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OPTIMISING COMBAT TRACKED VEHICLE MAINTENANCE WITH RCM

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The article deals with the application of the RCM methodology in this case of combat tracked vehicles used in the Czech Republic Armed Forces and with the problems which appeared during the project, and it describes procedures how to solve them. A practical application of the methodology is demonstrated with the example of the vehicle drive-train. Using the RCM methodology, relatively simple design adjustments were recommended and a package of preventive maintenance tasks was developed to effectively reduce the intensity of the drive-train's failures and its maintenance costs. The results of the analysis of the drive-train failures also showed that the time schedule of some time-directed tasks of preventive maintenance is not established well. Based on the results of the vehicle monitoring, a model describing the LCC dependence on the duration of time interval to the accomplishment of such preventive maintenance tasks was presented. The proposed model then enabled one to optimise the periodicity of scheduled preventive maintenance. In practice, a set of suggested measures in the area of design and preventive maintenance was implemented. The results of the subsequent monitoring of the vehicles in service show that the implementation of the recommended measures resulted in the improvement of vehicle availability as well as in the reduction of its LCC.

Keywords: *RCM (Reliability Centred Maintenance), armament and military equipment maintenance, reliability, life cycle costs, tracked vehicles*

INTRODUCTION

In the Army of the Czech Republic, a large number of heavy military vehicles were observed in service over a long time period to collect data on their reliability and maintainability, including relevant economic data. The data obtained were used for the determination of basic dependability characteristics of the vehicle and its main subsystems and for the analysis of the vehicle's LCC. Among other findings, the results of this analysis showed an unsatisfactory level of the costs associated with maintaining the vehicle. For this reason, it was decided to look for ways to reduce maintenance costs through a change of the maintenance concept of the vehicle. There was also an effort applied to solve the unsatisfactory situation regarding several vehicle‘s parts due to their failures intensity.

The results of analysis were based on the data of the power-pack failures and apart from others showed that time schedule of some time-directed tasks of preventive maintenance is not established well. Based on the results of the vehicle monitoring, we will present a model describing the LCC dependence on the duration of time interval to accomplishment of such preventive maintenance tasks. The proposed model enables to optimise the periodicity of scheduled preventive maintenance [8].

In practice, a set of suggested measures in the area of design and preventive maintenance was implemented. The results of the subsequent monitoring of the vehicles in service show that the implementation of recommended measures resulted in the improvement of vehicle availability as well as in the reduction of its LCC by more than 25%. Also, an assessment of sub-system and components failures was carried out. As the cause, mode and effect of failures were investigated, it was discovered not only operational condition being the main reason of failures. For such failures, a relatively simple solution was also proposed. Using the RCM methodology [2], relatively simple design adjustments were recommended and a package of preventive maintenance tasks was developed to effectively reduce the intensity of the power-pack's failures and its maintenance costs.

1. RELATION OF SAFETY AND RCM ASSESSMENT

The role of safety has different importance if we talk about civilian or military vehicles. Military systems are supposed to operate in very specific environment under very rough conditions comparing to civilian ones. The failure of technical object (talking about civilian cars for instance) may occur in typical operational conditions. As far as the failure does not influence safety immediately (this is not very often) the failure consequence process is usually normal and safe. Different is the situation in the military environment. As we know, the military vehicles have to conduct missions in specific conditions, especially like for instance battle vehicles in real fight. If a failure of a military vehicle occurs in a battle operation the failure consequence does not have typical, normal and safe process as in the case of civilian applications. Such a failure may not avoid only mission completion but, moreover, it may bring crew members of a vehicle into life threat. That is why, we have to assess safety circumstances of military vehicles failures very carefully and precisely. This description characterises the main relation of failures and safety both for civilian systems assessment and for military systems assessment [9].

2. DESCRIPTION OF RCM METHOD APPLIED

We assess military application represented by heavy tracked armed vehicle. That is why, it is necessary to evaluate it very precisely. As we speak about real battle vehicle which is supposed to fulfil battle missions there is a desperate need to differentiate between training operations of that vehicle and between real. As we mentioned above, parts – subsystem of vehicles´ power-pack namely gearboxes were assessed. The function of this part is required in both types of operational usage. Losing the function capability of gearbox then all basic measures and features describing mobility are lost as well. That is why, we have to concentrate our interest onto possible failures elimination as well as onto investigation of causes' occurring failures. As we mentioned above, the vehicle might fulfil tasks both in peacetime and wartime. Both of these options lead to consequential failures´ effects estimation according to the RCM procedure [5]. That is why, we always consider failures effect upon safety. The mobility features losing while performing a battle mission due to different reasons might be lethal for all crew members working inside a vehicle as well as destroying the whole vehicle. We take into account the worst scenario possible for the vehicle, which means direct endangerment of crew members due to loss of mobility features on the battlefield (during mission completion) caused by internal reasons.

Generally all of the failures detected have hidden (latent) character in the gearboxes assessed. That is why, we concentrate our interest on RCM way speaking about hidden (latent) failures with safety influence. A possible way of failure assessment is as follows. According to the methodology given in international standards [2], we follow the line given in this case for gearbox assessment. As you know, the flow diagram for effects estimation we use it in following way. See Fig. 1 where the basic scheme of RCM logical tree of deciding is presented.

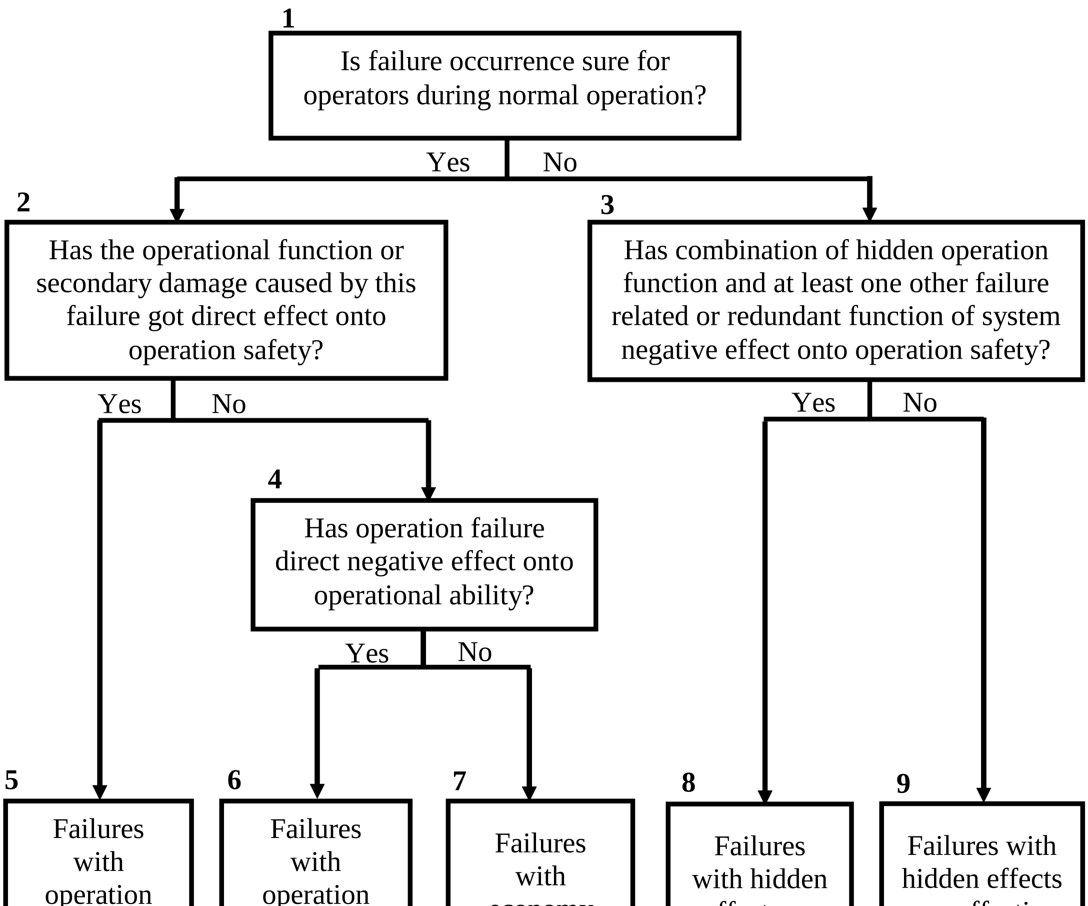

Fig. 1. Logical tree of RCM deciding

Source: [2]

We continue in this logical tree and select box 5 representing our technical case. There is a set of questions in logical structure for this box insert in steps and evaluating effects influencing safety. We take from this sub-logical tree a diagram belonging to box 5 (for the whole structure see [2]) only those steps which are applicable and suit our case of assessment.

1. Are lubrication tasks or maintenance tasks applicable?

   Yes, we are supposed to check periodically the level and amount of lubricants, such as oil and others. We are also supposed to perform control parts lubrication while performing several of the maintenance operations at different level of complexity. We also have to change oils and other lubricants in time periods prescribed, etc.

2. Does applicable and effective check out procedure for operation assessment exist?

   No, unfortunately we do not have applicable diagnostics system for operational assessment of gearbox just before or during an operation.

3. Is review or function check out or function monitoring applicable and effective for degradation detection?

   Yes, we know and also apply check out procedures such as tribo-diagnostics, which suits the evaluation of fragmental parts content in lubricants. According to such a an analysis (presence of small abrasive fragmental parts) we might determine possible source and reason of certain parts abrasion and we may decide consequential steps for improving this state.

4. Is repair task applicable and effective for failure rate decreasing?

   Yes, we have to follow and respect either preventive repairs timing dealing with preventive parts replacement or we also might perform other (small, non-complex) repair procedures while different part (usually at higher level) is repaired. During strictly prescribed times for preventive maintenance (scheduled repairs) we have to carry out precise detection, then real diagnostics onto certain components with replacement those which do not fit or fulfil measures required (e.g. their technical life is evidently shorter than vehicle's life expected). Than the whole subsystem is fixed and put back into operation.

5. Is disposal task applicable or effective for failures prevention or failure intensity decreasing?

   No, we usually do not improve this part (gearbox) measures when disposal applied.

6. Does task or task combinations for improving exist?

   Yes, when we optimize several procedures or set up some tasks (e.g. usage and handling accesses) we might expect partial improvement of several measures. But this area has not been solved systematically yet.

At this moment the chain is over for those effects assessment which influences safety (according to steps prescribed in standard). After performing and assessing all of these steps and if we still want improve our object measures or capabilities we have actually two options. We might either carry out design change or apply the best task or tasks combination available for measures improvement. According to results really obtained from our operated gearboxes assessment and based on real pursuable procedures available we had decided for practical application of several steps of RCM methodology mentioned in the description above.

3. PRACTICAL APPLICATION OF METHOD

A practical application of the methodology is demonstrated on two examples. The first effort for reaching a solution was situated in the field presented by step 4 – proper new maintenance policy adjustment let say optimization of maintenance period. Such a way saves money regarding keeping the level of failures intensity required due to avoiding failures (during preventive maintenance scheduled repairs procedures). This way was limited by the requirement not to change the basic principles of the maintenance concept, which are determined by the general maintenance policy of the army. It meant that the improvement desired could be achieved only through a change in the frequency of preventive maintenance. The original maintenance concept of the vehicle included also, besides classical preventive maintenance actions, scheduled repairs with the aim to replace or repair the stated vehicle's sub-systems and parts whose life cycle is shorter than the expected vehicle life cycle as such. The accomplishment of these scheduled repairs is very expensive and represents a decisive part of preventive maintenance costs of the vehicle. For these reasons, it was decided to analyse especially the influence of these repairs' frequency on the amount of maintenance costs.

The second effort was aimed at the field represented either by step 6 or pure output of the flow diagram. This means either task/tasks combination application (step 6) or partial low expenses construction changes which might influence the failure rate in positive way. We speak about construction changes for maintenance procedures improvement. Several failures, which are caused by rather elemental reasons, were discovered during our gearboxes assessment, for their solving would be very useful to make easy, quick and relative cheap construction changes. One of the possible solutions is also presented below.

As a solution to the above-mentioned tasks, the article's authors created a mathematical model describing relationships between the overall LCC of the vehicle and frequency of the prescribed maintenance actions. This model allows us to determine the frequency of repairs in which LCC of the vehicle reaches the minimal level. The authors also suggest a way for several failures ceasing due to proposed way of one part of vehicle construction change. All of these proposals are related to those output of flow diagram which they represent. The procedures carried out separately both maintenance procedure optimization and design revision or both of them together increase measures of dependability especially availability and closely related features.

4. MODEL OF OPTIMIZATION OF MAINTENANCE PERIOD

Let us have a vehicle in the design of which a certain subsystem is used, and a periodical replacement should be carried out as a form of certain preventive maintenance action. The subsystem's faults detected in service are corrected by repair of a subsystem. In addition, the subsystem under research undergoes a scheduled preventive maintenance consisting in a simple checkout and setting-up. The aim of optimization is to determine a period of replacement of a subsystem so as to minimize the vehicle unit life cycle costs [6, 7]. Let us assume that all necessary subsystem technical-economic data are known.

The proposed optimization model disregards those components of LCC, which are not influenced by the scheduled maintenance action and so they cannot influence own optimization [4]. In this case, it is possible to express the total LCC of the subsystem by equation:

$$C_C = C_B + C_M + C_R , \tag{1}$$

where:

C_C – total LCC of the subsystem;

C_B – subsystem acquisition price and costs related to its replacement;

C_M – total preventive maintenance costs of the subsystem;

C_R – total repair costs of the subsystem.

It is further assumed that the subsystem acquisition price is constant and that it does not depend on the operating time, and that preventive maintenance costs and subsystem repair costs depend on the operating time. So called "unit cost", which represents a quotient of cumulative costs expended during the operating time t to the operating time t, are used for the next solution:

⇒ unit acquisition costs of the subsystem:

$$c_B(t) = \frac{C_B}{t} , \tag{2}$$

⇒ unit repair costs of the subsystem:

$$c_R(t) = \frac{C_R(t)}{t} , \tag{3}$$

⇒ unit preventive maintenance costs of the subsystem:

$$c_M = \frac{C_M(t)}{t} . \tag{4}$$

For further solution, it is assumed that term (3) which expresses the unit costs for preventive maintenance is constant. Unit LCC then can be expressed by the next equation:

$$c_C(t) = c_B(t) + c_R(t) + c_M . \tag{5}$$

Fig. 2 shows a graphical representation of above described mathematical model. From the Fig. 3, it is obvious that optimization condition is met for a length of maintenance period $t = t_{opt}$, where a function $c_c(t)$ attains its minimum (point D on the graph of this function). Thus, if the subsystem under research will always be disassembled after the operating time t_{opt} and replaced by a new one, the unit LCC of the subsystem will be minimum $c_c(t_{opt}) = c_{c\,min}$.

5. EXAMPLE OF PRACTICAL APPLICATION OF OPTIMIZATION MODEL

A proposed mathematical model was practically used for optimization of the maintenance concept of military heavy tracked vehicles fielded in the Army of the Czech Republic. Next, a process of optimization of maintenance period at one subsystem of the vehicle drive train is presented. The applied concept of vehicle maintenance required always after covering 12,000 km, to perform a scheduled preventive repair consisting in a given subsystem replacement.

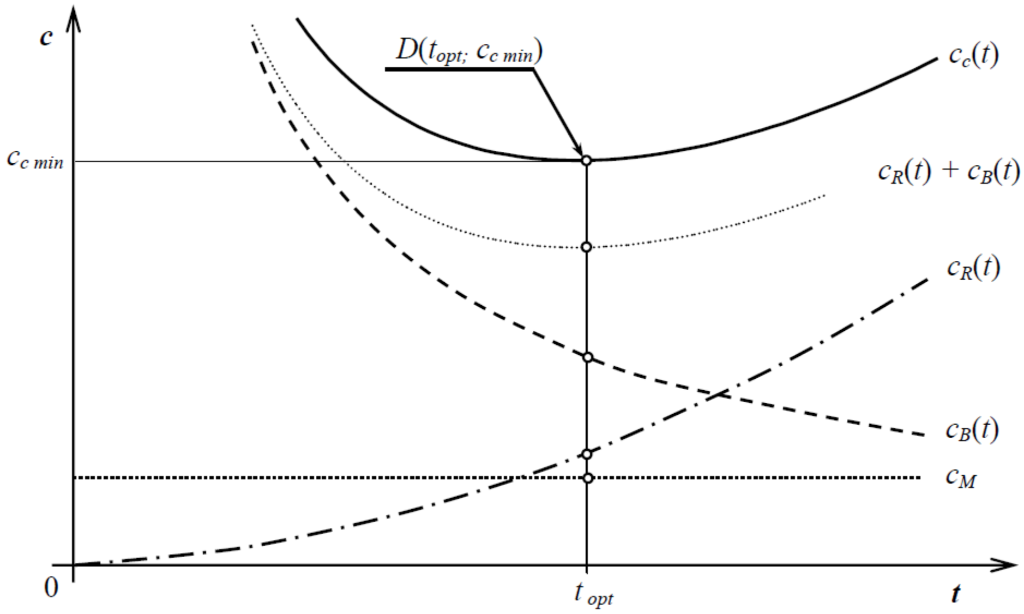

Fig. 2. Graphical representation of optimization model

Source: Own elaboration

Based on the long-term observation of a great number of vehicles, the costs related to repairs of failures of this system were evaluated. The results of this evaluation are graphically expressed in the Fig. 3. In this case, it is not possible to establish an exact length of optimum operating time since no data about the behaviour of the subsystem with operating time more than 12,000 km are available. However, from the charts in Fig. 3 it can be anticipated that optimum operating time will probably be within 15,000-17,000 km. In accordance with the above-mentioned conclusions, a change of operating time to the replacement of observed subsystem from 12,000 km to 15,000 km was recommended [7].

Using the described method, a suitable replacement time at all subsystems and vehicle parts where the applied concept of maintenance a similar replacement is expected was evaluated. In cases when it revealed that that the operating time to replacement of subsystem or a part of vehicle is not established as optimum (it is shorter or longer), the appropriate changes were recommended. Justification of recommended changes in the conception of vehicle maintenance would be verified in the next observation of vehicles with modified periods of maintenance.

A presented method indicates that data from the observation of vehicle operational reliability can be with success employed for optimization of conditions of their maintenance. By means of the proposed model, it is relatively easy to find reserves in the conception of vehicle maintenance and by using a simple measure – an administrative change of maintenance periods – to attain significant savings in the vehicle LLC.

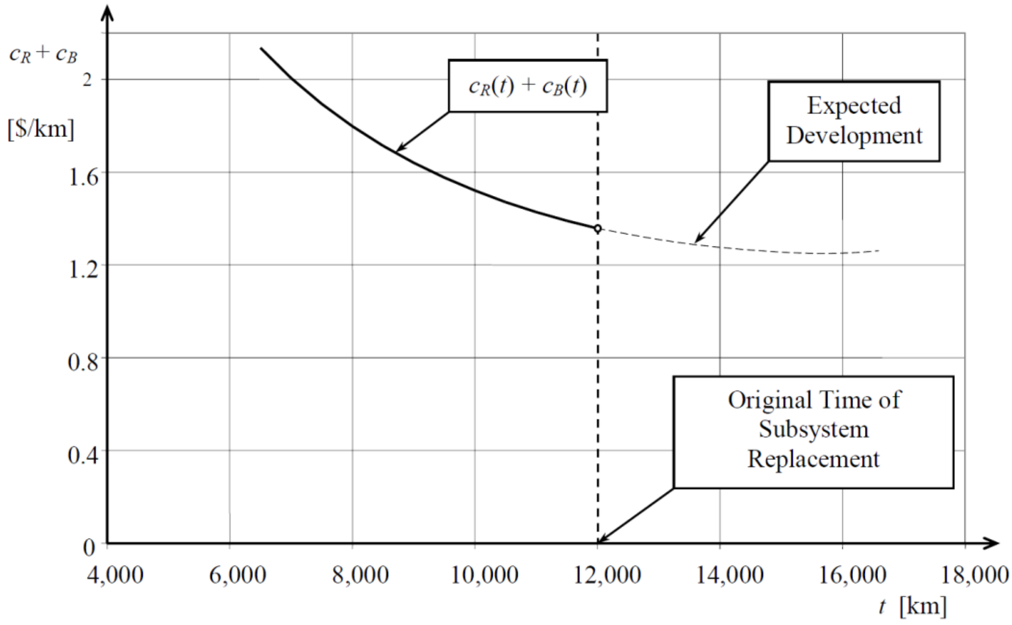

Fig. 3. Graphical model of optimization

Source: Own elaboration

6. PROPOSAL OF CONSTRUCTION CHANGES

As the previous model was focused on maintenance procedures optimization using LCC data, the second part of this contribution is aimed at possible low cost construction improvements which might cease some failures occurrence. The parts and subsystem observed were not investigated from the LCC point of view only. Especially proper investigation and tests on gearboxes of the heavy armoured vehicles had gone on. Special attention was paid to investigation of all failures occurred.

Because this system of gearbox as a whole is complex mechanical and hydraulic part of vehicle and it consists of plenty of components which may fail due to different reasons. The FMECA method was used for all possible failures detected or predicted [1, 3]. All the components were investigated in terms of possible failure occurrence as well as its cause, mode, effect and criticality. After performing this procedure we considered results and focused our attention on most important parts of the gearbox. Because this gearbox is a system which is already implemented into vehicle and an essential amount of those vehicles operate in frame of the armed forces it is not so easy to make radical constructional changes in terms of improving several parts measures. We consider those which might be applicable, pursuable and possible.

Apart from this, there is a desperate pressure on the armed forces to be able to stand by in time period defined and/or stay in readiness state defined. These requirements are supposed to be guaranteed not only by soldiers but also by availability of technique and equipment introduced. As we said above we cannot replace these vehicles while performing extensive constructional changes but we may consider possible other changes using another technique.

One of the components of the gearbox are lamellas which transfer the rotational forces between other elements. These lamellas work in very hard conditions under high pressures, very high temperatures, influenced by friction and abrasive environment. Moreover, the lamellas are very important for drive train as a whole as essential part. That is why we classify them as a weak point of mobility assurance. Due to relatively big amount of these lamellas it is useful to investigate them more properly.

It was discovered during investigation that failures of lamellas occurred. The way of failures assessment shown below uses well known terms from the so called FMECA sheet. Typical failure of lamella was total burn and destruction caused by high pressures on structure burned and loss of consistence. This mechanism of failure mode is caused by mechanical overload – huge area pressure onto lamella surface, high friction lasting for longer time period than usual, while temperature is rising exponentially. Such as failure does not occur frequently and the character of failure is hidden (latent). It may occur by one lamella only as well as by more of them while discovering (which is a paradox) is the easier the more of them does not work. We also record another features unfortunate for us – the more lamellas do not work the higher probability of operation disability. Several types of such failures were discovered during the investigation of gearboxes available. The primary cause of the lamella failure might be these main reasons:

- operation and its aspects;
- construction design and manufacturing;
- environmental conditions;
- human misuse or mishandling (by operation, by omitted maintenance, etc.);
- others.

Congruence of all of the above mentioned aspects might play a significant role in failure occurrence. When collected failures of those lamellas were assessed, no construction, manufacturing or environmental aspects were observed or discovered. All of the failures recorded and put under investigation were caused during an operation and related to human mishandling.

After the precise estimation of failure cause the main reason was discovered as improper shifting operations while vehicle races. The whole possible (presumable) mechanism of failure is described as follows. From the typical (current) construction as well as an operational point of view it is possible to put gear from driver's position during a vehicle moving and during shifting operations without clutch down. This may be carried out into both upwards direction and downwards direction but always with one gear level only. In such a situation it happens that the whole system does not release current gear put into drive train in gearbox and does not cease power transfer from mechanical parts connected while the new gear is put into the whole chain to operate. The reaction onto lamellas´ surface which are the most important as well as sensitive parts for gears switching cause an incredible increase of load onto lamellas, it also causes the rise of temperature and it consequently causes unacceptable friction forces.

Due to braking (no-releasing) of several degrees of freedom, needed to be transferred from lamellas but not allowed, the burn of lamellas occurs. This is just the beginning of complete change in the lamellas structure, which influences their measures – namely consistency. The huge pressures onto lamella's surface cause impossibility to keep consistency of lamella and stand by for the operation required which instantly leads to destruction. The whole mechanism needs to last only several seconds for the destructive behaviour to be completed. From this moment it is not possible to rely both on lamella's right function and vehicles right operational features – capabilities.

We might observe this situation either immediately – the vehicle terminates operation instantly due to failure or later on when all failure consequences influence current operational requirements. Such a failure causes a vehicle's unavailability which might be solved only when a proper corrective maintenance (the right level of prescription) is performed. Such a procedure of corrective maintenance (usually carried out as gearbox replacement) is very expensive and might be avoided. There are two differences in a vehicle's operation already mentioned above. Firstly, we speak about training preparation, and secondly, about real battle deployment.

We have to determine conditions for such failure avoidance. Our recommendation leads to easy construction change which ensures right shifting operation required. This solution will also guarantee the correct drive technique required. The trick is to install simple control device into place of driver. Such a device assures clutch down necessity in the process of shifting. It will never be possible to shift another gear with not clutch down. Nowadays we presume that this method of solving problem might be eliminated due to the different access of military drivers. The previous data were obtained from the training of conscripts who used to be main manpower in the Czech armed forces. Today we presume that such manners should be eliminated due to professionals, but this is not ensured automatically. Apart from the different natures of men, which might be cared during preparation training phase, there is always the eventuality of real deployment into battle where it is very difficult to determine about our real behaviour in crisis situation. Such a situation can never be simulated. That is why, such a tendency for shifting without clutch down may occur when a driver works under pressure and a real possibility of danger.

Another argument might talk about abandoning these old military tracked vehicles controlling systems and replacing them with better ones (such as power pack). This is a correct argument but still we use many older non-modernized types of such vehicles and, moreover, there are other armed forces in the world with the same type of equipment and no money enough neither for modernization nor for new vehicles. That is why, we presume such a solution in one of the subsystem part assessed as beneficial.

CONCLUSION

We have presented two methods for maintenance procedures improvement in this contribution, both of them based on RCM procedure.

The first one is focused more on the field of related aspects of maintenance investigation. This way uses costs and trays to propose a new optimized method for preventive maintenance periods performing. Such a method wants to save money due to preventive maintenance intervals optimization, which is always good.

The second method wants to optimize maintenance procedures as well, but wants to avoid extra additional costs spent for extra maintenance performed. Different way was used in this case. We have presented one type of failure of heavy military armoured vehicle gearbox occurred, which is caused by human mishandling only. Such a repair for failure elimination costs also money and quite a lot. But the principle for this kind of failure avoidance stands in the field of little, cheap and easy construction changes. After performing such a change we might presume not the occurrence of this failure any more.

Both of these methods have their reason for carrying out and are limited by different circumstances set up. Both of them were applied into the framework of the Czech armed forces with success. In the next or other similar applications it is necessary to evaluate the boundary conditions for possible implementation. The partial or full success is guaranteed when this fragment of the whole recommendation is applied.

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OPTYMALIZACJA UTRZYMANIA POJAZDÓW GĄSIENNICOWYCH PRZY WYKORZYSTANIU METODY RCM

Streszczenie

W artykule rozważono wykorzystanie metody RCM (Reliability Centered Maintenance – eksploatacja ukierunkowana na niezawodność) w odniesieniu do gąsienicowych pojazdów bojowych wykorzystywanych w Siłach Zbrojnych Republiki Czeskiej oraz opisano procedurę rozwiązania problemu, który pojawił się podczas realizacji projektu naukowego. Praktyczna aplikacja metody została zademonstrowana na przykładzie układu przeniesienia mocy pojazdu. W celu zastosowania metody RCM zaprojektowano relatywnie prosty system pomiarowy oraz opracowano zestaw zabiegów z zakresu obsługiwania prewencyjnego, aby skutecznie zredukować intensywność uszkodzeń i koszty eksploatacji układu napędowego. Analiza uszkodzeń badanego układu wskazuje, że dedykowane zabiegi z zakresu eksploatacji prewencyjnej nie zostały jeszcze właściwie określone. Bazując na rezultatach monitoringu technicznego pojazdu, zaprezentowano model opisujący zależność kosztów jego cyklu życia od przedziałów czasowych realizacji zabiegów obsługiwania prewencyjnego. Zaproponowany model umożliwił następnie optymalizację czasookresów zaproponowanych obsługiwani prewencyjnych. W praktyce zaimplementowano zestaw przedsięwzięć z zakresu projektowania eksploatacji i zabiegów prewencyjnych. Rezultaty monitoringu kolejnych pojazdów w czasie eksploatacji wskazują, że zastosowanie zarekomendowanych przedsięwzięć skutkuje poprawieniem ich niezawodności, a także zredukowaniem kosztów życia.

Słowa kluczowe: *RCM (Reliability Centered Maintenance), eksploatacja uzbrojenia i sprzętu wojskowego, niezawodność, koszty cyklu życia, pojazdy gąsienicowe*

BIOGRAPHICAL NOTE

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Lt. Col. David VALIS, PhD, Associate Professor – he has been working at the Department of Combat and Special Vehicles of the Defence University in Brno since 2005. He is a representative of the Czech Republic in the IEC/ISO Technical Commission 56 - Dependability. His extensive technical, research and publishing activity address especially the area of development of safety, risk and dependability analyses in the complex technical systems, and applied research in the fields mentioned above. In the team of research workers he will focus on the area of events´ description, defining the causes and consequences of the events, specification and measures´ description of the events, consequences of events verification, implementation of the obtained results into the analyses, or dependability and safety assessment of complex systems During the last 5 years he has published more than 30 technical papers.