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A Maintenance Free Operating Period Policy for a Multi-Component System with Different Information Levels on the Components State

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This paper deals with the concept of Maintenance Free Operating Period (MFOP). This MFOP is defined as a period of operation during which the system should be able with a given level of confidence to carry out all its assigned missions without system faults or performance limitations. The idea is to ensure with a given level of confidence that no unscheduled repair operation will be required during each defined period of operation.

The main objective of this article is to present an approach to optimize maintenance strategy and to evaluate the system design based on MFOP concept. In this paper, the system design includes the problems of available state information and reliability properties of components which strongly influence the maintenance policy accuracy. An example based on a sub-system of commercial heavy vehicle is introduced to illustrate the proposed methodology.

1. Introduction

Nowadays, the performance assessment in the commercial vehicle industry is not only based on the vehicle configuration. Even if designing the right truck for the right usage is important for any customer, maintenance management is today another key of success. The commercial vehicle aftermarket network and processes are really centric in the sense that maintenance occasions are probably the only remaining place where vehicle manufacturers can meet their customers face to face.

Aware of these opportunities, the development of efficient maintenance management system started 10 years ago. These systems become more and more complex and integrate possibilities offered by new information and communication technology solutions. The integration of smart sensors and actuators to increase the actual knowledge of vehicles health status is an example of these new possibilities.

In this framework, the increase of the operational reliability and the decrease of downtime and maintenance costs are the targets for every commercial heavy vehicle companies in the world. In order to attend these objectives, a reliability-centred maintenance (RCM) strategy can be used. The main objective of these strategies is to find the best balance between corrective and preventive maintenance operations.

Traditional RCM strategies are based on the concepts of mean time between failure (MTBF) and mean time to failure (MTTF). In Kumar et al. (1999), the authors agree that these strategies accept that failures cannot be accurately forecast and avoided. In the commercial heavy vehicle industry, the unplanned downtime resulting of system failures generates a high immobilization cost. This comment imposes to

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develop strategies able to ensure failure free operation with a high confidence level to decrease the associated risks. Aware of these issues, the Royal Air Force proposed in 1996 the concept of the Maintenance Free Operating Period (MFOP).

The rest of the article is organized as follows. Section 2 defines the concept of MFOP. Section 3 develops the system design based on MFOP concept. Section 4 presents the implemented maintenance policy. Section 5 deals with the total maintenance cost definition and the maintenance strategy optimization. The last section illustrates the method on a numerical example.

2. Maintenance Free Operating Period Concept

Definition 1: The MFOP is defined as a period of operation during which the equipment must be able to carry out all its assigned missions without any maintenance action and without the operator being restricted in any way due to system faults or limitations (Hockley, 1998).

Each MFOP (or cycles of MFOP) is usually followed by a maintenance recovery period where the system is repaired to complete the next MFOP with success. Thereby this concept avoids unscheduled activities in moving all upcoming corrective maintenance to a scheduled period of time of preventive maintenance.

In practice, the probability of not having any unscheduled maintenance for a defined period can be measured and the Maintenance Free Operating Period Survivability (MFOPS) is implemented.

Definition 2: The MFOPS is defined as the probability that the system maintains its functionalities during the MFOP given that it was in a state of functioning at the start of the period (Kumar et al., 1999). The probability that the system will survive the *i*th cycle of MFOP of t_{MFOP} life units given that it survives (i-1) cycles is given by:

$$\mathrm{MFOPS}(\mathrm{t_{MFOP}}, \mathrm{i}) = \frac{\mathrm{R_{syst}}(\mathrm{i} * \mathrm{t_{MFOP}})}{\mathrm{R_{syst}}((\mathrm{i}-1) * \mathrm{t_{MFOP}})} \tag{1}$$

where $R_{syst}(t_{MFOP})$ is the system reliability for t_{MFOP} life units. Illustration: consider a system with two components connected in parallel. The MFOPS for the *i*th cycle MFOP of t_{MFOP} life units is given by:

$$\mathrm{MFOPS}(\mathrm{t_{MFOP}}, \mathrm{i}) = \frac{\mathrm{R_1}(\mathrm{i} * \mathrm{t_{MFOP}}) + \mathrm{R_2}(\mathrm{i} * \mathrm{t_{MFOP}}) - \mathrm{R_1}(\mathrm{i} * \mathrm{t_{MFOP}}) * \mathrm{R_2}(\mathrm{i} * \mathrm{t_{MFOP}})}{\mathrm{R_1}((\mathrm{i}-1) * \mathrm{t_{MFOP}}) + \mathrm{R_2}((\mathrm{i}-1) * \mathrm{t_{MFOP}}) - \mathrm{R_1}((\mathrm{i}-1) * \mathrm{t_{MFOP}}) * \mathrm{R_2}((\mathrm{i}-1) * \mathrm{t_{MFOP}})} \tag{2}$$

where $R_k(t_{MFOP})$ is the reliability of the *k*th component for t_{MFOP} life units.

The major advantage of the MFOPS is the update with the reliability of the installed components at each period. Based on this property, the computation accuracy of the MFOPS strongly depends on the system design. This relationship will be developed in the next section.

3. System design based on MFOP concept

3.1 MFOP and System Design

According to Warrington et al. (2002), the MFOP concept drives the change in operation, maintenance planning but also in designing the system to achieve operational success with a minimal maintenance cost. Long et al. (2009) develop a method based on MFOPS prediction which allows among others things to evaluating the MFOP based reliability design of the products. In their article, they introduce the following example. If there is absolutely no way to achieve an MFOPS greater than 94 % for an MFOP of 500 h given the current design so the duration of MFOP would be needed to be shortened or the reliability design of this system have to be improved.

The reliability design of the products is one way to design a system with an MFOP concept. Relf (1999) specifies the durability, the reliability but also the testability as fundamental elements of MFOP. Thereby it will be interesting in the system design based on MFOP to consider the available state information per component and to combine this information with the component reliability design. The combination of these two elements will be implemented in the next sections in order to define a best system design based on MFOP philosophy.

3.2 Information levels definition

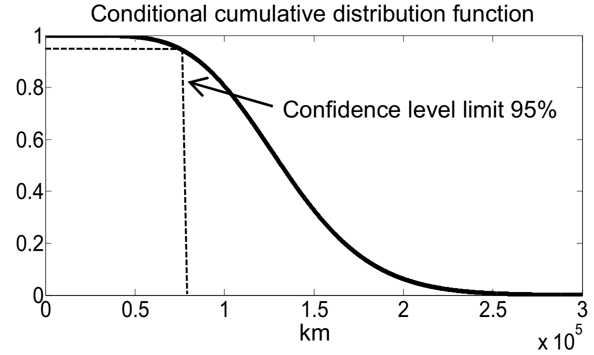
In this paper, three information levels are considered. Table 1 gives the information levels definition. For the first level, only information at the system level is available. The second level focuses on the component state and the last information level provides more precise information on the component state thanks to degradation measures.

A best knowledge about the component state in operation allows taking a maintenance decision based on MFOP with a higher accuracy level. With the first level of information, the MFOPS measurement realizes an average of possible situations per component. When the higher levels are available, the MFOPS takes into account this information to eliminate possible situations. The measurement accuracy is thus increased.

Table 1: Information levels definition

Information level	System Information	Component Information
Level 1	Working / Failed	No available information
Level 2	Working / Failed	Working / Failed
Level 3	Working / Failed	Degradation measure

To illustrate the impact of different information levels, consider a system composed of two components connected in parallel. For each component, the deterioration increments follow the same gamma process with parameters α = 5e-5 and β = 0.25 and degradation limit = 20. The MFOP is fixed at 30,000 km. A maintenance operation is required if the conditional cumulative distribution function becomes lower than a confidence level. The confidence level is fixed at 95 % in Figure 1. This confidence level appears in Figure 2 (vertical lines) to determine whether a maintenance operation is required or not.


Conditional cumulative distribution function

Confidence level limit 95%

Figure 1: Conditional cumulative distribution function and confidence level definition

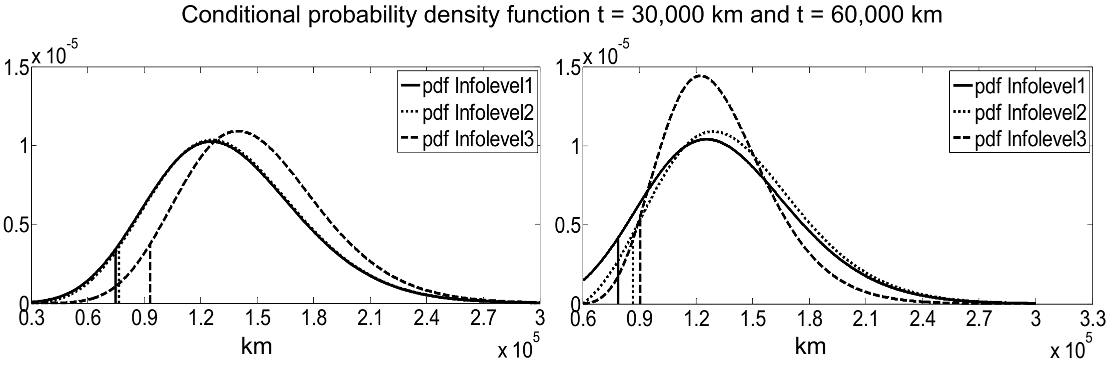

Conditional probability density function t = 30,000 km and t = 60,000 km

Figure 2: Conditional probability density function at t = 30,000 km and t = 60,000 km following the different information levels (pdf = probability density function)

Figure 2 shows that following the available information level, the maintenance decision is different. At t = 30,000 km, even if the conditional probability density functions are slightly different, the confidence level limit for the three situations exceeds the next MFOP fixed at 60,000 km, no maintenance operation is required. At t = 60,000 km, the confidence level limit exceeds the next MFOP only for the situation where the degradation measure is available (level 3). For the others levels, a maintenance operation is required at 60,000 km.

Note that the added costs to provide a higher level of information are not taken into account in this paper.

4. Maintenance policy based on MFOP

4.1 Problem formulation

In order to ensure the MFOP, the implemented maintenance policy consists in estimating, at each end of MFOP cycle or when a failure occurs, the probability that the multi component system works until the next defined period given the system available information.

In the event of failure or that MFOPS is estimated to be lower than specified confidence level, a maintenance operation should be performed on one or several system components. In this case, the problem can be mathematically formulated as follows:

$$Min \sum_{i=1}^{n} x_i \, C_i \ \text{ s.t } \ MFOPS > L \tag{3}$$

where n is the number of system components, C_i is the operation cost (labour + spare part cost) of component i, x_i is a binary variable which indicates the maintenance operation on the component i and L is the specified confidence level.

Further, the following assumptions are made for solving this optimization problem. After each maintenance operation on a component, its reliability is considered "as good as new" and after each end of MFOP cycle without maintenance operation, the component reliabilities are considered to be unchanged.

4.2 Sequences elimination

To solve the previously mentioned problem, the main difficulty is that when the number of components increase, the sequence number to be considered step by step exponentially increases. In that case it is necessary to develop criteria to drastically reduce the considered sequences. According to Galante et al. (2009), a Branch-and-Bound method can be implemented. To solve this problem, it is not necessary to find all the non-dominated sequences but only to find the sequence capable to meet the proposed requirements of reliability at the minimum cost.

A Branch-and-Bound algorithm consists of a systematic enumeration of all candidate solutions, where large subsets of candidates are discarded, by comparing the possible developments of each partial sequence of the quantity being optimized. Thereby each partial sequence evolves within two extreme values the lower bound (LB) and the upper bound (UB) values.

The LB value for a partial sequence {s} is obtained by considering that no maintenance operation is performed on the component not yet considered at this step. For the UB value, the hypothesis is that maintenance operations are performed in all remaining components. Based on these meaningful values, two criteria to reduce the solution space can be implemented:

- Criterion 1: If UB{s} < Specified confidence level, the partial sequence {s} is erase because the best possible development cannot achieve the reliability requirement.
- Criterion 2: If LB{s} > Specified confidence level, the partial sequences having a greater cost are removed.

We can notice that this method gives good results for system of medium size (<50 components) even if it could be necessary to arrange the components by importance order to be more efficient.

5. Maintenance Strategy optimization based on Total Maintenance Cost

In order to evaluate the alternative maintenance strategies and to optimize the system design based on MFOP point of view, the total maintenance cost could be evaluated over 5 years which represents the nominal contract duration. The Total Maintenance Cost (TMC) is expressed as:

$$\mathrm{TMC} = \mathrm{C_{prev}} + \mathrm{C_{cor}} + \mathrm{C_{Diag}} \tag{4}$$

where $\mathrm{C_{prev}}$ is the preventive maintenance cost, $\mathrm{C_{cor}}$ is the corrective maintenance cost and $\mathrm{C_{Diag}}$ is the diagnosis cost. Assume $\mathrm{C_{Diag}}$ is the system diagnosis cost to identify which component with information level 1 is failed. The computation of these three costs can be defined as:

$$\mathrm{C_{prev}} = \sum_{i=1}^{n} \mathrm{C_i} * \mathrm{N_i} \qquad \mathrm{C_{cor}} = \mathrm{C_{immo}} * \mathrm{N_{failure}} \qquad \mathrm{C_{Diag}} = \mathrm{C_{udiag}} * \mathrm{N_{failure}} * \mathrm{N_{level1}} \tag{5}$$

where n is the number of system components, $\mathrm{C_i}$ is the operation cost (labour + spare part cost) of component i, $\mathrm{N_i}$ is the number of replacements of component i, $\mathrm{C_{immo}}$ is the vehicle immobilization cost, $\mathrm{N_{failure}}$ is the number of system failure, $\mathrm{C_{udiag}}$ is the unitary diagnosis cost for components with an information level 1 and $\mathrm{N_{level1}}$ is the number of component with information level 1. By Monte Carlo simulation, different maintenance strategies and system designs can be examined. The optimal solution should be a maintenance scenario corresponding to the lowest value of TMC.

6. Numerical Example

6.1 System definition

Define a multi component system based on field data for a commercial heavy vehicle (see Figure 3). Since these data are strictly confidential, the model, which is applied in this section, tends to be close to the real system model.

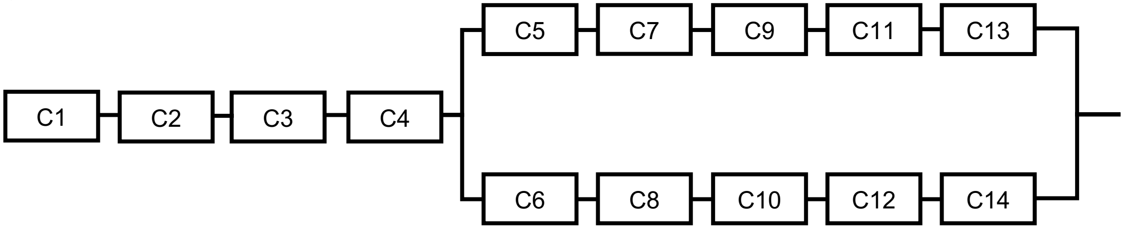


Figure 3: System structure definition

The immobilization cost is fixed at 5,000 and the unitary diagnosis cost is fixed at 30. The component reliability properties and the specific maintenance costs are defined in Table 2.

Table 2: System parameters (W=Weibull distribution and G=Gamma process)

	C1	C2	C3	C4	C5	C6	C7
Reliability Model	W(6e5,5)	W(5e5,5)	W(5.5e5,4.5)	W(4.5e5,3.5)	W(3.5e5,1.7)	W(3.5e5,1.7)	W(4.3e5,1.5)
Cost (Euro)	842	1,268	458	407	311	311	305

	C8	C9	C10	C11	C12	C13	C14
Reliability Model	W(4.3e5,1.5)	W(4.4e5,1.4)	W(4.4e5,1.4)	G(1.09e-4,1.5)	G(1.09e-4,1.5)	G(8e-5,1.5)	G(8e-5),1.5)
Cost (Euro)	305	276	276	108	108	302	302

6.2 Cost-optimized MFOP and confidence level

A maintenance model is developed in order to calculate the TMC index over 5 years based on Monte Carlo simulation. Table 3 presents the TMC estimation for different MFOP and confidence level. Assume that only the information level 1 is available for all system components.

Table 3: The TMC value (Euro) under different MFOP (km) and confidence level

MFOP/Confidence level	0.9	0.91	0.92	0.93	0.94	0.95
10,000	22,205	21,253	21,362	20,367	19,766	18,519
20,000	18,254	17,574	16,614	16,642	16,077	16,185
30,000	16,222	16,228	16,023	15,702	16,195	16,451
40,000	15,575	15,502	15,806	16,373	17,778	18,063
50,000	15,565	15,430	15,631	16,335	17,421	18,564
60,000	17,339	17,845	18,068	18,809	20,128	22,687

TMC is minimal when MFOP and confidence level are respectively equal to 50,000 km and 91 %. This cost-optimized solution provides the best balance between corrective and preventive maintenance operations.

For some configurations, the TMC value increases with the confidence level. This behavior can be explained by the fact that the additional preventive maintenance cost can be higher than the gain saved by the immobilization costs reduction.

6.3 Impact of information levels

In order to implement the optimal maintenance policy, the MFOP and the confidence level parameters could be cost-optimized as previously presented but also the information level per component.

In the Table 4, four scenarios are defined to illustrate the impact of information level on the TMC value with MFOP and confidence level respectively equal to 40,000 km and 90 %. The scenarios 1 and 2 represent the extreme cases with respectively the minimal and maximal information available. The percentage of saved cost between these two scenarios is higher than 20 %.

Table 4: The TMC value (Euro) under different information level per component

Information level	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	TMC
Scenario 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15,575
Scenario 2	1	1	1	1	2	2	2	2	2	2	3	3	3	3	12,029
Scenario 3	1	1	1	1	2	2	2	2	1	1	1	1	1	1	13,698
Scenario 4	1	1	1	1	1	1	1	1	1	1	2	2	2	2	15,416

An example based on these two scenarios illustrates this result (see Figure 4). At 80,000 km, even if no maintenance operation was required before, the maintenance decision is different for the two scenarios. Thanks to the available information on components for the scenario 2, no maintenance operation is required contrary to scenario 1.

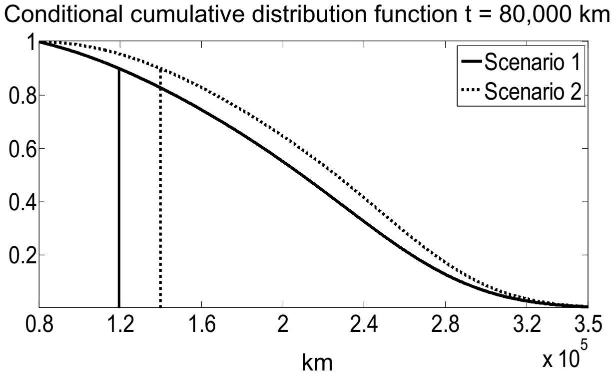


Figure 4: Conditional cumulative distribution function for the system at t = 80,000 km following the different scenarios

In the scenarios 3 and 4, the information level 2 is implemented on four components with different costs and reliability properties. Besides the cost difference, the main explanation is that the information level impacts more the TMC when the variance of component is high.

7. Conclusions

In this article, a methodology for optimizing the maintenance strategy based on MFOP concept has been proposed. The developed approach can be used, not only to optimize the maintenance policy parameters, but also to evaluate the different system design in terms of reliability or information levels. The evaluation between the alternative maintenance strategies is performed thanks to the TMC value.

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