Cost Effective Maintenance Policy: A Case Study

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(Received on August 31, 2009, revised May 15, 2010)

Abstract: European Rail Traffic Management System (ERTMS) is a major venture by European Union in order to create interoperable railway network within Europe. Manufacturers of ERTMS strive to attain a competitive edge by demonstrating the efficiency of their systems. Cost effectiveness is one of the significant ways to address efficiency of the system which deals in maximising availability and minimising life cycle cost of the system over the system life cycle. One of the important ways of maximizing cost effectiveness of a system can be attained by optimising maintenance policy. This paper demonstrates the estimation of cost effectiveness of an ERTMS system. The degradation and repair process of the system is modelled by Petri-Nets. Failure, maintenance and cost data are used as parameters for the model. The model will be useful for the systems that experience degradations and subjected to imperfect maintenance.

Keywords - Availability, life cycle cost, maintenance policy, Petri-net

1. Introduction

Each country in European Union has its own railway signalling system. Each system is stand-alone and non-interoperable, and therefore requires extensive integration, engineering effort, raising total delivery costs for cross-border traffic. This restricts competition and hampers the competitiveness of the European rail sector vis-à-vis road transport by creating technical barriers to international journeys. To fulfil this requirement a major industrial project named as European Rail Traffic Management System (ERTMS) was originated. The objective of ERTMS is to replace existing signalling systems with such system which will boost cross-border freight and passenger transport. This will help the countries to establish more sustainable railway network. ERTMS has two basic components i.e., European Train Control System (ETCS) and GSM- Radio (GSM-R). ETCS is an automatic train protection system where as GSM-R provides voice and data communication between the track and the train. There are 3 levels of ERTMS with Level 1 and Level 2 already in operation in Europe.

Apart from achieving interoperable railway network, ERTMS also increases capacity, speeds, safety for passengers on existing lines and at the same time reduce maintenance costs. To be competitive and to gain approval by infrastructure managers as well as train operating companies, ERTMS manufacturers should demonstrate cost effectiveness of their systems as per stakeholders’ requirement. Cost effectiveness of any system depends on the operational availability and life cycle cost (LCC). In order to make the system more cost effective, higher availability should be attained at lower LCC.

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However, there are numerous challenges to attain the desired cost effectiveness of the system over a period of time because of degradation of the systems, change in traffic scenario etc. Optimisation of maintenance policy is one of the major ways to attain desired cost effectiveness of the system in the long run. All these optimisations should be done at maximum system availability and minimum life cycle costs as well as minimum train delays for a specific traffic scenario. In this paper the authors have demonstrated a model that can help to maximise the cost effectiveness of the systems. ALSTOM Transport has developed the ATLAS® platform for ERTMS application for railway operations. ATLAS® consists of various sub-systems such as Automatic Train Supervision (ATS) system, Interlocking system, Automatic Train Control (ATC) system and Track side products e.g., Track Circuits. This paper deals with a case study to develop optimum maintenance policy to achieve desired cost effectiveness of Radio Block centre (RBC) which is a part ATC track side system. ATC sub-system consists of both track side and train borne components. The objective of this work is to achieve higher availability and lower LCC of the system and then develop optimum maintenance policy to achieve cost effectiveness.

As decisions on maintenance policies have a major impact on the operations of the system, the cost effectiveness of long term design and maintenance decisions should be guaranteed. Life cycle cost (LCC) analysis, an engineering economics technique, can be utilised to focus on maintenance strategies to minimise maintenance cost in system’s life cycle, while meeting the dependability requirements. Cost effectiveness of a system can be defined as

\[
\text{Cost effectiveness} = \frac{\text{Availability}}{\text{LCC}}
\]

Higher cost effectiveness of the system ensures better operation of the system. The paper presents the key influential variables of maintenance policy that affects cost effectiveness. Section 2 of the paper discusses the system description of RBC. Petri-net model is shown in section 3. Section 3 also discusses the results of the model. Finally, conclusions are depicted in section 4.

2. Radio Block Centre (RBC) System

In most of the systems which are in use at ALSTOM Transport, active redundancy is the choice, i.e., the various units are active simultaneously, so that, in the event of failure of one unit, the function is preserved without the need for switching on a back-up unit [1]. In ERTMS application level 2, ETCS uses a GSM-R radio channel to exchange data between the trackside Radio Block Centre and the trains. The interlocking reports the status of the objects controlling the routes of the trains to the RBC which, in turn, generates the correct movement authorities for the different trains in the section. RBC consists of different sub-systems such as computing channel, input/output system and cabinet. The reliability block diagrams of these systems are given in Figs. 1a, 1b, 1c and 1d. Computing channel is 2-out-of-3 (2oo3) system. Two channels must be working any time for computing channel to work. Similarly, input/output group is a 1oo2 system.

Any failure in RBC is detected by built-in-test-equipment (BITE). However, failures are detected depending upon the detection probability or detectability of the BITE system. When a failure is not detected, it remains in the system till the next inspection occurs.
Eq. 1 provides an estimation of the undetected failure time if the fault remains undetected till the next inspection. The relationship shown in Eq. 1 considers only constant failure rate, however later in the paper we have developed Petri-Net model which considers non-constant failure rate.

\[ T = \text{Inspection interval} \]
\[ t = \text{time of occurrence of undetected failure during the interval } (0, T) \]
\[ T-t = \text{duration of undetected failure time} \]
\[ \lambda = \text{failure rate of the component following exponential distribution} \]

The expected undetected failure time of the component during the interval \((0, T)\) is given by:

\[
E(T-t) = \frac{1}{\lambda T} \left( \frac{T}{1 - \exp(-\lambda T)} - 1 \right) \tag{1}
\]

when \(\lambda T \ll 1\), \(E(T-t) = T/2\).

The failure rate of a repairable component depends on the type of corrective maintenance that is applied: from perfect maintenance to minimal maintenance. Perfect maintenance repair brings the component age to zero \textit{i.e.}, the component becomes as good
as new (AGAN) where as minimal repair keeps the component’s age un-modified i.e., the component stays as bad as old (ABAO). In real world cases the repairs are neither AGAN nor ABAO, they are something in between. [2] proposed two models (type I and II) that estimate the virtual age of the component after a repair.

Kijima models consider a parameter called maintenance factor that estimates the virtual age. If maintenance factor is 1, the repair is ABAO and for maintenance factor 0, repair is ABAN. The model type I assumes that the repairs can only fix the damage incurred during the last period of operation. Thus, the nth repair can only remove the damage incurred during the time between the (n-1)th and nth failures. The model type II assumes that the repairs fix all of the damage accumulated up to the current time. As a result, the nth repair not only removes the damage incurred during the time between the (n-1)th and nth failures, but can also fix the cumulative damage incurred during the time from the first failure to the (n-1)th failure.

If the times between failures are denoted by $x_1, x_2, \ldots, x_n$, virtual age of the component after nth repair is given by

$$V_n = V_{n-1} + \text{(maintenance factor} \times x_n)$$

Kijima model type I

$$V_n = (\text{maintenance factor} \times V_{n-1}) + (\text{maintenance factor} \times x_n)$$

Kijima model type II

The maintenance factor can be calculated from the past failure times of the component by applying the Kijima models discussed above.

3. Case study on cost effectiveness estimation of fan system of RBC

Cost effectiveness of the RBC system has been estimated. In this paper we are presenting a case study on the fan system. As discussed earlier, fan system in RBC is a 2oo3 system. Petri-Net (for details see [3]) model for estimation of cost effectiveness of the fan system is illustrated in Fig. 3. The places that represent the states are depicted in Table 1.

<table>
<thead>
<tr>
<th>State description</th>
<th>Place</th>
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<th>Place</th>
<th>State description</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan 1 working</td>
<td>1</td>
<td>Fan 3 working</td>
<td>7</td>
<td>Fan system working</td>
<td>13</td>
</tr>
<tr>
<td>Fan 1 failed</td>
<td>2</td>
<td>Fan 3 failed</td>
<td>8</td>
<td>Fan system degraded (detected)</td>
<td>14</td>
</tr>
<tr>
<td>Fan 1 repaired and waiting in stock</td>
<td>3</td>
<td>Fan 3 repaired and waiting in stock</td>
<td>9</td>
<td>Fan system degraded (un detected)</td>
<td>15</td>
</tr>
<tr>
<td>Fan 2 working</td>
<td>4</td>
<td>Spare fan working</td>
<td>10</td>
<td>Fan system failed</td>
<td>16</td>
</tr>
<tr>
<td>Fan 2 failed</td>
<td>5</td>
<td>Spare fan failed</td>
<td>11</td>
<td>Inspection starts</td>
<td>17</td>
</tr>
<tr>
<td>Fan 2 repaired and waiting in stock</td>
<td>6</td>
<td>Spare fan repaired and waiting in stock</td>
<td>12</td>
<td>Inspection ends</td>
<td>18</td>
</tr>
</tbody>
</table>

There are three fans in the system and one fan is kept as a spare and all the fans are repairable in nature. As illustrated in the model, when a fan fails it goes to the failed state. The time to failure depends on the failure probability density function of the fan. The model captures the time to failure each time a fan fails and estimates the virtual age of the fan after repair work is done depending on the maintenance factor of the repair described earlier. If a fan fails and the failure is detected, it is removed from the system and is substituted by the fan in the stock. The failed fan goes the workshop for repair and after repair it waits till the next fan failure occurs. Over a period of time fans may have different virtual ages depending on the number of repairs done on each fan. In this model, we can keep a track of number repairs each fan goes into so that we can estimate the time...
when the next fan fails. Now, place 13 denotes that all three fans are working. If one fan fails depending on the time explained above, the system can go to state 14 or state 15. If the failure is detected by the BIT system, the system will be in state 14 otherwise it will be in 15. Both 14 and 15 states are degraded states but the system is still working because two fans are still working. If the system is in 14, it can go to 13 depending upon the deferred maintenance time. The maintenance is deferred because it is not always cost effective to stop the train operation to repair the system so the system can be repaired after the train running period. If the system goes to 15, the failure can only be detected in the next inspection to bring the system to 13. However, if the deferred maintenance time and the inspection intervals are high, then there is probability that the system can go to the failed state if another fan failure occurs.

Table 2: Parameters used in Petri-Net model for cost effectiveness estimation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation hour/ year</td>
<td>6000 hours</td>
</tr>
<tr>
<td>Inspection time</td>
<td>0.5 hour</td>
</tr>
<tr>
<td>Preventive maintenance time</td>
<td>0.5 hour</td>
</tr>
<tr>
<td>Corrective maintenance time</td>
<td>3 hours</td>
</tr>
<tr>
<td>Labour cost/ hour</td>
<td>€ 40</td>
</tr>
<tr>
<td>SRU repair time</td>
<td>720 hours</td>
</tr>
<tr>
<td>Discount rate</td>
<td>4%</td>
</tr>
<tr>
<td>Fan failure (scale parameter)</td>
<td>20000</td>
</tr>
<tr>
<td>Fan failure (shape parameter)</td>
<td>2</td>
</tr>
<tr>
<td>Deferred maintenance time</td>
<td>9 hours</td>
</tr>
<tr>
<td>Inspection interval</td>
<td>6000 hours</td>
</tr>
<tr>
<td>SRU repair cost</td>
<td>€ 50</td>
</tr>
<tr>
<td>Maintenance factor</td>
<td>0.8</td>
</tr>
<tr>
<td>Detectability</td>
<td>0.9</td>
</tr>
</tbody>
</table>

In case of the system failure, corrective maintenance is performed on the system to bring the system to 13. This depends on the availability of two fans in the stock. If the fans are under repair, then the unavailability of the system increases. The parameters that are used in the Petri-Net model are illustrated in Table 2. Monte Carlo simulations are performed on the model to estimate availability and LCC of the fan system over a period of 20 years.

Figure 4 illustrates the cost effectiveness of the fan system with time. The step decrease in cost effectiveness curve is due to the discounted value of life cycle cost.
Figure 3: Petri-Net model for estimating cost effectiveness of fan system

Figure 4: Cost effectiveness of the fan system with time
Over a period of time the cost effectiveness curve will be parallel to the x-axis. This is due the fact that after a period of time LCC will constant because of discounting of future costs.

Sensitivity analyses have been performed on the maintenance factor, detectability, inspection interval and deferred maintenance time to see their effects on the cost effectiveness of the system. The results are shown in Fig. 5 and Fig. 6. Cost effectiveness decreases with increase in maintenance factor. That is because with increase in maintenance factor, the quality of maintenance tends to minimal maintenance thereby increasing the number of failures. In case of detectability, cost effectiveness increases with increase in detectability. This analysis can help to design better built-in-test system to achieve better cost effectiveness of the system. With increase in inspection interval the probability of repairing failures before they fail decreases and hence LCC increases.

With decrease in inspection interval, inspection costs increase and hence LCC decreases. In this case study as the failure rate is very low, the optimum inspection interval is obtained at very high inspection interval. But from safety point of view, we can not have a very high inspection interval. When deferred maintenance time increases, the probability of failure from degraded state increases. Hence, cost effectiveness decreases. But at the same time increase in deferred maintenance time also increases the possibility of opportunistic maintenance which decreases the overall costs.

We can also estimate the maintenance policy of the system for certain availability and LCC requirements. From Fig. 5 and Fig. 6, optimum value for each parameter to maximise cost effectiveness can be inferred. Further, optimum value of combinations of the parameters to achieve maximum cost effectiveness can also be estimated. The model can be useful to other mechanical redundant systems which are repairable in nature and subjected to degradations.

![Figure 5: Effect of maintenance factor and detectability on cost effectiveness](image1)

![Figure 6: Effect of inspection interval and deferred maintenance time on cost effectiveness](image2)
4. Conclusions

In view of the increasingly stringent availability requirements set by the market place, designers of complex systems have to pay close attention to test and maintenance strategies to achieve availability targets with low life cycle costs. In this paper maintenance policy based on cost effectiveness has been developed for fan sub-system of Radio Block Centre (RBC). Sensitivity analysis on different maintenance parameters has been performed to maximise the cost effectiveness of the system. This maintenance policy will help the systems to achieve higher availability at lower life cycle costs over the life cycle of the systems. Petri-Net model have been developed to calculate cost effectiveness of these systems. Cost effectiveness analysis will yield quantitative results to aid the decision maker, with risk analysis, and provides a useful decision tool. The work presented in this paper is a part of the work carried out for systems developed by ALSTOM Transport for ERTMS applications. This work will help the ERTMS manufacturers to demonstrate the sustainable benefits in terms of availability and life cycle costs to the infrastructure managers as well as train operating companies in order to keep a competitive advantage.

Acknowledgement: The work presented in this paper is supported by ALSTOM Transport Information Solutions, Paris. The authors would like to acknowledge this support.

References


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