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OPTIMAL COMBINATORIAL REPLACEMENT POLICY UNDER A GIVEN MAINTENANCE INTERVAL FOR THE COMBINED GOVERNOR IN DIESEL LOCOMOTIVES

OPTYMALNA STRATEGIA WYMIANY KOMBINATORYCZNEJ DLA DANEJ CZĘSTOTLIWOŚCI PRZEGLĄDÓW REGULACJI MIESZANEJ W LOKOMOTYWACH SPALINOWYCH

Combined governor is one of key components in diesel locomotives, as a subcomponent it must meet the existing maintenance periodic of the diesel locomotive, while it is passively replaced or maintained in a midway because of over/under-maintenance in practice. In this paper, four reliability models of a sequential PM cycle are developed using three years of maintenance data of combined governors in one Chinese Railway Bureau to determine its reliability distribution, in which some zero-failure data and censor data are used. Meanwhile, a novel combinatorial replacement (CR) policy is proposed to optimize its preventive maintenance (PM), in which a component is replaced several times using a preventively maintained one in a given operational interval. After that, necessary optimizations are introduced based on the determined reliability models and the maintenance interval given by the PM criterion of diesel locomotives (23000km ~25000km), and then the genetic algorithm is also used to solve the constraint optimization function. Results show that the proposed CR policy is the best policy among the existing policy and the general (T,δ) policy, and other results can be viewed as an optional policy when spare components are limited.

Keywords*: Reliability models, mixed-Weibull distribution, combinatorial replacement policy, combined governor of diesel locomotives.*

Regulacja mieszana jest jednym z kluczowych elementów w lokomotywach spalinowych, i jako taka musi być ujęta w istniejącym systemie konserwacji okresowej lokomotyw spalinowych. W praktyce jednak, podlega ona biernej wymianie lub przedwczesnej konserwacji z powodu niewystarczających lub nadmiernych praktyk utrzymania w ruchu. W niniejszym artykule opracowano cztery modele niezawodnościowe sekwencyjnego cyklu konserwacji zapobiegawczej z wykorzystaniem danych z trzech lat konserwacji mieszanej regulacji jednego Biura Kolei Chińskich w celu ustalenia ich rozkładu niezawodności, przy użyciu wybranych danych nt. nieuszkadzalności oraz danych cenzurowanych. W celu optymalizacji konserwacji zapobiegawczej (PM), zaproponowano nową strategię wymiany kombinatorycznej (combinatorial replacement – CR), w której element składowy zostaje kilkakrotnie zastąpiony innym elementem uprzednio poddanym konserwacji zapobiegawczej w danym okresie eksploatacyjnym. Następnie, wprowadzono konieczne optymalizacje na podstawie opracowanych modeli niezawodnościowych oraz częstotliwości przeglądów podanej w kryteriach konserwacji zapobiegawczej lokomotyw spalinowych (23000 km ~ 25000 km). W dalszej kolejności, wykorzystano algorytm genetyczny do rozwiązania funkcji optymalizacji ograniczeń. Wyniki pokazują, że proponowana strategia CR jest najlepsza spośród istniejących strategii i ogólnych strategii (T, δ); inne wyniki można traktować jako strategię opcjonalną w sytuacji gdy dostępność elementów zamiennych jest ograniczona.

Słowa kluczowe*: Modele niezawodności, rozkład Weibulla, strategia wymiany kombinatorycznej, lokomotywa spalinowa o mieszanej regulacji.*

1. Background

There are 11,000 diesel locomotives (about 40% all locomotives) in China and most of them are still on service at the main or the branch railway line. The combined governor is one of their key components and plays a significant role in the transmission and control system, which is a typical mechanic-electronic-hydraulic set, and is composed of the mechanical driving part and hydraulic operating control system and electron control system. Its main functions include: a) to control the rotating speed and power of the engine automatically; b) to modify the fuel supply based on the signal of driver-controller, the load and with zero-failure data. Especially, the Weibull distribution is widely used in reliability and lifetime analysis due to its versatility, such as discussed in [8, 10, 11, 20, 21]. Attention has been paid to zero-failure data since the paper by Martz & Waller [3, 14] was published, and yet it is a focus in development and less application in reality. Miller et al, [15] introduced formulae for estimating the probability of failure for software when testing reveals no errors. Jiang et al, [7] proposed a method to combine the initial guess of the reliability with the estimation from zero-failure data, to acquire a more reliable estimate for the Weibull distribution, while the method is on the basis of some additional information. Han [5] applied the hierarchical Bayesian and the "E-Bayes" methods to estimate production reliability by zero-failure testing data. This method can be used to deal with some maintenance observations when there is no failure occurring. In practice, due to the limitation of the maintenance decision, some key components are maintained under zero-failure state, while zero-failure data is valuable operational information and ignored on some occasion, the combined governor of diesel locomotives is a case in point. Meanwhile, most existing research on maintenance problem assumed that the reliability of components is a two-fold Weibull distribution or a known distribution. While it is difficult to fit the lifetime distribution using the two-fold Weibull model in some real cases. Therefore, four novel models are proposed applying the zero-failure data and the censored failure data in this paper.

For the research on maintenance policy, most research have been widely investigated since the repair model was presented in 1960 by Barlow and Hunter [16]. Wang[19] summarized the recently years PM policies and classified them into five classes: Age-dependent PM policy, Periodic PM policy, Failure limit policy, Sequential PM policy and Repair limit policy. Most of the existing research focused on optimal replacement policies with new components from the literatures review, only several literatures considered the replacement components with used one. Tango[18] proposed a extended block replacement policy with used items based on the assumption that if items fail in $[(k-1)T, kT-v)$, they are replaced by new items, and if in $[kT-v, kT)$, they are replaced by used items. Sheu et al[17] introduced a extended block replacement policy with shock models and used items, in which an operating system is preventively replaced by new ones at times iT (i=1,2,…) independently of its failure history. If system fails in ((i-1) T, iT-δ) it is either replaced by a new one or minimally repaired, and if in [iT-δ, iT) it is either replaced by a used one or minimally repaired. Zhao et al[23] considered three imperfect PM policies at time T, shock numbers N, and damage k of a used system, and expected cost rates were obtained by using the techniques of cumulative processes and reliability theory. While some existing literatures assume that the effective age of a used component is known that is difficulty to obtain in practice, meanwhile, due to the requirement of precise and reliability, once the component is used and take-down, a PM action must be made before next operation in some cases, such as the combined governor. Furthermore, most research regarded that the maintenance periodic is a fixed value, but it is an interval (23000 km ~ 25000 km) in diesel locomotives. Therefore, the existing maintenance models are unfit for combined governors.

3. Reliability Model of Combined Governors

As mention above, due to the importance of the combined governor in locomotives, it must be preventively maintained at every PM process of diesel locomotives. Consider that the PM action might change its reliability distribution, observations are classified into four groups based on the frequency of PMs: new combined governors (before the first PM, group1), after the first PM but before the second PM (group 2), and after the second PM but before the third PM (group 3) and after the third PM (group 4). The overhauling cycle of diesel locomotives is divided into four operational phases by three PM actions, and the overhauling cycle is performed at the end of the last operational phase. In additional, the lifetime of components in the diesel locomotive is running mileage, and the maintenance interval is also running mileage. Thus their units are kilometer (km) in this paper.

3.1. Model Assumption

Taking the above into consideration and following the two hypotheses given below.

1) The hazard rate is zero for a new combined governor or one that suffered multiple PMs at the beginning.
2) Malfunctions can be detected upon its occurrence and can be removed by a minimal repair at once which will restore the function of equipment without changing the hazard rate, and the time of a minimal repair and PM and replacement can be ignored.

3.2. Data Preprocessing

In this section, the real running observations of the combined governor deprived from DF4 diesel locomotives of one Railway Bureau (2009–2011) are analyzed. The statistics data include the censored data and the failure data labeled with "+", part of them can be seen as Table 1, from which it can be found that without failure occurs during the first operational phase, these observations can be viewed as zero-failure data. The rest observations include failure data and censored data in the second to the forth operational phase.

3.3. Distribution Fitting

1) Reliability distribution for the first operation phase

In the first operational phase, the observations are zero-failure data. The Hierarchical Bayesian and "E-Bayes" methods are employed to describe the distribution of zero-failure data. The latter is found to be an easier approach to the description [5], the process of which goes as follows:

a) Let (s_i, t_i) be the zero failure data, and pi the failure probability at time t_i.
b) Assume that the prior distribution of pi is Beta distribution with density function

$$\pi(p_i \mid a,b) = \frac{p_i^{a-1}(1-p_i)^{b-1}}{B(a,b)}$$

Where $0 < p_i < 1$, B(a,b) $= \int_0^1 t^{a-1}(1-t)^{b-1}dt$, and a > 0, b > 0, and both a and b are hyper parameters and separately below

Table 1. Part Maintenance records of the combined governor

group1	28868	21194	22673	20051	21768	22074	28075	24611
group2	22521	23852+	21031	24304	21457	24915+	23363	8154+
group3	22436	22565	20205	24913	20549+	24092	23388	21383
group4	25159+	28330	7025+	4869+	23572	22286	24195+	22870

P.S: "+"is the failure data.

the rotate speed of the engine; and c) to match the excitation current of generator. Due to its important role in diesel locomotives and the limitation of the structure, it must follow the existing maintenance periodic of the existing diesel locomotives. The current Railway Technical Management Criterion stresses that it must be disintegrated for tests of all its springs, fly hammers, pistons and motor as well as for renewing of the oil in every PM action to improve its control precision and reliability. This maintenance policy may cause over/under-maintenance, and leads to passive replacement/maintenance or accidents in midway in practice. Meanwhile, the maintenance cost and malfunctions still become outstanding problems bothered railway enterprises in the daily operation. Statistics show that the failures also increase with the PM action frequencies, and thus there is a critical requirement to investigate the reliability and PM policy of combined governors.

At present, various approaches have been devoted to improve the maintenance strategy for key components of diesel locomotives, in additional to improving their function. Some of them focused on condition-based maintenance, where the maintenance duration or some aided decision are made via collecting actual technical state of key components based on monitoring [1, 4] or detecting information [1, 13]. Though potential failures of certain key components may be detected in time by this mode, it has not gained wide application to most of Chinese diesel locomotives as only a small number of components which can be checked. Only few of them determine maintenance according to some parameters of key components. Lingaitis et al, [12] proposed a method to determine the maintenance data using the state of fuel consumption of diesel locomotives, while the fuel consumption of diesel locomotive is easily influenced by some unpredictable rand factors, such as state of railway and traction weight and outside condition and so forth. Zhang et al, [22] considered the influence of environmental condition to diesel engine system of diesel locomotive and optimized the PM interval in different seasons, while the reliability does not consider the sequential PM and the maintenance limitation of the whole machine in that paper. Di [2] employed a physical model based on calculating the accumulative damage degrees of main generator according to plenty of operation records, and then determined their major maintenance period, and yet the physical model is restricted more because of the complexity of its failure mechanism. While it is difficult to monitor or detect the working state of the combined governor, and thus the PM is seen as an effective approach to improve the reliability of component in reality.

However, for the combined governor, PM activities must obey the laws of the PM Criterion of diesel locomotives. The current PM interval in diesel locomotives is decided by the operational state of the whole locomotive, and a PM action is performed when running-mileage of locomotives reached a fixed interval (23000 km ~25000 km). Combined governors always passively replaced or maintained when failures occurs, and failures usually cause large economic loss. Thus, in order to hold a high operational reliability and meet the requirements of the reality, a CR policy using the preventively maintained spare component in the PM process is discussed in this paper. Meanwhile, authentic failure data on the combined governors of DF4 diesel locomotives from one Chinese railway bureau are taken as an example, from which reliability models on four sequential operational phases are obtained. In a word, the present study as a whole falls into two main parts: one is on the modeling of lifetime distribution for four sequential operational phases using real data, the other is on the maintenance optimization of the CR policy based on obtained lifetime distribution models and the PM Criterion of diesel locomotives, and then four optimization results are obtained for the corresponding operational phases using the genetic algorithm.

The rest of the paper are organized as follows: some related works are reviewed in section 2, the process of building four reliability models of combined governors are introduced in section 3, the maintenance optimization is presented in section 4, and then a brief summary is given in the last section.

Prior to providing a detailed description on maintenance policy, some terminologies that are widely used in the forthcoming sections are introduced as follows:

$F_i(t)$ The failure function before the i_{th} PM action
$R_i(t)$ The reliability function before the i_{th} PM action
$h_i(t)$ The hazard rate function before the i_{th} PM action

$H_i(t)=\int_0^t h_i(x)dx$ Cumulative failure rate before the ith PM action

$$\delta_{i,j,k}=\begin{cases}1 & \textit{if the component of the group } j \textit{ is selected at the kth replacement in the ith operational phase}\\ 0 & \textit{else}\end{cases}$$

$$S_i(X)=g_i^2(X) \qquad i=1,2,\cdots,m$$

$R(X)$ Penalty factor
$V(X)$ Objective function
$P(X)$ Penalty function
$U(X)$ Modified objective function
T The fixed maintenance period
C_p PM cost
C_f Minimal repair cost
C_{Re} Replace cost
C_{st} Set-up cost

2. Related works

For the modeling of general lifetime distribution in maintenance fields, complete data and censored data are attached more importance than zero-failure data. These observations are divided into two categories according to their source: one is the testing data from laboratories, the other from some practical occasion. Both include complete data, censored data and zero-failure data. Models on lifetime distribution with complete data or censored data are more mature than those uniform distribution on the domain (0,1) and (1,c). Let c=4 in this case.

c) Set the likelihood function of p_i as $L(0\,|\,p_i)=(1-p_i)^{s_i}$. According to the Bayesian theorem, the posterior density function of p_i is:

$$h(p_i\,|\,s_i)=\frac{\pi(p_i\,|\,a,b)L(0\,|\,p_i)}{\int_0^1 \pi(p_i\,|\,a,b)L(0\,|\,p_i)dp_i}$$

d) Using quadratic loss function gives the Bayesian estimation of p_i as:

$$\hat{p}_{iB}=\int_0^1 p_i h(p_i\,|\,s_i)dp_i$$

e) Calculate the E-Bayes estimation of p_i is

$$\begin{aligned}\hat{p}_{iEB}&=\iint_D \hat{p}_{iB}(a,b)\pi(a,b)dadb\\&=\frac{1}{3}\int_1^4\int_0^1\frac{a}{s_i+a+b}dadb\end{aligned}\tag{1}$$

Then, Each t_i versus reliability $R(t_i)$ is converted into a new axis by the Weibull Conversion and plot the Weibull Probability Plot (WPP), as shown in Fig. 1, from which can find that the distribution tendency is a concave curve with monotone increase, and which is befitting

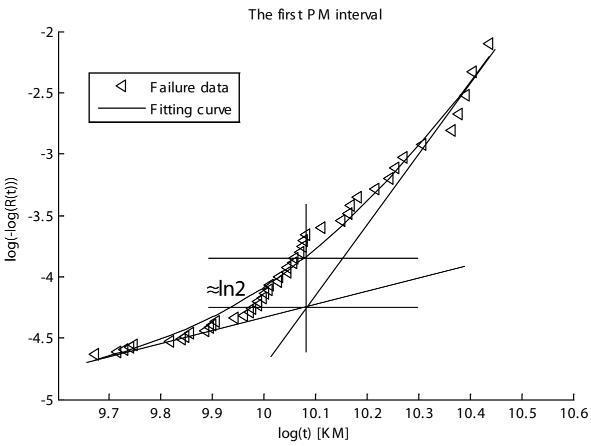


Fig. 1. WPP Plot for the 1st operational phase

for the two-fold Weibull distribution of a competing risk model. The initial parameters are estimated by graphic method, reader can refer literature [8]. The further parameters estimation is made by the least square method using the Matlab 2010b. The reliability distribution function for the first operational phase is determined as follows:

$$R_1(t)=\exp(-(t/49862)^{6.19}-(t/237810)^{0.65})\tag{2}$$

2) Reliability model for the second to forth operational phase

The statistics of other three PM intervals are made up of censored data and failure data, their initial reliability can attain from the Median Rank Estimates as formula (3).

Median Rank Estimates of initial reliability:

$$R(t_i)=1-\frac{i-0.3}{r_i+0.4}\,.\tag{3}$$

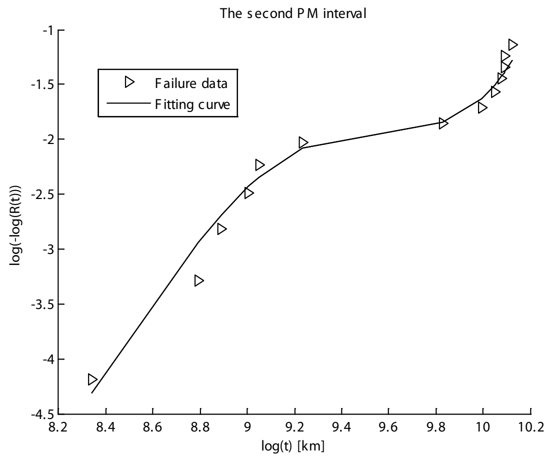
Where $r_i=r_{i-1}+\dfrac{n+1-r_{i-1}}{n+2-j}$

Where j is the sequence number of failure data among the whole data, and i is the sequence number of the failure data. Then every t_i is converted into versus initial reliability $R(t_i)$ utilizing the Weibull conversion and plot the WPP. As separately shown in Fig. 2 (a), (b) and (c), from which it can find that the distribution tendency are befitting with the two-fold Mixed-Weibull model.

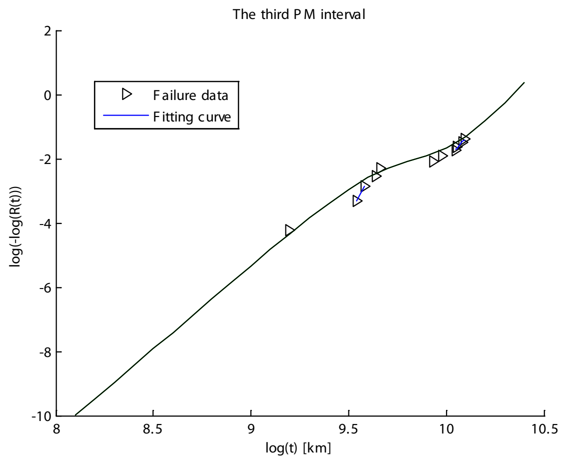
Finally, the initial parameters are estimated by graphic method, their distribution model can be determined initially from the distribution trend of the failure data, which are satisfied with the two-fold mixed-Weibull distribution. The method of their initial parameters estimation can refer literature[9], and the further parameters estimation is made by the least square method using the Matlab 2010b. It is not difficulty to find that the failure data and fitting curve have a good fit from the WPP plot.

The following are lifetime distribution functions for the second to the forth operational phase, and their WPP Plots are respectively shown as Fig.2 (a), (b) and (c).

$$R_2(t)=0.867\exp(-(t/32919)^{7.23})+0.133\exp(-(t/8151)^{3.37})\tag{4}$$

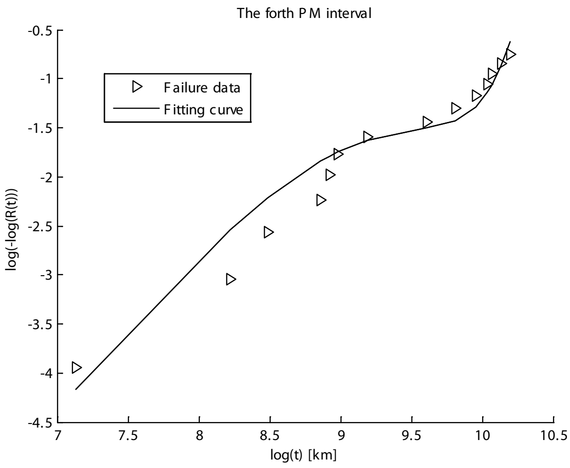


(a)



(b)

Fig. 2a, 2b. WPP Plots for the 2nd to the 4rd operational phase



(c)

Fig. 2c. WPP Plots for the 2nd to the 3rd operational phase

$$R_3(t) = 0.9\exp(-(t/31629)^{7.1}) + 0.1\exp(-(t/14732)^{5.2}) \quad (5)$$

$$R_4(t) = 0.8\exp(-(t/31488)^{7.2}) + 0.2\exp(-(t/5821)^{1.6}) \quad (6)$$

3.4. Model Analysis

It can be found that there exists large difference between the first maintenance interval and the others on reliability and hazard rate distribution from four reliability/hazard rate distribution plots. With the PM times increase, the reliability distribution is decreased rapidly when the running mileage less than 10000 km and greater than 20000 km, and it keeps relatively steady at 10000 km ~20000 km, which is benefit for users to make a maintenance decision. Meanwhile, it is a pity that the reliability is always greater than 0.9 at the first operational phase, while the combined governor must be preventively maintained according to the *PM criterion* of diesel locomotives, and thus the maintenance optimization will be discussed in section 3.

It is perfect for the first operational phase that the hazard rate is less than 1×10^{-5} when the PM action performed. For the other three hazard rate, there is an undulation near 5000 km at every hazard rate distribution, and it increase rapidly when the running mileage over 30000 km, which can be found from Fig. 3. Therefore, users should give more attention near 5000 km, and control the running mileage less than 30000 km.

4. Maintenance Optimization

Due to the importance of the combined governor in diesel locomotives, it must be preventively maintained or replaced at every PM activity of diesel locomotives in practice. Consequently, unreasonable maintenance actions maybe cause maintenance cost and down frequency increase. One effective approach is to replace the unstable operating component with a spare one in the midway, where the spare component is preventively maintained and without service after the PM action. Thus, how long the replacement should be performed and how to combine the operating component with a spare one must be determined. Therefore, in this section, a CR policy is discussed in detail.

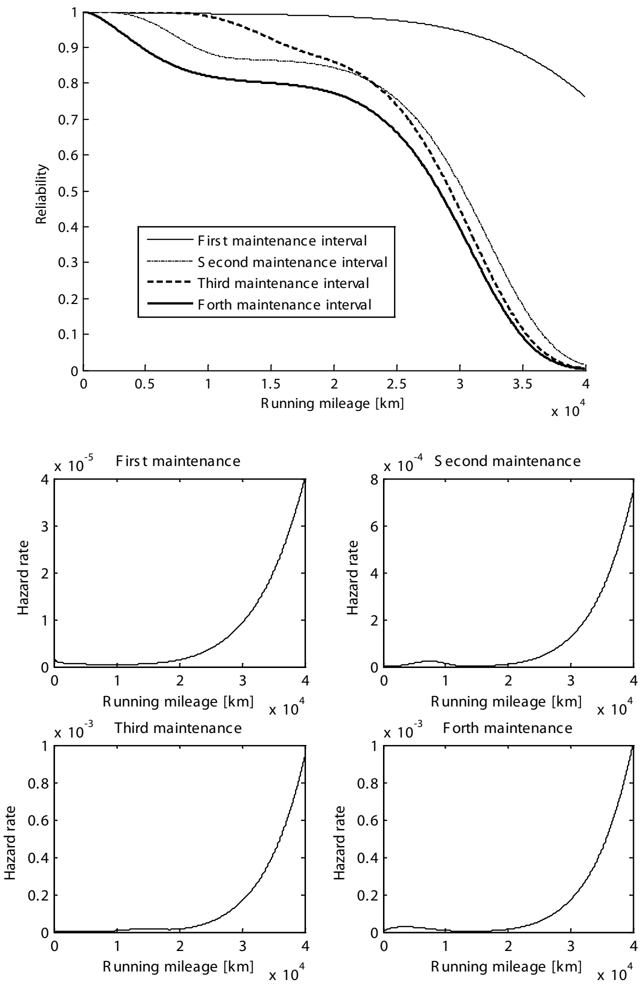


Fig. 3. Reliability/Hazard rate distribution

4.1. Analysis of Existing PM Approach of Combined Governors

As mentioned above, the existing maintenance criterion of diesel locomotives in China includes periodic PM and overhauling. The upper limit of the periodic maintenance interval is not a fixed value, but it is usually a domain such as 23000 km~25000 km. During the overhauling period, three periodic PM actions are performed, and almost each main component must be maintained at a PM process, which may cause some components being preventively replaced in the midway because of the under/over-maintenance, the combined governor is a case in point. Once its operational condition is unsatisfied the operational requirement or malfunctions take place frequently, a replacement or a minimal repair must be done. The spare combined governor which is preventively maintained (<4) is random selected if need to be replaced, and it would be scrap or instead by a new one after a fixed maintenance activities. Take into consideration its cost, it is impossible to replace an unstable one using a new one for enterprises, while preventively maintained component is always performed to replace the unstable one. Meanwhile, the combined governor must be preventively maintained if an installation and take-down take place.

4.2. The CR Policy

According to the current maintenance condition and obtained reliability models, a CR policy is proposed for the sequential PM of combined governors under a given maintenance interval of diesel locomotives.

The CR policy is based on the maintenance criterion of diesel locomotives that three PM actions are performed in a periodic of an overhauling which is divided into four operational phases, at the end of the last operational phase, a overhauling or renewal is done. During each operational process, malfunctions are removed by minimal repair, and the CR policy is performed under the following assumptions:

1) During an operation period, the finite CR action is performed using spare components which are preventively maintained at least once and without service after PM. Spare components are sufficient and in cold standby state, and can be selected randomly if needed. New components are only used at the first operational phase.
2) The minimal repair time and set-up time can be ignored, while the repair cost and the set-up cost exist and are regarded as a fixed constant.
3) A component which undergoes the same number of PM activities has the same service time in one operational phase.

The CR process is illustrated as follows:

In the *i*th operational phase, a CR action occurs at the time $t_{i,j}$ (i,j =1,2,…,n), in which a spare component which is in cold standby state after PM is selected to replace the failed one. The CR process in one operational phase is indicated as Fig. 4, where $x_{i,j}$ denotes the operational interval of the component which is underwent *j*-1 PM actions (belongs to the group *j*) and served in the i^{th} operational phase, and the number *j* (*j=2,3,4*) denotes the component which belongs to group *j*, and "no" denotes no replacement. Components used in a CR process in one operational phase is represented as ($a_1\ a_2 \ldots a_n$), where the value of a_j (*j*=1,2,…,n) denotes the accumulative using number of components which belong to the *j*th group used in the ith operational phase. When *j*=1, the selected component is new, such as (1 0 0 2) represents that three components are applied in this operational phase, one is new and the other two belong to the group 4 and are employed thrice PM action.

According the maintenance theory, the replacement times may be infinite, while for real maintenance processes, the system cannot be performed by repair actions all along for minimizing the long-term total cost. That is to say, repair actions cannot be chosen without any restriction, because there will never be an infinite number of repairs in finite time, and thus the replacement times less than 4 in this paper.

Based on the maintenance cost, the mean cost rate in the ith operational phase can be show as the follows:

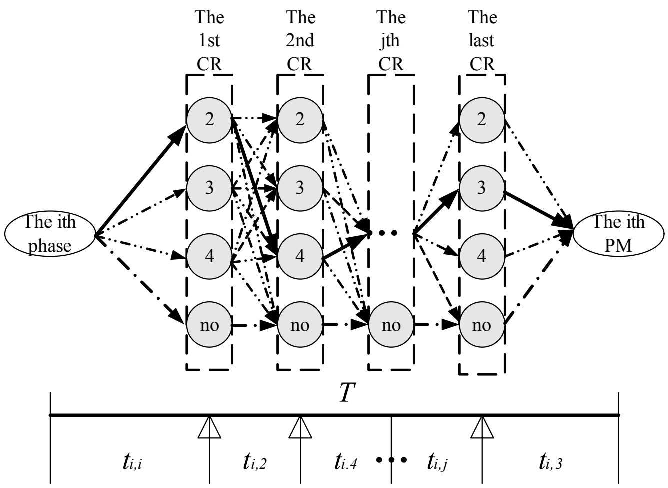


Fig. 4. CR process

$H_i(x_{ii})$ is accumulative failure times of the component which is suffered *i*-1 PM actions and employed in the *i*th operational phase, $x_{i,i}$ is its operational time, and $x_{i,j}$ is the same as above. $\delta_{i,j,k}$ is discussed in the section 3.4. ($C_p|C_r$) means C_r or C_p, the cost is C_r if the operational component belong to the last group, and else it is C_p. The T_{lo} and T_{up} are lower limit and upper limit of the maintenance interval, and N_0 is the allowable accumulative replacement times in an operational phases. In this paper the replacement times is less than 4, and the operational phase number is 4, T_{lo}=23000 km and T_{up}=25000 km.

4.3. Solution of the maintenance model

The proposed maintenance model is a constraint optimization problem which is the most important and ubiquitous type of engineering optimization problems. Evolutionary algorithms (EA) have been applied extensively for tackling these problems with various degrees of success. The penalty function approach is a relatively simple approach and is remarkably easy to implement and, as a result, has been popularly used with an EA [6]. In this paper, the genetic algorithm (GA) is applied with the penalty function approach. The constrained objective function Eq. 8 can be converted into an unconstrained one by adding the penalty function. Then, the equivalent unconstrained optimization problem can be stated as:

$$\mathrm{C_i}(x_{i,i},x_{i,j}) = \frac{C_f(H_i(x_{i,i}) + \sum_{j=2}^{m_0}\sum_{k=0}^{K}\delta_{i,j,k}H_j(x_{i,j})) + (\sum_{j=2}^{m_0}\sum_{k=0}^{K}\delta_{i,j,k}+1)(C_{st}+(C_p\,|\,C_r))}{\sum_{\substack{j=2\\ j\neq i}}^{m_0}\sum_{k=0}^{K}\delta_{i,j,k}x_{i,j}+x_{i,i}} \tag{7}$$

$$\text{St.}\quad \begin{array}{l} \sum_{j=2}^{m_0}\sum_{k=0}^{K}\delta_{i,j,k}+1 \le N_0 \\ T_{lo} \le \sum_{j=2}^{m_0}\sum_{k=0}^{K}\delta_{i,j,k}x_{i,j}+x_{i,i} \le T_{up} \end{array} \tag{8}$$

$$\text{Where}\quad \delta_{i,j,k} = \begin{cases} 1 & \textit{if the component of the group } j \textit{ is selected at the kth replacement} \\ & \textit{in the ith operational phase} \\ 0 & \textit{else} \end{cases}$$

$$\text{Min}: U(X) = V(X) + P(X) \tag{9}$$

Where *V*(*X*) is the objective function, *P*(*X*) is the penalty function and *U*(*X*) is the modified objective function which is constrained by the function $g_i(X)$. The penalty function *P*(*X*) is defined such as:

$$P(X) = \begin{cases} 0 & X \in R^n \\ \sum_i S_i(X)R_i(X) & X \notin R^n \end{cases} \tag{10}$$

Where $S_i(X)$ is the real-valued continuous function defined by

$$S_i(X) = g_i^2(X) \qquad i = 1,2,\cdots,m \tag{11}$$

and $R_i(X)$ is penalty factor, which is stepwise changes with the violation for each of constraint and is indicated by:

$$R_1(X)=\begin{cases}0 & 23000\le X\le 25000\\ 200 & 1000<|X-24000|\le 1500\\ 280 & 1500<|X-24000|\le 2000\\ 350 & 2000<|X-24000|\le 2500\\ 500 & else\end{cases} \quad (12)$$

Then, the determined function $U(X)$ has a high-dimension, and thus the genetic algorithm is suitable for this case. Let C_f=8000, C_p=1000, C_{re}=400, C_{st}=300, and the variable t belongs to [500 25000] on the basis of the practice. The GA's parameters are chosen as follows:

Chromosome length=20, population size=400, crossover probability=0.85, mutation probability=0.02. Using the Matlab 2010b the optimization is obtained shown as Table 2.

4.4. Optimization Result

Optimization results are shown in Table 2, it can be seen that optimized replacement policy exists in every operational phase, and the optimal results are marked with grey. The determined policy for the first phase is (1 0 0 0), the PM interval is 25000 km, and the minimal cost rate is 0.1305. For the second phase, the results respectively are: (0 1 0 0), 23000 km and 0.1322, the third phase are: (0 0 2 0), 25000 km and 0.1274, and the forth phase are: (0 0 1 1), 25000 km and 0.14361. It can be seen from the first two phases that the existing maintenance method is reasonable and no CR is needed, but the combination (1 0 1 0) in the first phase and (0 1 1 0) in the second phase are regarded as optional policy if spare components are limited. The reasonable combined CR can decrease the cost rate at the last two phases, and thus the existing maintenance approach should be modified. Moreover, the others optimization results are useful, which can be viewed as a dynamic conference for users when the replacement is limited by spare components.

4.5. Discussion

1) $\delta_{i,j,k}$

$\delta_{i,j,k}$ is the indicator function, it is 1 if a component of the group j is selected at the kth replacement in the ith operational phase, and else it is 0. In order to convenient discussion, let $\sum_{k=0}^{n}\delta_{i,j,k}=n_{i,j}$, the $n_{i,j}$ is accumulative total number of a component with j-1 PM actions used in the ith operational phase, which is a permutation and combination value decided by the i and the allowable CR times n. Let m denotes the maintenance phase and n denotes the allowable CR times. The permutation and combination value N_{one} in one operational phase and the total number N_{total} indicates as follows:

$$N_{\text{one}}=(\text{m}-1)^{n-1}+1 \quad (11)$$

$$N_{total}=3N_{one}-1 \quad (12)$$

It can be seen that with the increase of m and n, N_{one} and N_{total} are with exponential growth. In reality of railway enterprises, the value m usually is 4~6, and n is 2~4. Thereupon, the enumerate approach can be used. For instance, in this paper, m=4, and n=3, N_{one} is 10 for one maintenance phase, and the total number is 29 which can be seen in Table 2.

2) Comparative on the CR policy and (T,δ) policy

In the section 1, the policy that Tango proposed and Sheu proposed are introduced briefly. Tango held if items fail in [$(k-1)T$, $kT-v$), they are replaced by new items, and if in [$kT-v$, kT), they are replaced by used items. Sheu considered that an operating system can be preventively replaced by new ones at times iT ($i=1,2,\ldots$) independently of its failure history, and if system fails in (($i-1)T$, $iT-\delta$) it is either replaced by a new one or minimally repaired, and if in [$iT-\delta$, iT) it is either replaced by a used one or minimally repaired. The parameters v and δ can be seen as a threshold for these policies, in which one maintenance approach is performed if the lifetime less than the threshold otherwise another maintenance method is made. We also assume that failures are removed by minimal repair if the components fail in (0, δ] ($0<\delta<T$), otherwise, the component is preventively replaced by a component that is employed PM actions at least once in (δ, T), and which is preventively maintained or replaced at T. This policy is similar with Tango's and Sheu's and marked as (T,δ) policy. Table 3 (a) and Table 3 (b) is separately show the optimal results of δ=18000 km and δ=20000 km, where italics are policies with minimal cost rate, which proved that CR policies proposed this paper are more reasonable than (T,δ) policy.

3) The optimization results

According to the PM *criterion of diesel locomotives* that the locomotives' PM action is performed in the interval of 23000 km ~25000 km instead of a fixed value, which is reasonable because the PM action always is effected by some dynamic factors in the reality. Optimization results for CR policy are shown in Table 2, which illustrated that the existing maintenance approach is the same as proposed CR policy in the first two operational phases and no CR is needed, while it should be replaced by the proposed policy in the last two operational phases. According to the common consideration, the (T,δ) policy is easily accepted by ordinary costumers, while the compare in Table 4 show that the proposed CR policy is more reasonable than others. In addition, the rest optimization results of proposed CR can be regard as a conference to make a replacement decision if spare components are finite.

5. Conclusions

It is widespread that subcomponents must follow the PM schedule of the whole machine, just as combined governors of diesel locomotives which must be preventively maintained together with the diesel locomotive, this maintenance policy may cause over/under-maintenance and leads to passive replacement/maintenance and large economic loss in practice. How to determine an optimal policy considered the reality of railway enterprises, which includes compare components and preventive maintenance criterion of diesel locomotives, is much helpful to railway enterprises. Therefore, four reliability models for combined governors are obtained via making the most use of the real data from one Chinese Railway Bureau. Furthermore, a novel CR policy is also presented under sequential PM of diesel locomotives, in which replaced components apply used items instead of new items for the consideration of cost in practice, and the upper limit of the PM interval is not a fixed value, but it is in 23000 km ~25000 km. The results demonstrate that:

1) The reliability of combined governors in the first phase is very reliable, indicating that no PM action is needed which is the same as the optimized results. Then, the reliability decreases rapidly when the lifetime over 20000 km and there is an undulation of hazard rate in 5000 km ~10000 km after a PM performed at the rest operational phases, suggesting the users should keep in mind. Obtained reliability models of combined governors can be used to in grouped maintenance and performance improvement in diesel locomotives.
2) The optimal results show that the proposed CR policy is the best policy among the existing policy and the (T,δ) policy. It is the same as the existing maintenance approach for the first two operational intervals, while the current maintenance policy

Table 2. Optimization results on every operational phase

Phase	Group 1	Group 2	Group 3	Group 4	Cost rate	CR policy				Interval
the 1st	24998.51	0	0	0	0.130467	1	0	0	***0***	***24999***
	24499.18	0	0	500.8065	0.182226	1	0	0	1	25000
	23999.8	0	0	500.0895	0.234032	1	0	0	2	25000
	14520.25	0	10479.68	0	0.161302	1	0	1	0	25000
	14238.72	0	10261.16	500.1194	0.213373	1	0	1	1	25000
	500	0	12249.4	0	0.183232	1	0	2	0	24999
	21384.31	3615.678	0	0	0.175229	1	1	0	0	25000
	20858.58	3641.236	0	500.1194	0.227228	1	1	0	1	25000
	10799.76	3605.548	10592.89	0	0.207013	1	1	1	0	24998
	18420.85	3289.464	0	0	0.221275	1	2	0	0	25000
the 2nd	***0***	***23001.13***	***0***	***0***	***0.132197***	***0***	***1***	***0***	***0***	***23001***
	0	22921.64	0	1628.198	0.184266	0	1	0	1	24550
	0	22478.55	0	1260.724	0.232655	0	1	0	2	25000
	0	16594.63	8405.362	0	0.153641	0	1	1	0	25000
	0	4816.213	19571.46	612.328	0.208291	0	1	1	1	25000
	0	3668.288	10665.85	0	0.170046	0	1	2	0	25000
	0	12499.81	0	0	0.194488	0	2	0	0	25000
	0	3526.155	0	17947.61	0.237732	0	2	0	1	25000
	0	5269.242	14461.43	0	0.194598	0	2	1	0	25000
	0	8332.923	0	0	0.24418	0	3	0	0	24999
the 3rd	0	0	23001.13	0	0.1294	0	0	1	0	23001
	0	0	21667	1536.598	0.179661	0	0	1	1	23204
	0	0	21748.63	1625.673	0.227887	0	0	1	2	25000
	0	16460.45	8539.382	0	0.153657	0	1	1	0	25000
	0	16566.91	7932.964	500.1194	0.206427	0	1	1	1	25000
	0	5229.446	14541.07	0	0.194598	0	2	1	0	25000
	0	3712.789	10643.59	0	0.170046	0	1	2	0	25000
	0	***0***	***12499.81***	***0***	***0.127395***	***0***	***0***	***2***	***0***	***25000***
	0	0	12249.4	501.1953	0.178659	0	0	2	1	25000
	0	0	8332.923	0	0.160921	0	0	3	0	24999
the 4th	0	0	0	23001.13	0.144281	0	0	0	1	23001
	0	0	0	12499.81	0.218299	0	0	0	2	25000
	0	0	0	8332.923	0.306472	0	0	0	3	24999
	0	***0***	***21566.4***	***3433.71***	***0.14361***	***0***	***0***	***1***	***1***	***25000***
	0	4836.668	19567.95	595.3517	0.18429	0	1	1	1	25000
	0	0	12247.21	505.5824	0.154659	0	0	2	1	25000
	0	3524.05	0	17951.89	0.213732	0	2	0	1	25000
	0	22392.84	0	1191.86	0.159329	0	1	0	1	23585
	0	0	21752.53	1623.733	0.203887	0	0	1	2	25000
	0	22497.34	0	1251.278	0.208655	0	1	0	2	25000

Table 3 (a). δ=18000

Phase	Group 1	Group 2	Group 3	Group 4	Cost rate	CR policy				Interval
the 1st	***24999.87***	***0***	***0***	***0***	***0.130464***	***1***	***0***	***0***	***0***	***25000***
	21481.41	3518.585	0	0	0.175246	1	1	0	0	25000
	18000	0	6999.991	0	0.165028	1	0	1	0	25000
	24499.92	0	0	500.0597	0.182225	1	0	0	1	25000
the 2nd	***0***	***23000.03***	***0***	***0***	***0.132195***	***0***	***1***	***0***	***0***	***23000***
	0	18000	6999.991	0	0.154408	0	1	1	0	25000
	0	22921.88	0	1628.198	0.184266	0	1	0	1	24550
the 3rd	0	0	***23000.03***	***0***	***0.129394***	***0***	***0***	***1***	***0***	***23000***
	0	0	21666.44	1536.598	0.179661	0	0	1	1	23203
	0	5014.835	19985.08	0	0.157342	0	1	1	0	25000
the 4th	0	0	0	23000.03	0.144276	0	0	0	1	***23000***
	0	4898.265	0	20101.72	0.171069	0	1	0	1	25000
	0	0	6999.155	18000.81	0.154599	0	0	1	1	25000

Table 3 (b). δ=20000

Phase	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Cost rate**	**CR policy**				**Interval**
the 1st	***24999.91***	***0***	***0***	***0***	***0.130464***	***1***	***0***	***0***	***0***	***25000***
	21379.12	3620.861	0	0	0.175228	1	1	0	0	25000
	20000.07	0	4999.889	0	0.16925	1	0	1	0	25000
	24499.86	0	0	500.1194	0.182225	1	0	0	1	25000
the 2nd	***0***	***23000.03***	***0***	***0***	***0.132195***	***0***	***1***	***0***	***0***	***23000***
	0	20000.07	4999.889	0	0.158505	0	1	1	0	25000
	0	22921.85	0	1628.198	0.184266	0	1	0	1	24550
the 3rd	***0***	***0***	***23000.03***	***0***	***0.129394***	***0***	***0***	***1***	***0***	***23000***
	0	0	21666.47	1536.598	0.179661	0	0	1	1	23203
	0	4998.397	20001.57	0	0.157343	0	1	1	0	25000
the 4th	***0***	***0***	***0***	***23000.03***	***0.144276***	***0***	***0***	***0***	***1***	***23000***
	0	4886.292	0	20113.71	0.17107	0	1	0	1	25000
	0	0	4999.889	20000.07	0.163649	0	0	1	1	25000

Table 4. Results

Phase	**the 1st CR**	**the 2nd CR**	**the 3rd CR**	**the 4th CR**	**Cost rate**	**CR policy**				**Interval**	**policy**
the 1st	24998.51	0	0	0	0.130467	1	0	0	0	24999	same
the 2nd	0	23001.13	0	0	0.132197	0	1	0	0	23001	same
the 3rd	0	0	23001.13	0	0.12941	0	0	1	0	23001	existing
	0	*0*	*12499.81*	*0*	*0.127395*	*0*	*0*	*2*	*0*	*25000*	*CR*
	0	0	23000.03	0	0.129394	0	0	1	0	23000	*δ=18000*
	0	0	23000.03	0	0.129394	0	0	1	0	23000	*δ=20000*
the 4th	0	0	0	23001.13	0.144281	0	0	0	1	23001	existing
	0	*0*	*21566.35*	*3433.712*	*0.14361*	*0*	*0*	*1*	*1*	*25000*	*CR*
	0	0	0	23000.03	0.144276	0	0	0	1	23000	*δ=18000*
	0	0	0	23000.03	0.144276	0	0	0	1	23000	*δ=20000*

need to be modified with (0 0 2 0) and (0 0 1 1) in the last two operational phases. Meanwhile, the others combinatorial replacement results applying maintained items can help users to make a decision when spare components are limited.

In the future working, we will further investigate the application of proposed models into improvement of the maintenance effect of diesel locomotives. Further, since spare components are critical factor in maintenance, the effects of spare components number on the maintenance of locomotives is also very interesting and promising work.

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