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Application of Reliability Centered Maintenance Methodology for Maintenance of an Special Vehicle Engine

Slavko Rakic[1*], Ugljesa Bugaric[2]

[1] Sector for Material Resources, Ministry of Defence of Republic of Serbia, Belgrade, Serbia,

[2] Department of Industrial Engineering, Faculty of Mechanical Engineering Belgrade, University of Belgrade, Serbia

The paper analyses the possibility of revising the existing maintenance program of special vehicle engine by applying RCM methodology. The main objective in considering the application of the new maintenance methodology was to improve the effectiveness and efficiency of the maintenance of the internal combustion engine, retaining the required reliability of the engine. Analysis was carried out on the fuel supply engine subsystem, which is the most critical engine subsystem from the standpoint of the number of failures in the observed period during its exploitation. As a result of these systematic analyses, the maintenance concept of the critical parts and assemblies of the fuel supply subsystem were selected and the intervals of realization proposed maintenance activities in accordance with a predefined request that the reliability of the fuel supply engine subsystem is not less than 0.985. Based on the results, the conclusion is that the application of RCM for special vehicle engine would be justified since it would contribute to improving the effectiveness and efficiency of maintaining the engines.

Keywords: Reliability Centered Maintenance, Engine, Failure, Special vehicle

1. INTRODUCTION

Special vehicles engine has an important role in achieving of one of the three key characteristics of special vehicles – the mobility. Maintainability, cost effectiveness of maintenance, reliability and readiness are very important factors of special vehicles engines.

This paper aims to analyse revision possibility of the existing maintenance program of a special vehicle engine by applying Reliability Centered Maintenance (RCM) methodology. RCM is one of the best known and most used tools to preserve the operational efficiency and reliability of large and complex systems (marine, aircraft, etc.), so the consideration of its application possibility on special vehicles is a real challenge. Expectations of this methodology application are to improve the readiness and availability of technical systems, which is very important for special vehicle.

RCM applies a systematic approach to determine the maintenance requirements of system in its operating context. It is often used to optimize preventive maintenance (PM) strategies.

2. RELIABILITY-CENTERED MAINTENANCE METHODOLOGY

Reliability-centered maintenance (RCM) is the best mix of reactive, time or interval-based, condition-based, and proactive maintenance practices. These principal maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths in order to maximize facility and equipment reliability while minimizing life-cycle costs [5].

The components of RCM program are shown in Figure 1. This figure shows that RCM program consists of (reactive maintenance, preventive maintenance, condition based maintenance, and proactive maintenance) and its patterns.

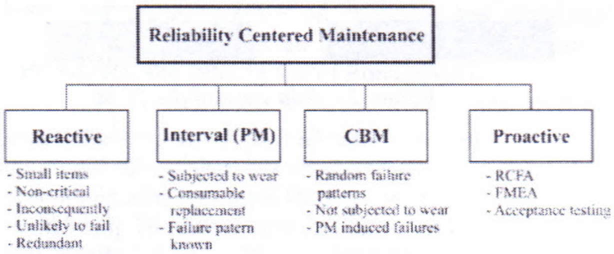

Figure 1: Components of RCM program

As shown in Figure 2, the RCM steps are presented. The steps describe the systematic approach used to implement the preserves the system function, identifies failure mode, priorities failure used to implement the preserves the system function, identifies failure mode, priorities failure modes and performs PM tasks.

3. ANALYSIS OF THE POSSIBILITIES OF APPLICATION OF RCM METHODOLOGY FOR MAINTENANCE OF THE SPECIAL VEHICLE ENGINE

Special vehicles engine subsystems that had defined maintenance and in accordance with the Pareto principle are found in 20-30% of engine subsystems which had 70-80% of the recorded engine failures in the observed period, will be subject to revision of current maintenance. At the end, there will be made selection of appropriate maintenance concept for assemblies and parts of the most critical engine subsystem.

In this regard, there will be carried out failure analysis for individual subsystems of the special vehicle engine in the observed period of exploitation. The engine subsystem that shows critical from the standpoint of reliability will be subject to consideration of the possibility to apply RCM methodology in the context of the revision of the existing maintenance program engine. Access to maintenance revision of the most critical engine subsystem would be further applied to other engine subsystems.

*Slavko Rakic: Petra Konjovica 12Z, Belgrade, Serbia, raleslavko76@gmail.com

Additionally, should be done rationalization of maintenance activities intervals.

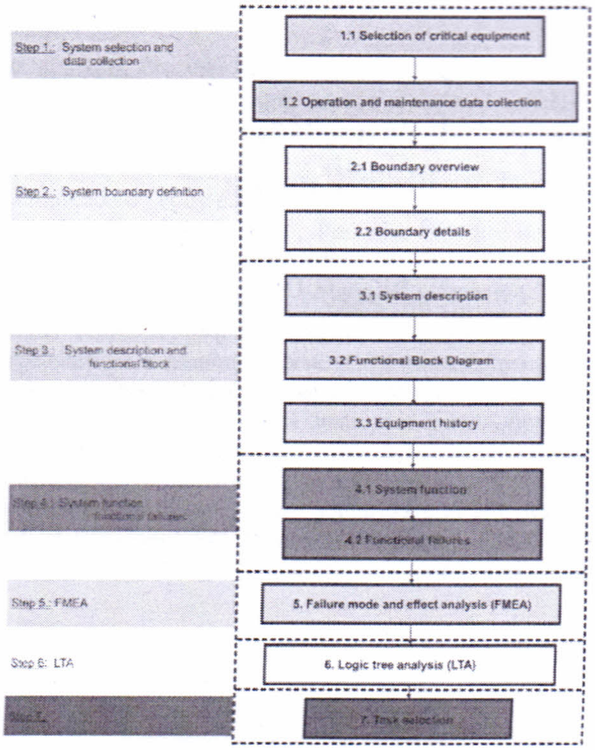

Figure 2: Main steps of the RCM

The main objective was to create conditions using some engineering methods and analysis for the Condition Based Maintenence (CBM) algorithm selection in order to systematically, in addition to previously preventive and corrective maintenance, consider the options for the application and other suitable concept maintenance with priority of maintenance according to the condition.

Revision of preventive maintenance and selection of concepts in the new maintenance algorithm should primarily achieve engine reliability improvement with the possibility of the maintenance cost reduction.

Also, as imperative is given the task to analyze a lack of preventive maintenance activities in existing maintainance, which could be the cause of the unexpected failures with possible safety or major systematic effects.

3.1. Determining the Probability and Cumulative Density Function of engine operating time to failure

Calculating an adequate mathematical model that can represent a principle of special vehicle engine performance during its exploitation, in terms of the appearance of failure, is one of the first steps to be undertaken. Based on the calculated results, there can be done an analysis of existing maintenece programs and if necessary, their revision in order to primarily optimize the engine maintenance in terms of improving its reliability.

For the purposes of this paper, the efficiency of the existing maintenance program has been carried out on twelve-cylinders diesel engine with 735 [kW] which is built-in in special vehicle.

There has been conducted a data collection of the engine operating times to the failure expressed in engine operating hours (EOH), which were obtained by observing the vehicle exploitation and are shown in Table 1. Data were recorded only for engines that had failure. There are shown 105 records of times to engine failure, which is more than sufficient statistical collection in relation with the optimal plan of short tests for assessing the reliability (with the approved variation coefficient of 0.5, a prior relative error of assessment of the reliability of work of 0.05 and an initial number of necessary records of 40) [1]. The procedure for determining the Cumulative Density Function of engine operation time to failure, on the basis of empirical data, is executed in three steps. There have been estimated indicators of reliability in the first step. In the second step, based of the values obtained in the first step, are determined the theoretical models of the distribution for the approximation of the empirical distribution. Afterwards, in the third step is determined the confirmation approval of adopted theoretical model of the distribution with empirical distribution [1].

Table 1: Data of the engine operating times to the failure

Ordinal number of failure	Operating time to failure [EOH]	Ordinal number of failure	Operating time to failure [EOH]	Ordinal number of failure	Operating time to failure [EOH]	Ordinal number of failure	Operating time to failure [EOH]	Ordinal number of failure	Operating time to failure [EOH]
1	135	22	345	43	392	64	448	85	523
2	166	23	355	44	397	65	448	86	523
3	221	24	355	45	400	66	449	87	526
4	221	25	360	46	404	67	459	88	526
5	229	26	360	47	404	68	464	89	532
6	248	27	363	48	406	69	466	90	536
7	251	28	367	49	406	70	473	91	546
8	260	29	371	50	407	71	473	92	561
9	263	30	372	51	409	72	474	93	561
10	272	31	379	52	415	73	474	94	569
11	294	32	379	53	415	74	480	95	572
12	294	33	380	54	415	75	480	96	572
13	307	34	382	55	415	76	486	97	581
14	317	35	382	56	416	77	488	98	581
15	317	36	382	57	419	78	495	99	586
16	320	37	384	58	436	79	496	100	605
17	320	38	391	59	436	80	496	101	605
18	322	39	391	60	438	81	498	102	609
19	331	40	391	61	444	82	498	103	615
20	332	41	391	62	447	83	498	104	634
21	345	42	391	63	447	84	521	105	643

3.1.1. The assessment of the reliability indicators

Based on the records from Table 1 the law of reliability distribution can be calculated.

From Table 1, it can be seen that:

- the total number of data (sample size): n=105,
- minimum operating time to failure: t_{min}= 13… [EOH],
- maximum operating time to failure: t_{max}= 64… [EOH].

From the data presented in Table 1 statistical measures are calculated:

- mean operating time to failure: t_{mot}= 423.56… [EOH],
- the standard deviation of operating time to failure: SD= 105.24 [EOH],
- median operating time to failure: median = 4… [EOH],
- rang (range) operating time to failure: rang= 5… [EOH].

Based on the calculated statistical measures, the coefficient of variation is calculated as follows:

$CV = SD/t_{mot} = 0.25.$

Since the calculated value of the coefficient of variation is less than approved (CV=5), it can be started with determining of Probability Density Function of engine operating time to failure.

The number of intervals of operating time to failure is determined by the formula [2]:

$z = 1 + 3.3 \cdot \log10(n) = 7.67$, so it adopts a number of intervals: z = 8.

Table 2: The estimated value of reliability indicators

i	n_i	sv_{int}	cn_{is}	f	F	R	h
1	2	166.75	1	0.000287	0.008772	0.991228	0.000289
2	6	230.25	4	0.00086	0.035088	0.964912	0.000891
3	10	293.75	9	0.001433	0.078947	0.921053	0.001556
4	19	357.25	18.5	0.002723	0.162281	0.837719	0.003251
5	29	420.75	33	0.004157	0.289474	0.710526	0.00585
6	17	484.25	41.5	0.002437	0.364035	0.635965	0.003831
7	13	547.75	48	0.001863	0.421053	0.578947	0.003218
8	9	611.25	52.5	0.00129	0.460526	0.539474	0.002391

Symbols used in Table 2 have the following meaning:

i - ordinal number of the interval,

n_i - number of failures in the interval,

sv_{int} - the mean value of the interval [EOH],

cn_{is} - the estimated value of the number of failures in the middle of the interval (calculated as the arithmetic mean of the number of failures at the beginning and the end of the interval);

f $[EOH^{-1}]$ = $n_i/(n \cdot \Delta t)$ - Probability Density Function, n = 105 sample size, Δt = rang/z,

F [-] = cn_{is}/n - Cumulative Density Function

R [-] = $(n-cn_{is})/n = 1-F$ - Reliability Function,

λ $[EOH^{-1}]$ = f/R - Failure Intensity Function.

Figures 3. and 4. give a graphical representation of the estimated indicators of reliability.

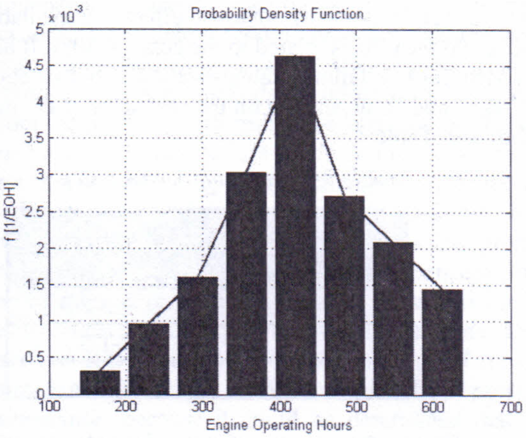

Figure 3: Estimated value of failure state density graph

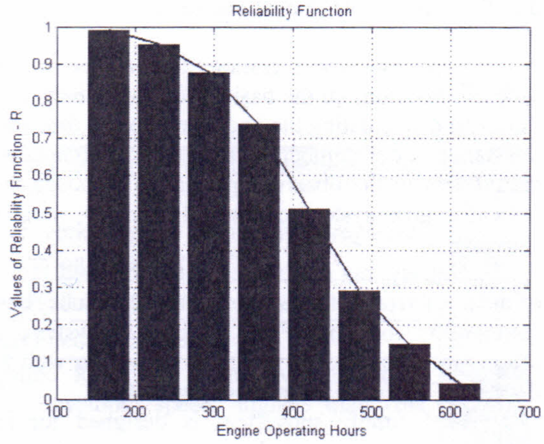

Figure 4: Estimated value of reliability function graph

3.1.2. Determination of the distribution model and parameters with the evaluation of the compliance

In order to determine the theoretical distribution model which could be used to approximate the empirical distribution, there was used an approximation of the empirical distribution with theoretical Weibull (Weibull), exponential, Rayleigh (Rayleigh) and normal distribution. Rating of compliance of the empirical and theoretical distributions was conducted by using the Kolmogorov-Smirnov test and Pearson test of Romanovski.

For the statistical analysis of data was used the Statistics Toolbox for use with MATLAB [3].

As quantitative deviation indicators (D_n and χ^2) for two of the three applied tests, are the far smallest for Weibull distribution, Figure 5., for the approximate model of the special vehicle engine reliability has been adopted the two-parameter Weibull distribution with Scale parameter η_w=463.6393 and Shape parameter β_w=4.5746, so the formula for reliability function of engine is:

$$R(t) = e^{-\left(\frac{t}{\eta_w}\right)^{\beta_w}} = e^{-\left(\frac{t}{463.6393}\right)^{4.5746}} \quad (1)$$

When calculating the reliability function according to the preceding equation, the variable t is expressed in the EOH.

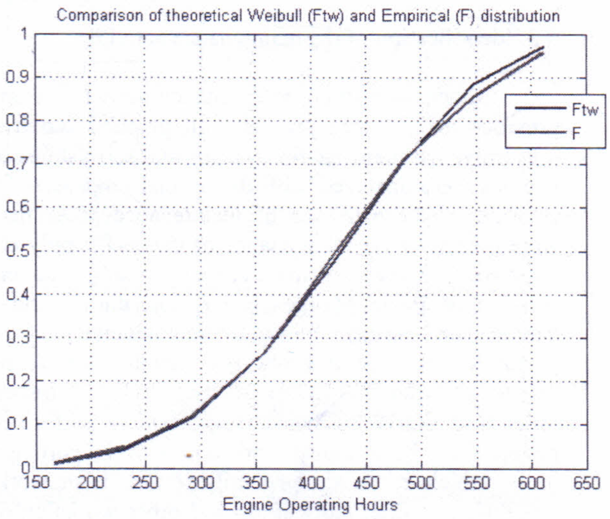

Figure 5: Graphic display of Weibull approximate distribution from the empirical distribution deviations

3.2. Selection of the critical engine subsystem

For further consideration of the engine maintenance program revision, on the basis of collected data on engine failure and calculating the engine reliability function, from the standpoint of number of failures of its components and subsystems in the observed period, it is chosen the most critical engine system of special vehicle - Fuel supply subsystem.

Namely, out of a total of 105 analyzed failures, 74 of them referred to the failures of devices, subsystems and components of the Fuel supply subsystem, which according to the Pareto principle contribute with 80% in the cost of engine maintenance, Figure 6.

Fuel supply subsystem is designed for storage, purifying and supply of the necessary quantities of fuel into the engine cylinders. The system also provides the fuel needed to operate the engine preheating system, engine cold start system, smoke screen forming system, as well as the overflow of the excess fuel from High Pressure Pump (HPP), injectors and heating system for the engine. Fuel supply subsystem comprise: the fuel tank, fuel distribution valves, electric pump for fuel supply, low-pressure pump, double-purifier tank, HPP, injectors, one-way valve for the fuel overflow, vent, pipes, hoses and electric fuel pump switches.

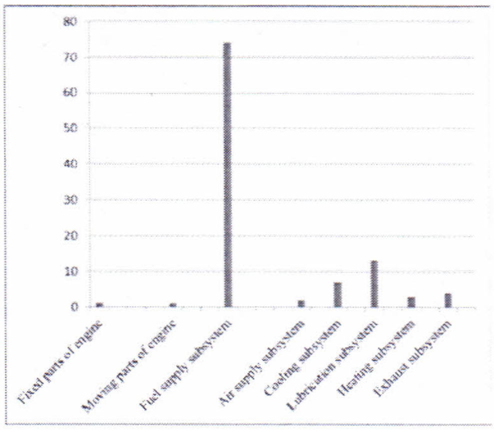

Figure 6: Number of failures by individual subsystems of the engine in the observed period

3.3. Identification of the maintenance activities

When identifying maintenance activities from the previous maintenance program, all planned activities of preventive maintenance for systems and subsystems of the engines were analyzed with the special emphasize to the analysis of the activities of maintenance programs that were related to the maintenance of the fuel supply engine subsystem. Preventive maintenance of subjected engine consists of Basic Maintenance (prior, during and after exploitation check), Periodic Maintenance (which is performed at least 2 times per month), 1st Technical Inspection (after 180 EOH) and 2nd Technical Inspection (after 350 EOH). Technical Inspection is performed by people from the technical workshop with the participation of the vehicle crew, who primarily perform basic work like washing, cleaning, lubricating, and other works entrusted by the specialists who perform supervision and checking of executed works.

During the analysis of the preventive maintenance activities it was concluded that provided technical guidelines do not plan activities on preventive maintenance of critical components and elements of the fuel supply engine subsystem of the vehicle, except checking the seals and tension of fuel tank caps, draining the fuel tanks with discharging of sludge from the tank, washing the vent with a float opening and washing of coarse fuel filter.

3.4. Failure modes and effects analysis

Failure modes and effects analysis (FMEA) is a tool that examines the potential system or process failures and helps to determine the specific activities in the field of maintenance in order to avoid the consequences of identified failures. Table format allows easy and simple overview of the analysis. FMEA helps to identify ways of creating functional failures. Table 4. represents the FMEA for the most critical fuel supply engine subsystem. It was performed FMEA at the local level, then at the level of the engine, and finally the analysis of the final effect of the failure to the entire special vehicle's mission, from the standpoint of whether it is a hidden failure, failure danger to the security of the system or the environment, failure with consequences for the system's functioning or failure without consequences for the system's functioning.

3.4.1. Failures risk analysis

Consequences of failures can be categorized in various ways. The risk analyisis of the fuel supply engine subsystem failures was performed, with analysis how the consequences of failure affect on availability and security as two key parameters essential for consideration of appropriate maintenance procedures of this engine subsystem. Also, the risk analysis takes into account the values of the particular engine systems. The performed failures risk analysis should serve for the ranking of the individual parts and assemblies of the fuel supply subsystem regarding prioritization of their maintenance work, reliability and availability improvement, maintenance cost reduction and others.

The effects of failure regarding safety were taken with a weight factor of 30%, the effects on availability of 40% and the effects related to the costs of 30%. It has been carried out risk failures categorization into 4 categories of A, B, C and D, depending on the criticality of the index, as shown in Table 3.

Table 3: Groups of the risk index

Group	The risk index
A	3-2.5
B	2.5-2
C	2-1.5
D	1.5-1

Due to the volume of work for risk analysis for a complete engine, it was performed the failures risk analysis for the fuel system as it is the most critical engine's system. In Table 4 are given indices which belong to the risk group of individual parts and components of the fuel subsystem.

Table 4: FMEA and groups of risk

Elements and assemblies of fuel supply subsystem	The mode and effect of failure	The cause of failure	A group risk
High-pressure pump (HPP) with commands	Decreased power of engine.	Elements of HPP not work (Worn out of element is the main cause of failure)	B
		HPP Regulator not work properly (Worn out of regulator or cracking of the spring regulator).	B
		No well-setting of HPP commands.	B
		No well-tuned fuel injection angle.	B
	The engine achieves high revs (may cause large damage)	High pressure pump Rack and Pinion Mechanism is blocked (engine develops speed higher than the maximum)	A
Injectors	Decreased power of engine. Engine smokes and not develop full power. Engine noises.	The defective injectors (uncontrolled leakage of fuel through a nozzle needle spray hole, nozzle needle is blocked or not close well, fracture of the return spring)	B
Low-pressure pump	Engine cannot start or starts but after the first revs stops.	Low pressure pump not deliver fuel to HPP.	C
Fuel filters	Engine cannot start.	Dirty filters or fuel pipelines closed.	B
Pipelines fuel assemblies	Engine noises. Engine cannot start. Engine after the first revs stops.	Air in the fuel supply subsystem.	C

At this step is achieved a key activity preparation for the determining of the maintenance on the basis of the result of failure concept, and not for maintenance due to failure occurrence. In other words, it is attempted to have the maintenance that manages the failures and not the failures that manage the maintenance.

3.5. Decision algorithm

Decision algorithm (DA), shown in Figure 7, is used to decide whether to use the corresponding optimal maintenance concept. The figure shows that making decisions, takes into account three key parameters: 1) security 2) availability 3) costs. After the completion of certain engineering methods mentioned in the previous section as well as performing the analysis of th repairs level, every possible failure mode is introduced into the algorithm by answering the typical questions through DA, so depending on the response and algorithm branch direction it is come to the final guidelines and proposals for the selection of optimal maintenance concept for that type of failure.For each maintenance activity is analyzed the technical feasibility and effectiveness, as already described. It is not ruled out and the selection of corrective maintenance for failure modes extracted from preventive maintenance, because it could be determined that some maintenance actions were previously identified on false assumptions. As for failure modes extracted from the earlier corrective maintenance, the assumption is that the majority of them will be again within the corrective maintenance after the application of the DA.

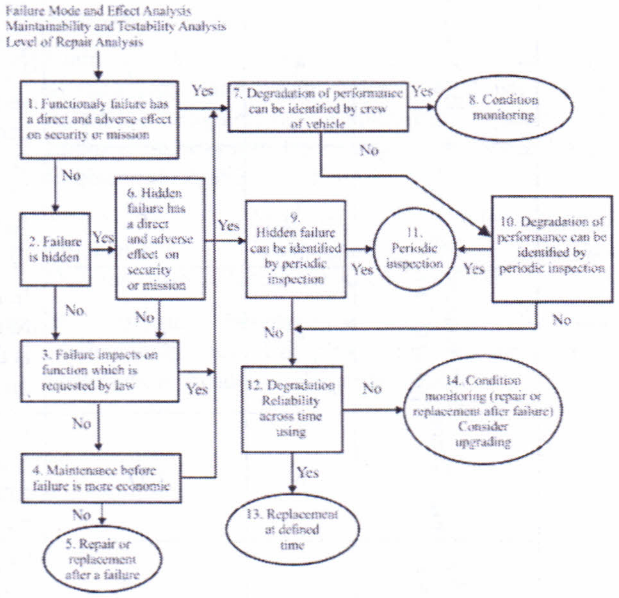

Figure 7: RCM decision algorithm

3.6. Selection of the optimal maintenance concept

After performing the above given analysis, it starts the selecting of optimum condition based maintenance by single engine subsystems, where for this particular case this will be presented only for the fuel supply subsystem.

One of the major advantages of using RCM methodology for maintenance is a mode that enables easy, precise and easily understandable criteria for deciding which (if any) of the preventive tasks is technically feasible in any context, and if so to decide how often they should be done and who should do it.

When considering the possibility of determining the concept of maintenance by the individual elements and engine fueling system assemblies, the main condition was that the reliability of the engine is less than 0,985.

Concepts of maintenance that were considered in the selection of the fuel supply subsystem maintenance concept were: run to failure (RTF) or corrective maintenance, maintenance on the basis of time resources (TD) and condition based maintenance (CD). The selected maintaining concepts by individual assemblies and elements of the fuel supply engine subsystem with the intervals of their implementation are illustrated in the Table 5.

3.6.1. Rationalization of maintenance intervals

When the selection of maintenance concept is completed, as the result is obtained a set of maintenance actions within different time intervals, which is, from the viewpoint of efficiency, necessary to group into a certain maintenance programs or to incorporate into existing ones. One of the reasons may be that some maintenance actions are performed by crew and some require the capacity and resources of the repair facility, like engine test benches and stands or other specialist's equipment.

Table 5: Selection of the optimal maintenance concept and maintenance intervals

Elements and assemblies of fuel supply engine subsystem	Ordinal number	The concept (task) of maintenance	Description of maintenance activities	Frequency [EOH]
High-pressure pump (HPP) with commands	1	TD	Checking of setting commands of HPP and, if necessary, adjust it. Crew of vehicle is not carried out the setting of the commands. A mechanic performs the mentioned activities.	100
	2	CD	Dismantling and testing of HPP on bench. The engine is not removed from the vehicle. The activities are carried out by expert team from Overhaul Institute.	200
	3	CD	Disassembly and overhaul of HPP depending on condition of HPP. Then, assembly and setting of HPP on the bench. Checking of injection angle setting and, if necessary, adjust it. The activities are carried out by expert team from Overhaul Institute.	400
Injectors	4	TD	Dismantling and test of injectors on bench. Depending on of the test results, injector shall be replaced or repaired. The activities are carried out by expert team from Overhaul Institute.	200
Low-pressure pump (LPP)	5	RTF	In the previous period, the LPP was extremely reliable the assembly without failure. The proposal is that the LPP runs to failure without taking action on preventive maintenance.	
Fuel filters	6	CD	It is necessary to carry out a visual inspection of the fine filter cartridge. If during the inspection of filters, filter cartridges do not meet the declared characteristics, it should be replaced.	100
Pipelines fuel assemblies	7	TD	The emergence of air in the fuel supply subsystem is the result of the leakage of fuel, cracking pipes, bad hermetic of filter fuel. Checking of the subsystem is carried out on each of 100 [EOH], by a mechanic.	100

For example, two or more maintenance activities require repair capacity, and should be performed in a different, close time interval. In this case, from the standpoint of cost effectivness and overall readiness is better to perform them in one interval.

If the maintenance activity which is determined by the interval, is faced with shortening the interval, the higher maintenance costs will occur. This is obvious because the maintenance activities are more frequent.

On the other hand, if the maintenance interval is extended, the maintenance costs will decrease, but increases the risk of failure. Here the problem of rationalizing interval will not be considered in detail, so only the basic remarks are given, bearing in mind that the optimal maintenance intervals of other engine's systems and other components of the vehicle systems are not known.

In this specific case of the fueling system, the maintenance intervals of the single assemblies and subsystems are determined so that the following interval is obtained by multiplying the basic one. In addition, the proposal is that interval of 1st Technical Inspection of an special vehicle engine, shifts from the existing (180 EOH) to 200 [EOH] with additional maintenance activities, which are given in Table 5. (except the activity at the ordinal number 3.), and the current interval of the 2nd Technical Inspection (350 EOH) is to be performed at 400 [EOH], after expanding the content of maintenance activities according to Table 5. (except the activity in the ordinal number 2.), by removing the engine from the vehicle, and performing a complete test and diagnostics at the test table. Depending on the condition of the engine, the further activities would be undertaken in order to bring it to functionally correct state.

4. CONCLUSION

The paper analyses the possibility of revising the existing maintenance program of special vehicle engine by applying RCM methodology. Analysis was carried out for the fuel supply engine subsystem, which was showed as the most critical subsystem from the standpoint of the number of failures in the observed period during its exploitation. As the result of these systematic analyses, the maintenance concepts of the critical parts and assemblies of the fuel supply subsystem were selected and the intervals of realization proposed maintenance activities in accordance with a predefined request that the reliability of the fuel supply engine subsystem is not less than 0.985.

Compared to the existing program of the fuel supply subsystem preventive maintenance, a new program proposes additional maintenance activities as a condition based maintenance and maintenance on the basis of time resources of critical assemblies and elements of engine subsystems that are not covered by the current program of preventive maintenance. In order to optimize the maintenance interval, the recommendation is that proposed additional maintenance activities should be included during the first and second Technical Inspection with a slight extension of their maintenance interval.

Keeping in mind overall contents of the carried out analysis, which preceded the selection of maintenance concept of critical assemblies and elements of the fuel supply subsystem, the conclusion is that the application of the basic principles of the RCM methodology during the choice of optimal maintenance concepts and for other engine subsystems and by optimizing the interval of their execution would create conditions to significantly improve the effectiveness and efficiency of maintenance and thus the reliability and availability of these types of engines.

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