – periodically after each 300 km to 500 km; M998A2 diesel engines GM 6.5L – periodically after each 100 km to 250 km; more frequent intervals of technical service must be ensured in summertime, less frequent – in early spring, and medium intervals during other seasons.

Based on the obtained data of the failure flow parameters and intervals of periodic maintenance/service, the need for likely repairs over current month for each group of automotive engines can be found, as well as required numbers of automotive engine repair staff, necessary maintenance workload, and the list of tasks to be performed, however, this is not included in the scope of the article.

3. SUGGESTIONS FOR THE IMPROVEMENT OF ICE RELIABILITY

The analysis of the research results obtained on the engine operation under difficult conditions led to an observation that the components of different types of automotive engines under investigation tend to fail and their failure intensity is different.

A diesel engine is comprised of 4 systems and 2 mechanisms. If 100 % is divided by 6 engine elements, the result is 16% per each element.

Consequently, engine components should be considered the ones that reduce ICE reliability if their failure/fault frequency accounts for at least 16% compared to the total number of ICE failures:

$$G_{gr} = \frac{G_{ssk}}{G_s} 100, \qquad (7)$$

where:

- G_{ssk} – number of failures or faults of a particular engine system or engine mechanism;
- G_s – total number of failures or faults of engine systems and/or engine mechanisms.

All the engine failures/faults can be grouped by engine comprising systems and mechanisms, while taking into account the number of failures/faults of a particular engine system or mechanism as well as the total number of failures/faults suffered by all the engine systems and/or mechanisms.

Fig.6 and 7 depicts ICE reliability reducing the weak points of GM6.5L and 1HD–FTE engines which were found through equation (7).

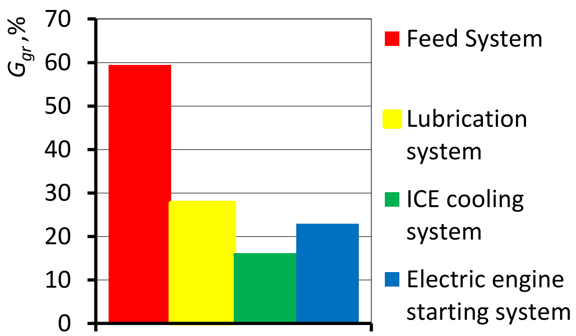

Fig.7. ICE reliability reducing failure parameter for the 1HD-FTE engine by its systems

Source: own work

The pace of changes in the characteristics of the oil used in ICEs under difficult conditions is also discussed leading to the observation that the SAE 15W-30 (API CF-4) engine oil, when used in a technically fit engine for more than 5,000 km fails to preserve its reserves of neutralizing, detergent and dispersive properties, and viscosity improving oil additives do not show resistance to destruction. For this reason engine oil loses its characteristics more rapidly than assumed, meaning that oil change intervals of 8,000 km of the SAE 15W-30 (API CF-4) engine oil used in diesel VDV 1DH–FTE, GM6.5L engines and OM 366 LA of Toyota Land Cruiser 100, M998A2, and Mercedes-Benz Unimog operated in Afghanistan are incorrect and must be reduced to 5,000 km.

According to the research completed in this context, there are four weak points of an engine that can be unambiguously blamed for a decrease in ICE reliability: ICE feeding, cooling, electric starting, and lubrication systems. The reliability of ICE cooling, electric starting, and lubrication systems might be improved by appropriately selecting technical personnel and using passive reservation of components prone to failures (replacements of a faulty component with a new one).

The first group includes frequent faults of the engine feed system. For example, an air filter lost its filtering capacity (throughput) after running only 500–4000 km. After travelling the previously mentioned distance, air filters were subject to regeneration using compressed air up to five times or filter cleaning with water in accordance with the guidelines provided by filter manufacturers in their operation manuals. There was a big difference in the characteristics of the fuel used in these engines and diesel fuel. It turned out that fuel filters happened to lose their filtering capacities (throughput) quickly and were replaced every 500–5000 km on the average. The failures of engine high-pressure fuel pumps were frequent, too (every 4,000–25,000 km) (the guaranteed kilometrage provided by the manufacturer for GM6.5L – 80,000 km, and for 1HD–FTE – 100,000 km). Some faults of an air-charge turbine and fuel injectors were recorded. Engine fuel consumption exceeded the established basic fuel norm by 15–20% on the average. Some parametric failures were found to be common for engine feed system: fuel pressure drop (in both high- and low-pressure sections), uneven fuel injection into cylinders, a changed angle of fuel injection, volumes of pollutants in the exhaust gas exceeding the established limit values.

Sudden engine failures: injector inactivity, leaking high-pressure fuel lines, turbocharger faults.

Engine failures dependent on climatic factors: premature decrease of fuel and air filtering capacities caused by filtration material clogging with various contaminants or fuel flow interruption caused by a negative temperature, complicated hot engine start (after fuel pump is cooled down, the engine starts successfully– this failure is only characteristic for the GM6.5L engine), water presence and its freezing in a fuel system and a fuel tank.

Another relevant group includes the faults of engine electric equipment (batteries, starters, glow plugs). The faults of engine electric equipment normally depend on the engine manufacturer and are common only for engines belonging to a specific group. This offers a solid basis for assuming that these failures feature characteristics of technological and structural faults. As regards the electric equipment of all types and models of engines, only a short battery life is distinguishable (6–11 months) independent on its type. This group of failures also includes engine generator (cooling ventilator) belt-drive faults. The failures of the engine electric starting system: glow plug failure, exhausted or inoperative battery, starter, loosened or broken starter mounting bolts, cable disruption or prevention of electrical current flow through connections, including tripped fuses.

The engine cooling system happened to demonstrate a reduced air circulation through the fins of the ICE radiator due to accumulated dirt, intensive evaporation of coolant, and problems with leaks in a system, which did not generate high repair costs. The failures of cooling systems in both types of engines: thermostat failure, failure of automatic control of the ventilator of cooling radiator, low level of coolant in the system, a cracked core of a cooling radiator.

The oil filters of the engine lubrication system were replaced on average every half a year or every 4000–8000 km, although the vehicle mechanical inspection showed the following problem with lubrication system: increased engine oil pressure in the system before the reducing valve opening pressure. The failure of lubrication systems in GM6.5L and 1HD–FTE engines were only of a parametric nature: an increase or decrease in engine oil level, a decrease in oil volume in the lubrication system, leaks in the lubrication system and engine oil leaks, increased oil pressure within the lubrication system, and the obstruction of oil suction.

Only a few failures of the cylinder piston engine group with a crank mechanism and of a gas distribution mechanism were observed, although automotive engines were replaced several times during the period between the summer of 2005 and the winter of 2011. The failures of the gas distribution and exhaust system: burned out sealing gaskets and rings.

Failures characteristic for the period of operation of the GM6.5L and 1HD–FTE engines operating in mountainous desert conditions include failures of their parts made of rubber and polymer materials: drive belts, sealing rings, glands, and different gaskets. The loss of physical characteristics of these parts causes leaks in ICE cooling and lubrications systems, air leaks in the ICE air suction system and the presence of uncleaned air in engine cylinders.

According to the research completed in this context, there are four weak points of an engine that can be unambiguously blamed for reducing ICE reliability: ICE feeding, cooling, electric starting, and lubrication systems. The reliability of ICE cooling, electric starting, and lubrication systems might be improved by appropriately selecting technical personnel and using passive reservation of components prone to failures (replacing a faulty component with a new one).

The ICE feeding system requires modernization. The high-pressure pumps of M998A2 vehicles should be modified following the recommendations set in the reference (Service Bulletin No. 484R4 [4] No. 284R2 [5], No. 125R4 [6]) by *Stanadyne Diesel Systems*.

When composing repair kits, it is necessary to use the branches of a hierarchical vehicle structure from the lowest to the top level. The lengths of hierarchical branches can differ, however, the lowest level must be a detail. Given the complicated and long way of the supply of spare parts, it is necessary to store additional reserves of the parts that tend to wear and tear faster when operating vehicles in dusty environments (for example, air and oil filters).

Using this methodology, the components of spare parts used for repairs must be selected in such a way that after replacing one of the components in the branch of a hierarchical vehicle structure, vehicle operability would be fully restored at the minimum labor and material costs.

Repair kits must be handed out as follows: an individual repair kit (incl. belts, lamps, fuses, etc.) – one for each vehicle; a repair kit for the department (incl. belts, lamps, fuses, starter, pump, generator, power steering, etc.) – one kit per 10–15 vehicles; a repair kit for the unit comprised of an assembly kit (incl. engine, axles, gear box, distribution box), spare parts kit (incl. belts, lamps, fuses, etc.), mounting kit (bolts, nuts, pins, washers, etc.), and materials kit (paints, varnishes, paranite, cardboard, oakum, different metals, etc.)– a kit per 50–70 vehicles. Such a range of supplies stored for the purpose of repairs is supposed to allow for 30 automotive running repairs (when replacing up to two components in a car) and maintain them fully operable for up to 6 months, provided the compulsory service of vehicles is performed on time. The replenishment of supplies must be made once every half year. The required repair parts absent from repair kits must be acquired in Afghanistan or from allies.

There are three techniques of maintaining vehicles in the state of their technical operability, following this strategy a technique is chosen based on general dependencies and taking into account the effect of vehicle technical condition on economic, operating and ecological parameters.

Moreover, it is necessary to note that the mountainous deserts of Afghanistan raises some requirements for the vehicles and their structures operated there, which must be taken into account when composing specific technical requirements of the engine design of vehicles and arranging acquisitions thereof:

a) Irrespective of the altitude of the location (at least up to 3000 m) where the vehicle is to be operated, the engine of the vehicle must retain the same engine power;
b) The engine must be equipped with fuel equipment and other auxiliary systems ensuring the formation of a high-quality fuel mixture and a combustion process in lowered air pressure conditions. The fuel system must ensure high-quality fuel cleaning and effectiveness while removing mechanical impurities starting with the size of 1 µm and larger, a fuel tank must be equipped with protection against dust penetration into fuel;
c) Automotive engines must be designed and produced to run on commonly used fuels;
d) The engine must maintain its appropriate thermal balance while driving a vehicle uphill or downhill for a longer period of time;
e) The engine must be equipped with the gear ratios that ensure the best dynamic and economic characteristics when the engine runs under a lowered load;
f) The automotive engine and its assemblies (components) must feature the technical operational resource at least equal to that of a standard vehicle operated over a flat area;
g) A possibility for the unification of components and assemblies.
h) The price of an engine must not exceed that of a basic car engine operated under normal conditions;

i) The engine must be fitted to operate under high concentrations of airborne dust (up to 3 g/m³).

The comprehensive knowledge of vehicle structure, peculiarities of vehicle operation and repairs and scientific discoveries and research as well as experience gained by soldiers taking part in combat action allow for setting a less frequent periodic service schedule than the one indicated by manufacturers in operation manuals, they also enable daily maintenance of automotive air filters and continuous checks if dust or sand is prevented from entering into the engine through an oil feeding device, air filter connections, and air feed pipes.

Given the fact that the lubrication of parts and appropriate temperature regime of engine operation allow to reduce wear-and-tear, it is necessary to clean a radiator and radiator blinds in the engine cooling system, to check the functioning of a radiator cap, to use engine oils and fluids in the engine lubrication system recommended by the vehicle manufacturer depending on the season of its operation and to replace oil filters in a timely manner.

Deposits of dusts must be removed daily by washing vehicles in mobile car wash plants equipped with autonomous water, pressurized air and electric power supply sources. In case of the unavailability of water or pressurized air supply sources, the engine, its devices, car glass, fuel tank refueling funnel, lubrication points of assemblies, vehicle lights must be cleaned with a cloth.

CONCLUSIONS

In summary of the research findings presented in this part of the article, the following conclusions were made:

1. Engine oil service intervals practiced in Afghanistan are unacceptable as engine oil features tend to vary much faster than the ones established in the manufacturer's documentation;
2. Periodic maintenance intervals for the 1HD–FTE diesel engine used in Toyota Land Cruiser 100, and the GM6.5L diesel engine used in M998A2, were set based on the engine failure flow parameter. Toyota Land Cruiser 100 must be periodically serviced every 300 to 500 km, whereas M998A2 – every 100 to 250 km. The periodic maintenance must be performed at more frequent intervals in summertime and at less frequent in early spring, medium intervals apply to other seasons;
3. An important feature characteristic for engine operation in the highlands of Afghanistan is varied engine operation intensity during the year. Vehicles are operated under hot and dry weather conditions in summertime and in cold weather conditions in wintertime. In summer, engine operation is associated with high concentrations of airborne dust increased by dust storms and the influence of highlands. These conditions cause engine systems (cooling, air cleaning, fuel and engine lubrication equipment) to work hard, thin and fine filters as well as air filters tend to clog and the parts of the engine responsi-

ble for reliable engine operation tend to wear out quicker. Engines to be operated under difficult conditions must be specially designed to withstand and prevent the negative effect of climatic factors;

4. The investigation showed that ICE has four weak points contributing to the reduced ICE reliability: ICE feeding, cooling, electric engine starting, and lubrication systems. The reliability of ICE cooling, electric engine starting, and lubrication systems might be improved by appropriately selecting technical personnel and using the passive reservation of components prone to failures (replacing a faulty component with a new one). The weakest point was found to be ICE feeding system as its failures accounted for more than 50% of the total number of ICE failures;
5. The failure flow parameter for Toyota Land Cruiser 100 with the 1HD-FTE diesel engine and that for M998A2 with the GM6.5L diesel engine, both operated under difficult conditions, has been investigated. The ICE failure flow parameter was found to vary dependent on the type of engine: for 1HD-FTE – 0.3 to 0.6 failure/1000 km; for GM6.5L – 0.7 to 2.0 failures/1000 km; ICE failures were found to be less frequent in autumn and spring. The fluctuation amplitude of the failure flow parameter was two times depending on the season;
6. Differently structured internal combustion engines offer different capabilities of their adaptation to operation under difficult conditions: 1HD-FTE diesel engines of Toyota Land Cruiser 100 offer twice as good capabilities of their adaptation for operation under difficult conditions when compared to GM6.5L of M998A2 diesel engines;
7. Some recommendations were offered for the improvement of the engine service system, namely to reduce engine oil change intervals (up to 5000 km), to adjust factory default settings of fuel injection (advance angle by 4–6), to modify high-pressure fuel pumps used in M998A2 (Service Bulletin Nr. 484R4, No. 284R2, Nr. 125R4) based on the guidelines promoted by Stanadyne Diesel Systems, to modify fuels used in engines by adding multifunctional fuel additives (S–1750, S–1745, S–1747, Stadis 450), and to include specific technical requirements on vehicle engine designs when arranging acquisitions thereof.

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BIOGRAPHICAL NOTES

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