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An Introductory Study on Imperfect Maintenance Effect in Rolling Stocks

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Abstract

The maintenance effect is a peculiar factor applied to repairable systems such as rolling stocks. Conventional statistical analysis for failure times takes into account one of the two following extreme assumptions, namely, the state of the system after maintenance is either as "good as new" (GAN, perfect maintenance model) or as "bad as old" (BAO, minimal maintenance model). Most of the papers concerning the stochastic behavior of railroad systems assume two types of maintenance: perfect and minimal maintenance. However, Lee, Kim & Lee (2008) analyzed the failure data of a door system in Metro EMU and the effect of preventive maintenance was imperfect. It is seen that the imperfect maintenance is of great significance in practice. This article describes how to deal with the maintenance effect in reliability studies of rolling stocks. Maintenance policies under imperfect maintenance are described and the method is proposed to evaluate their performance.

Keywords : *Maintenance effect, Reliability, Repairable system*

1. Introduction

The maintenance effect is a peculiar factor applied to repairable systems such as rolling stocks. Conventional statistical analysis for failure times takes into account one of the two following extreme assumptions, namely, the state of the system after maintenance is either as "good as new" (GAN, perfect maintenance model) or as "bad as old" (BAO, minimal maintenance model). Under GAN assumption, the failure process follows the renewal process and under BAO, the failure process follows the non-homogeneous Poisson process. In practice, the perfect maintenance assumption may be reasonable for systems with one unit which is structurally simple. On the other hand, the minimal maintenance assumption seems plausible for systems consisting of many components, each having its own failure mode. In the imperfect maintenance model in Pham and Wang (1996), a maintenance action does not make a system like GAN, but younger. Usually, it is assumed that an imperfect maintenance restores the system operating state to somewhere between GAN and BAO.

Most of the papers concerning the stochastic behavior of railroad systems assume two types of maintenance: perfect and minimal maintenance. It is well known in practice that maintenance may not yield a functioning item which is as "good as new". On the other hand, the minimal maintenance assumption seems to be too pessimistic in realistic maintenance strategies. From this it is seen that the imperfect maintenance is of great significance in practice. Lee, Kim & Lee (2008) analyzed the failure data of a door system in Metro EMU. The paper described that the effect of the preventive maintenance which were done every 3 years was imperfect while the corrective maintenance was assumed to be minimal maintenance.

This article deals with why we should and how to incorporate the maintenance effect in reliability studies of rolling stocks. The advantage and the necessities of analyzing the maintenance effect of rolling stocks are described. In addition, the procedure and the tasks necessary for that are presented.

2. Models of Maintenance Effect

Pham and Wang (1996) classified maintenances according to the degree to which the operating condition of an item is restored by maintenance in the following ways:

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- Perfect maintenance: a maintenance action that restores the system operating condition to as good as new. That is, upon perfect maintenance, a system has the same lifetime distribution and failure rate function as a brand new one. Complete overhaul of an engine with a broken connecting rod is an example of perfect maintenance. Generally, replacement of a failed system by a brand new one is a perfect maintenance.
- Minimal maintenance: a maintenance action that restores the system to the intensity function it had when it failed. Minimal repair is first studied Barlow and Proschan (1965) and after it the system operating state is often called as "bad as old". Changing a flat tire on a car or changing a broken fan belt on an engine are examples of minimal repair because the overall failure rate of the car is essentially unchanged.
- Imperfect maintenance: a maintenance action that does not make a system as "good as new", but younger. Usually, it is assumed that imperfect maintenance restores the system operating state to somewhere between as "good as new" and as "bad as old". Clearly, imperfect maintenance is a general maintenance that can include two extreme case: minimal and perfect maintenance. Engine tune-up is an example of imperfect maintenance because an engine tune-up may not make an engine as good as new but its performance might be greatly improved.
- Worse maintenance: a maintenance action that makes the system intensity function or actual age increase, but the system does not break down. Thus, upon worse maintenance a system's operating condition becomes worse than that just prior to its failure.
- Worst maintenance: a maintenance action that unintentionally makes the system fail or break down.

Conventional statistical analysis for failure times takes into account one of the two following extreme assumptions, namely, the state of the system after maintenance is either as "good as new" (GAN, perfect maintenance model) or as "bad as old" (BAO, minimal maintenance model). Under GAN assumption, the failure process follows the renewal process and under BAO, the failure process follows the non-homogeneous Poisson process. In practice, the perfect maintenance assumption may be reasonable for systems with one unit which is structurally simple. On the other hand, the minimal maintenance assumption seems plausible for systems consisting of many components, each having its own failure mode.

Most of the papers concerning the stochastic behavior of repairable systems assume two types of maintenance: perfect and minimal maintenance. It is well known in practice that maintenance may not yield a functioning item which is as "good as new". On the other hand, the minimal maintenance assumption seems to be too pessimistic in realistic maintenance strategies. From this it is seen that the imperfect maintenance is of great significance in practice.

In the imperfect maintenance model in Pham and Wang (1996), a maintenance action does not make a system like GAN, but younger. Usually, it is assumed that an imperfect maintenance restores the system operating state to somewhere between GAN and BAO. It is thought in the imperfect maintenance model that the failure intensity (rate) can be reduced by maintenance. We can roughly consider two types of failure intensity reduction models: one is a fixed reduction model and the other is an adjustable reduction model.

In the fixed reduction model, the failure intensity is reduced such that all jump-downs are the same, but in the adjustable reduction model, after effective maintenance, the failure intensity is reduced such that each jump-down is subject to the current failure intensity or age. We should determine two problems in the adjustable reduction model: one is "how much does the maintenance reduce the intensity just before maintenance?", and the other is "how will the intensity function be changed after maintenance?"

Suppose a system is put into operation at time 0 and effective maintenances occur at times $t_1, t_2, ..., t_k$. Let $\lambda_{n+1}(t)$ be intensity function between nth and $(n+1)$th effective maintenance times. Chan and Shaw (1993) suggested a proportional model such that $\lambda_{n+1}(t)=\lambda_n(t)-g\cdot\lambda_n(t_n)$; that is, maintenance reduces the intensity at the maintenance time in proportion to it and, after the maintenance, the shape of the intensity function is equal to when no maintenance is performed.

Some authors assumed that maintenance restores the system operating state to somewhere between GAN and BAO. Malik (1979) proposed an approach to model the improvement effect of maintenance, where maintenance is assumed to reduce the operating time elapsed from the previous maintenance in proportion to its age. On the other hand, in BMS's approach (1983), it is assumed that maintenance reduces system age. The two models can be expressed by virtual age concept which is suggested by Kijima(1989). Assuming $V^+(t)$ to be the virtual age right after effective maintenance, it can be calculated as;

- Malik's model : $V^+(t_n) = V^+(t_{n-1})+(1-\rho)(t_n-t_{n-1})$
- BMS's model : $V^+(t_n) = (1-\rho)[V^+(t_{n-1})+t_n-t_{n-1}]$

In both models, the virtual age is reduced in proportion to each system's age. In Malik's model, the age reduction

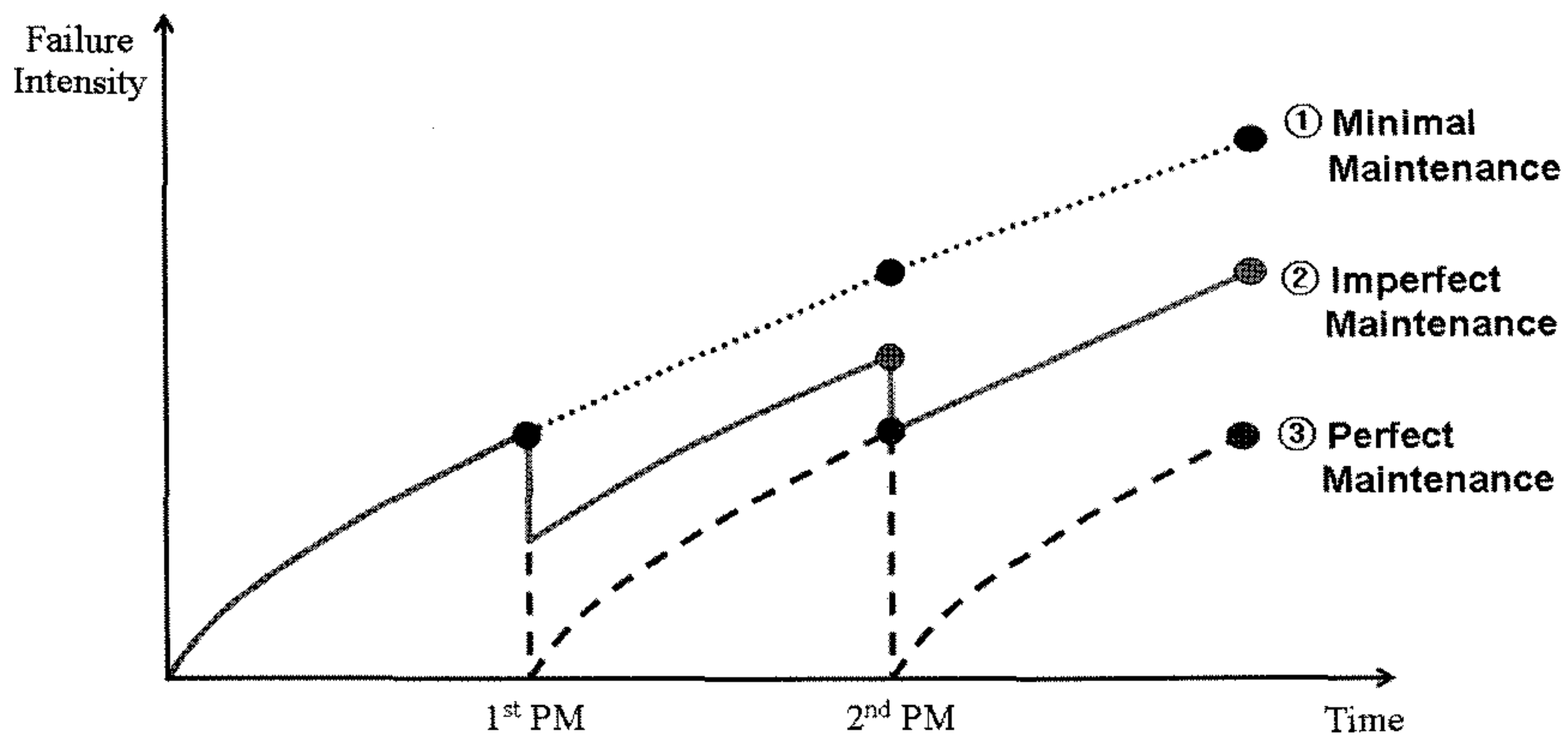


Fig. 1 Maintenance Effect Model

is proportional to the increased age(time elapsed) from the previous effective maintenance, whereas in BMS's model, it is proportional to their virtual age at the instant of maintenance.

It is necessary to define more precisely the term 'intensity function'. That is the intensity of failure at age t, $\lambda(t|H_t)$, where H_t denotes the history of the failure and maintenance process (number and timing of failures and maintenances) to age t. $N(t|H_t)$ is the number of failures occurring by age t, and the intensity is defined as:

$$\lambda(t|H_t) = \lim_{\delta \to 0+} \delta^{-1} Pr\{N(t+\delta|H_t) - N(t|H_t) > 0\} \qquad (1)$$

In the limit as $\delta \to 0$, $\lambda(t|H_t)dt$ tends to the probability of one or more failures occurring in the infinitesimal interval $(t, t+dt]$, given the previous history of the process up to age t. When the process is orderly, so that two or more failures never occur in the same infinitesimal interval dt, then $\lambda(t|H_t)dt$ is the probability that a single failure occurs in the infinitesimal interval dt, and so is also the expected number of failures occurring in dt. Hence, $\lambda(t|H_t)$ is also the expected failure rate at time t given the previous history of failures and maintenances.

If the effect of the preventive maintenance (PM) is minimal, the failure intensity after the PM does not changed like the dot line in Fig. 1. The perfect maintenance reduces the failure intensity to the start point and the imperfect the maintenance does the intensity between the point just before PM and the start point like Fig. 1.

3. Reliability Analysis Considering The Imperfect Maintenance Effect For Rolling Stocks

There are two representative tasks for reliability problems when operating rolling stocks; one is to estimate the reliability and the other is to make a maintenance policy. The reliability of repairable systems such as rolling stocks depends on the inherent failure intensity function and the maintenance effect. Therefore, we have to both of the inherent failure intensity function and maintenance effect for estimating the reliability in case of the imperfect maintenance. Section 3.1 describes the problems for it. The other important work in reliability when operating repairable systems is to make a maintenance policy which is considered in Section 3.2.

3.1 Estimating reliabilty considering the maintenance effect

The two functional forms of the inherent failure intensity which have been most commonly applied to repairable systems are:

- Power-law function: $\lambda_0(t) = \dfrac{\beta t^{\beta-1}}{\eta^{\beta}}, \beta, \eta, t \geq 0$

- Log-linear function: $\lambda_0(t) = \beta \exp\left(\dfrac{t}{\eta}\right), \beta, \eta, t \geq 0$

If considering the imperfect maintenance, the actual intensity of failure at age t, $\lambda(t|H_t)$ can be expressed as $\lambda(t|H_t) = \lambda_0[V(t)]$ where $V(t)$ is the virtual age at t and it is calculated as $V(t) = V^{+}(t_{n-1}) + t - t_{n-1}$, $t_{n-1} < t \leq t_{n-1}$.

If the effect of the maintenance is perfect or minimal, it is relatively easy to estimate the reliability because there are a lot of works on it and some commercial software to handle the failure data. However, if the effect of the maintenance is imperfect (between minimal and perfect), it is complex to estimate the reliability. There is no commercial tool of reliability analysis to cover the imperfect maintenance.

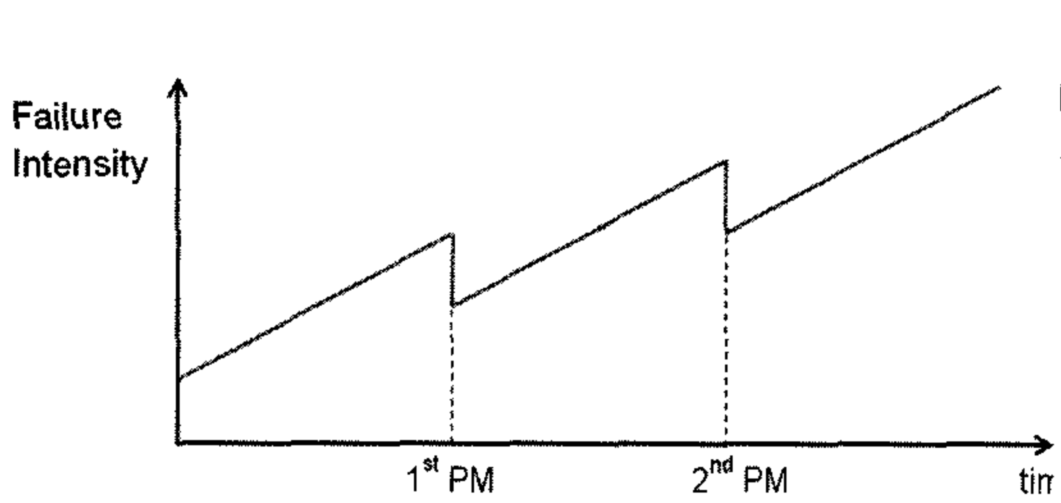
As mentioned before, there are the two representative forms of the inherent failure intensity for repairable systems, the power-law and the log-linear. It should be decided for reliability analysis which intensity function is fitter to failure data. The additional researches on it are needed because there are few researches about the quantitative goodness of fit test in case of the imperfect maintenance. If there are enough equipments which are repaired, data of the time to the first failure are used for the goodness of fit test. We can also refer to the remark of Shin, Lim & Lie (1996) which is that the power-law intensity function has different shapes depending on the range of β. If β is less than 2, the shape of intensity function is concave, and if â is larger than 2, it is convex. Thus it can be fitted to wide range if failure processes except one with an extremely fast increasing rate. The log-linear intensity function represents the extremely fast increasing rate.

There are some works on estimating the failure intensity for repairable systems. Tsokos and Rao (1994) considered an estimation problem for failure intensity under the Power-law process. Coetzee (1997) proposed a method for parameter estimation and cost models of non-homogeneous Poisson process under minimal repair. Shin, Lim and Lie (1996) proposed a method for estimating maintenance effect and intensity function in Malik's model. Jack (1997) estimated lifetime parameters and the degree of age rejuvenation when a machine is minimally repaired on failures and imperfect preventive maintenance is also carried out. Pulcini (2000) used the Bayesian approach to estimate overhaul effect and intensity function under minimal corrective maintenance and effective preventive maintenance.

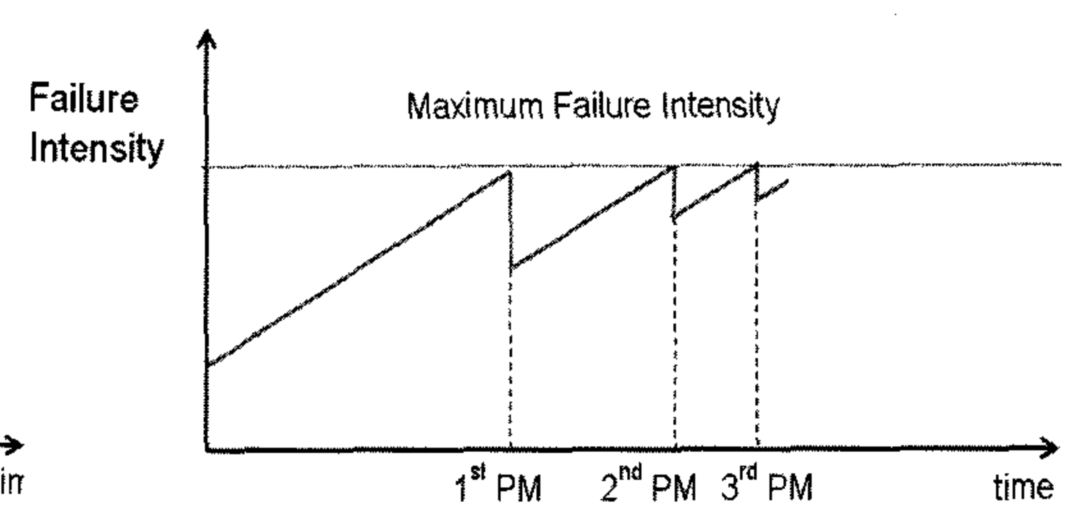
3.2 Maintenance polices under imperfect maintenance

Periodic preventive maintenances based on time or operating distance have been mainly performed for rolling stocks. If the maintenance is performed periodically and its effect is imperfect, the reliability decreases as time goes on like policy 1 in Fig. 2. To prevent the reliability decrease, we can consider the model where PM is performed whenever the system reaches the maximum failure rate as policy 2 in Fig. 2. The Optimal maintenance problem for this model was considered by Jayabalan & Chaudhuri(1992). However policy 2 makes availability decreases as time goes on. To diminish this disadvantage of policy 2, we can consider additional periodic perfect maintenance which is depicted on policy 3 in Fig. 2. We can also consider improve the maintenance effect for its effect to be perfect which needs higher PM cost and times like policy 4 in Fig. 2. There are no dominant police among 4 policies in Fig. 2. Therefore we need to evaluate the effectiveness of the maintenance policies.

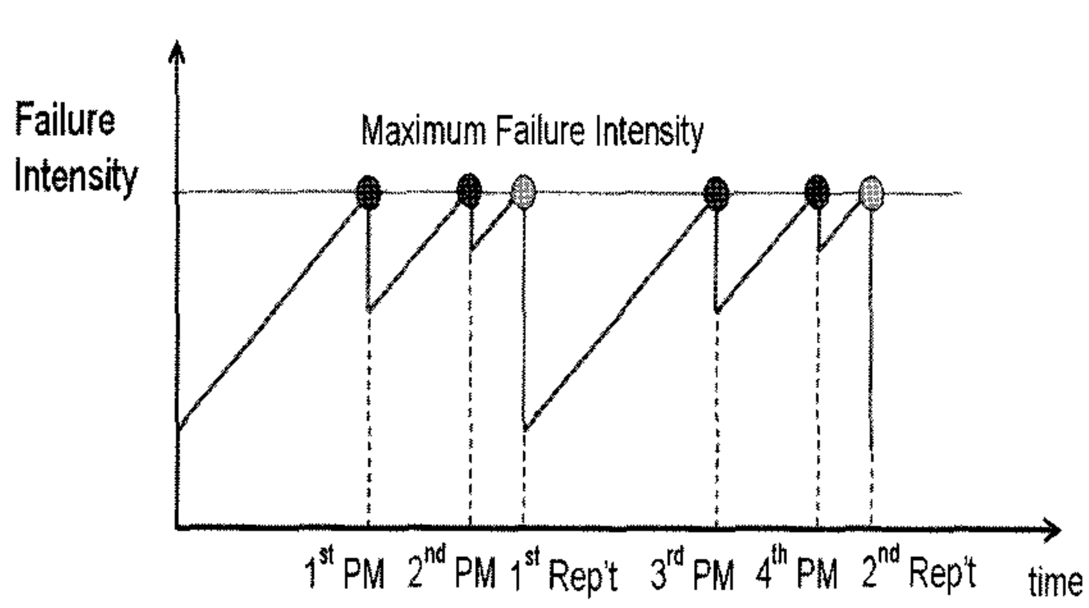
Kim et al. [7] proposed the four criteria and equations to evaluate the effectiveness of the maintenance policy when the maintenance effect is perfect. To apply the procedure of Kim et al. [7] to cases of the imperfect maintenance, we need to calculate the frequency of safety failures, MTBSF



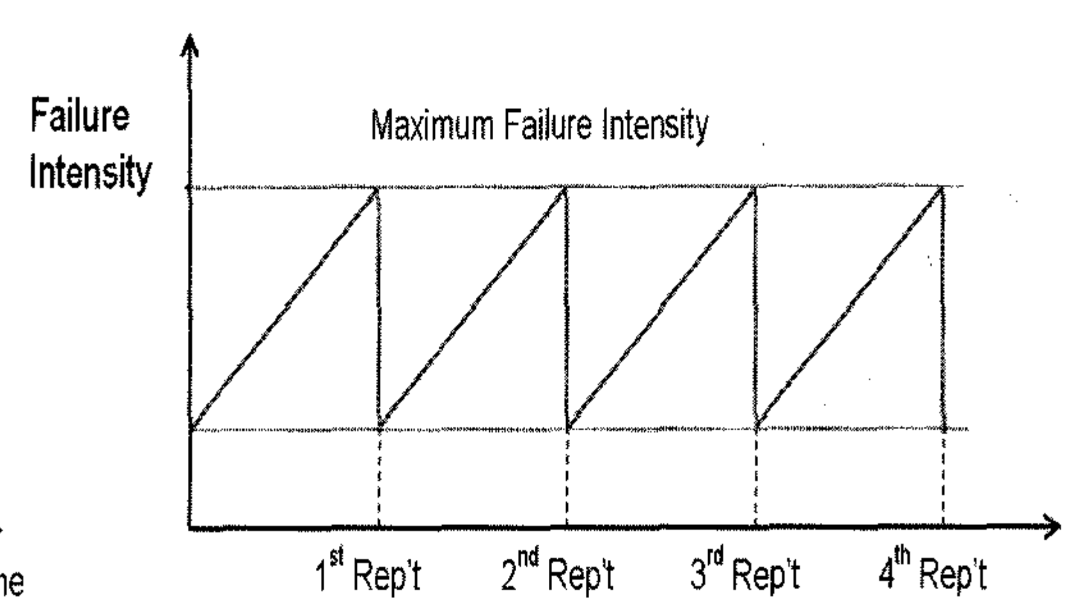
Policy 1: Periodic imperfect PM



Policy 2: Scheduled imperfect PM with maximum failure rate



Policy 3: Periodic imperfect PM and perfect maintenance (replacement)



Policy 4: Periodic perfect maintenance (replacement)

Fig. 2 Maintenance policies under imperfect maintenance

(Mean Time Between Service Failures), operational availability and life cycle cost (TC). The equations to calculate them for policy 3 are presented in this paper, because policy 3 is most complex among them.

The frequency of safety failures and MTBSF can be calculated as $\lambda_{safety}^{\max}\times OT$ and $1/\lambda_{service}^{\max}$, respectively. The maximum failure rate, $\lambda_{safety}^{\max}$ and $\lambda_{service}^{\max}$, can be obtained the failure intensity of the points of preventive maintenances. The operational availability and TC are calculated as equation (2) and (3)

$$A_o = \frac{t_r}{t_r + MT_{cm}\cdot\int_0^{t_r}\lambda(x)dx + MT_{pm}\cdot n_{pm} + MT_{rp}} \qquad (2)$$

$$TC = \frac{\int_0^{t_r}\lambda(x)dx\cdot[C_{mh}'\cdot MT_{cm} + C_{ma}' + C_{pe}'] + n_{pm}\cdot[C_{mh}''\cdot MT_{pm} + C_{ma}''] + C_{mh}'''\cdot MT_{rp} + C_{ma}'''}{t_r + MT_{cm}\cdot\int_0^{t_r}\lambda(x)dx + MT_{pm}\cdot n_{pm} + MT_{rp}} \qquad (3)$$

Where, t_r: replacement interval, n_{pm}: the number of PM in a period, NT_{cm}: corrective maintenance hour per task, MT_{pm}: preventive maintenance hour per task, MT_{rp}: replacement hour per task, C_{mh}': hourly cost for a corrective maintenance, C_{ma}': material cost per a corrective maintenance C_{pe}': penalty cost per a failure, C_{mh}'': hourly cost for a preventive maintenance, C_{ma}'': material cost per a preventive maintenance, C_{mh}''': hourly cost for a replacement, C_{ma}''': material cost per a replacement.

4. Concluding Remarks

Periodic preventive maintenances based on time or operating distance have been mainly performed for rolling stocks. If the maintenance is performed periodically and its effect is imperfect, the reliability decreases as time goes on. Therefore the maintenance effect should be considered when analyzing the reliability and making a maintenance policies. Lee, Kim & Lee (2008) analyzed the failure data of a door system in Metro EMU and the effect of preventive maintenance was imperfect. It is seen that the imperfect maintenance is of great significance in practice. This article introduced how to deal with the maintenance effect in reliability studies of rolling stocks. Maintenance policies under imperfect maintenance are described and the method is proposed to evaluate their performance. For further researches, we can consider maintenance and logistics (e.g. spare) optimization problems under imperfect maintenance.

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