Institution of MECHANICAL ENGINEERS
Journal of RAIL AND RAPID TRANSIT

Original Article

Proc IMechE Part F:
J Rail and Rapid Transit
0(0) 1–7

DOI: 10.1177/0954409719884215
journals.sagepub.com/home/pif
SAGE

A preventive, opportunistic maintenance strategy for the catenary system of high-speed railways based on reliability

Hongbo Cheng[1,2], Yufan Cao[2], Jiaxin Wang[2], Wei Zhang[2] and Han Zeng[2]

Abstract

The catenary is a vital component of the electrified railway system. It consists of many parts which are interrelated; the maintenance schedule of the catenary system should consider the influence of the interrelationship. In this study, a preventive, opportunistic maintenance method is proposed to schedule the maintenance process of the catenary system. First, the reliability of the key parts of the catenary is modeled using Weibull distribution. Second, a reliability margin is proposed to expand the maintenance time from point to interval, and the reliability margin is optimized to minimize the maintenance cost. Then, a preventive opportunistic maintenance schedule can be arranged on the basis of the optimal reliability margin. Case study results verify that the proposed preventive opportunistic maintenance method can reduce the number of maintenance schedules and can effectively save the maintenance cost.

Keywords

Prognostics and health management, railway safety, statistical analysis

Date received: 21 June 2019; accepted: 22 September 2019

Introduction

Catenary is a vital component of the electrified railway system, as it provides the energy to drive the locomotive. With the gradual expansion of the scale of high-speed railways and the continuous increase in operating time, the burden of maintaining the catenary is also increasing.[1] The catenary system managed by the power supply departments of railway bureaus is huge and covers a wide area, while the maintenance staff and resources are limited; the contradiction between the catenary maintenance workload and resource is becoming increasingly prominent. Therefore, a reasonable, economical and efficient maintenance strategy to ensure the high reliability of catenary while reducing the labor intensity and maintenance costs is of great significance. It is also the actual urgent need of the railway bureaus at present.

The maintenance of catenary has developed from a periodic maintenance to a condition-based maintenance. Periodic maintenance, also called as time-based maintenance, includes carrying out activities regularly according to a predetermined schedule in order to maintain the condition of catenary; it is expensive and may lead to over-maintenance.[2] With the improvement of monitoring methods and the increasing availability of monitoring data, condition-based maintenance is becoming more and more popular. Some researchers[3,4] developed an over-head monitoring service for monitoring the catenary in real time and to detect the potential risk needed for maintenance, thus improving the service quality of the catenary and reducing the costs of maintenance. Cost is an important factor to consider in maintenance[5]; many methods are used to optimize the maintenance schedule of the catenary. The individual components-based heuristic algorithm for solving the optimization model was developed in Chen et al.,[6] which considers the connections of components in the catenary system. Moreover, Chen et al.[7] incorporated the considerations of different levels of maintenance activities to balance between reliability and cost. By establishing the system reliability model, the contribution of individual component reliability toward the overall system reliability is extracted from the functional

---

[1]National Rail Transportation Electrification and Automation Engineering Technology Research Center, Chengdu, China
[2]School of Electrical and Automation Engineering, East China Jiaotong University, Nanchang, China

Corresponding author:
Hongbo Cheng, East China Jiaotong University, Shuanggang Road 808, Nanchang City, Jiangxi Province, 330013, China.
Email: waitingbo@126.com

relationship among the components. The optimization of the maintenance schedule is to achieve the maximum reliability of the catenary system and the minimum maintenance cost at the same time. To solve this typical multi-objective optimization problem, an advanced Chaos Self-adaptive Evolutionary Algorithm, called CSEA, has been proposed in Li et al.[8] Liu et al.[9] proposed an optimization model for the risk-based high-speed railway catenary system maintenance, which takes the minimum maintenance cost as the optimization objective; under the restrictions of fault risk and repair resource, a genetic particle swarm optimization algorithm with good convergence is designed to solve the optimization problem. In an aim to find a long-term tactical plan that optimally schedules train-free windows sufficient for a given volume of regular maintenance together with the wanted train traffic, Lidén and Joborn[10] presented a mixed integer programming model for solving an integrated railway traffic and network maintenance problem. D'Ariano et al.[11] modeled it as a mixed-integer linear programming formulation, in which the traffic flow and track maintenance variables, constraints and objectives are integrated under a stochastic environment. The resulting bi-objective optimization problem is to minimize the deviation from a scheduled plan and to maximize the number of aggregated maintenance works under stochastic disturbances.

In order to avoid the loss caused by failure, preventive maintenance fixes small problems before major ones develop.[12,13] By analyzing the catenary system based on fault tree model, and using different parameters of Weibull distribution to describe the device failure probability of the various parts of the catenary system, Liu et al.[14] proposed an optimization function of preventive maintenance strategy on the catenary system based on reliability constraints. The dynamic reliability model and the maintenance cost model on catenary have been established in Min et al.[15]; the objective is to optimize the maintenance actions so that the maximum reliability and minimum maintenance cost can be achieved. Guan et al.[16] provided a new maintenance strategy for the Overhead Contact System (OCS) based on the reliability-centered maintenance (RCM) technology; a maintenance plan can be worked out by the proposed RCM decision-making body. On the basis of a stochastic lifetime model, Ho et al.[17] presented a generic software evaluation tool that enables the operators to manage risk of failure and cost quantitatively in order to match their preferred levels of service quality.

The catenary is a complex component consisting of many parts: contact suspension, support device, positioning device, pillar and foundation, etc. Failure of any part will result in power failure of the catenary; therefore, the current maintenance method will lead to frequent power outages of catenary, which will result in higher maintenance costs and power outage losses. Moreover, frequent outage will lead to interruption of railway transportation and have a negative impact on the reputation of railway departments. Therefore, if the parts of catenary with low reliability can be repaired at the same time while repairing the faulty parts, the fixed maintenance cost and power outage loss can be shared, and the maintenance times of catenary can be reduced, also achieving the goal of cost saving.

The reliability of the key parts of catenary

As the complex mechanical structure is comprised of many parts, the reliability of catenary is greatly affected by the material strength. As a widely used model in equipment reliability analysis, Weibull distribution is most suitable for the characterization of catenary parts.[18–20]

The failure rate of catenary parts changes according to the bathtub curve shown in Figure 1. The failure distribution function of two-parameter model[21] is

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \tag{1}$$

The reliability function is

$$R(t) = 1 - F(t) = \exp\left[-\left(\frac{t}{\eta}\right)^m\right] \tag{2}$$

The failure function is

$$\lambda(t) = \frac{mt^{m-1}}{\eta^m} \tag{3}$$

where t represents time and m represents the shape parameter, which are related to the variation trend of the failure rate. η is the scale parameter which is related to the lowest failure rate.

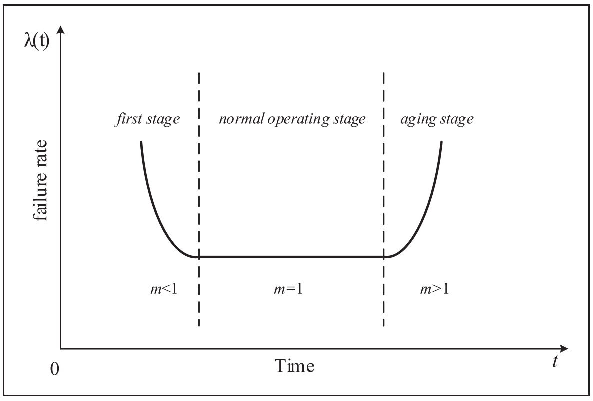

Figure 1. Bathtub curve of the failure rate.

From formula (3), when $m < 1$, the failure rate function $\lambda(t)$ is degraded and the failure rate decreases with increase of t, which applies to model failure in early period; when $m = 1$, the failure rate $\lambda(t)$ is a constant; the device works in the random failure period, which applies to model random failure; and when $m > 1$, the failure rate function $\lambda(t)$ is ascendant and the device works in wear-out failure period, which applies to model failure due to wear-out or aging. It corresponds to the three stages of bathtub curve in Figure 1.

Based on the failure record, the parameters m and η are obtained by using least square method; thus, the reliability of device can be obtained.

Preventive opportunistic maintenance model for the catenary

As it can be seen, the reliability of catenary parts varies with service time; when the reliability of a part decreases to a value that may affect normal operation, preventive maintenance is required. Let preventive maintenance time T_p represents this moment, the T_p of different parts will be different due to the different operation times and different rules of reliability. If every part is repaired at its preventive maintenance time, it will result in multiple overhauling and high maintenance cost.

Opportunistic maintenance extends preventive maintenance time to a time interval $[T_o, T_p]$, where T_o is the beginning time for opportunistic maintenance. The part can be repaired at any time within the time interval, so that there is an opportunity for different parts of the catenary to cooperate with each other in maintenance.

The schematic diagram of the preventive opportunistic maintenance model between different parts of catenary is shown in Figure 2, where R_o represents opportunistic maintenance reliability and R_p represents preventive maintenance reliability maintenance. $T_o^{(i)}$,$T_o^{(j)}$and $T_o^{(k)}$ represent the opportunity beginning time of part i, j, k, respectively, $T_p^{(i)}$, $T_p^{(j)}$, $T_p^{(k)}$ represent the preventive maintenance time of part i, j, k, respectively; they are determined by the acceptable reliability of different parts.

The preventive opportunistic maintenance model of catenary is defined as

1. For part i, preventive maintenance is carried out when its running time t satisfies

$$t = T_p^{(i)}(t) \tag{4}$$

2. When the preventive maintenance of part i is carried out, if another part $j(j = 1, \cdots, N$, and $j \neq i)$ satisfies

$$T_o^{(j)}(t) \leqslant t < T_p^{(j)}(t) \tag{5}$$

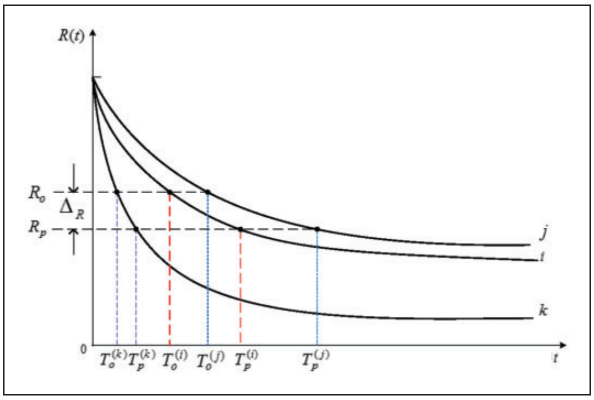

Figure 2. Schematic diagram of the preventive opportunistic maintenance model.

Then the opportunistic maintenance of j can be carried out at the same time.

3. When the preventive maintenance of part i is carried out, if part k, $(k = 1, \cdots, N$, and $k \neq i \neq j)$ satisfies

$$t < T_o^{(k)}(t) \tag{6}$$

Then no opportunistic maintenance for k while i maintenance, where N is the total number of the parts.

That is to say, preventive maintenance is carried out when i runs to its preventive maintenance time, checks other parts j, k at the same time, if $T_p^{(i)}$ is within the opportunistic maintenance interval of part j, j should implement opportunistic maintenance; on the contrary, if $T_p^{(i)}$ is not within the interval of k, there should no opportunistic maintenance for k.

With preventive opportunistic maintenance, the part has an opportunity to be maintained together with the part which has met the requirement of preventive maintenance. Only one maintenance is performed for them, which will reduce the number of outages and will save the cost; in addition, it can eliminate hidden trouble and meet the requirement of high reliability of the catenary by repairing parts in the latent period of failure.

Optimization of preventive opportunistic maintenance interval for the catenary

Solution for opportunistic maintenance interval

As the basis of maintenance decision, opportunistic maintenance interval affects the catenary reliability and maintenance cost at the same time. Long opportunistic maintenance interval will lead to too many times of opportunistic maintenance; over-repair will make parts defective and increase the maintenance cost. Short opportunistic maintenance interval will make it impossible for parts to cooperate with each other and cannot achieve the goal of reducing maintenance times and saving maintenance costs.

Opportunistic maintenance interval, $[T_o, T_p]$, is determined by preventive maintenance time T_p and opportunistic maintenance starting time T_o. Preventive maintenance time T_p, derived from reliability function and operation requirement of catenary, is generally fixed. Therefore, opportunistic maintenance starting time T_o is particularly important; only a reasonable opportunistic maintenance starting time can make it possible to combine the reliability and economy.

The opportunistic maintenance time margin Δ_T is defined to describe the distance between preventive maintenance time T_p and opportunistic maintenance time T_o, $\Delta_T = T_p - T_o$; accordingly, the difference between opportunistic maintenance reliability R_o and preventive maintenance reliability R_p is the opportunistic maintenance reliability margin, $\Delta_R = R(t)|_{t=T_o} - R(t)|_{t=T_p} = R_o - R_p$. The relationship between Δ_T and Δ_R is shown in Figure 3.

Compared with the whole service cycle, the distance between the opportunity starting time T_o and preventive time T_p is generally small, so that

$$\Delta_R \approx k_R \Delta_T \tag{7}$$

where k_R is the slope of the reliability curve at the point (T_p, R_p), which reflects the change rate of reliability function at this point. Since Δ_T is small, it can be concluded with equation (2) that[22]

$$\begin{aligned} k_R &= \frac{dR(\mathrm{t})}{dt} = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \\ &= \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} R(t) \end{aligned} \tag{8}$$

Therefore, k_R is the function of scale parameter η and shape parameter m. If η is large and m is small, k_R will be large, which means under the same requirement of Δ_R, the corresponding Δ_T is small, which leads to small opportunistic maintenance interval and small possibility of opportunistic maintenance. Otherwise, if η is small and m is large, k_R will be small, Δ_T is large for the same Δ_R, which leads to large opportunistic maintenance interval and large possibility of opportunistic maintenance. Therefore, appropriate reliability margin should be optimized for different parts of catenary, since they have different scale parameter η and shape parameter m.

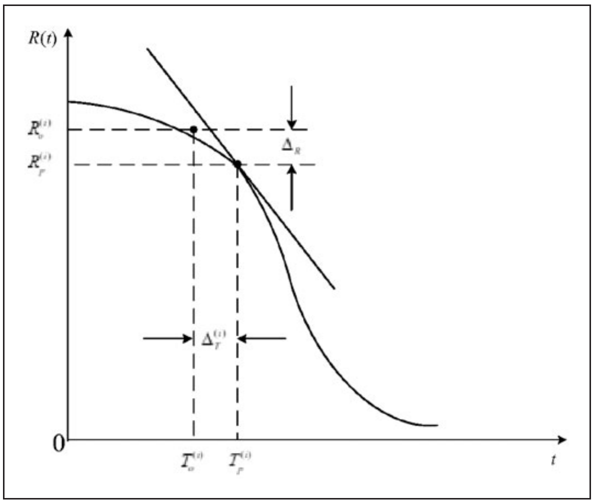

Figure 3. Relationship between opportunistic maintenance time margin and reliability margin.

In different operation stages of catenary, m will have different values, as shown in Figure 1. From equation (8) and Figure 3, it can be seen that k_R will remain as positive for each stage, and the amplitude will reach minimum when $m = 1$; that means k_R is minimum in the normal operating stage; in order to avoid excessive maintenance, Δ_R can take a large value which means the preventive maintenance intervals in normal operating stage can be large.

Optimization of opportunistic maintenance interval

Considering the catenary reliability and maintenance economy, opportunistic maintenance interval should be optimized by different reliability margins to different parts of the catenary. Therefore, on the basis of reliability requirement of catenary, a preventive opportunistic maintenance decision model is proposed aiming at the lowest maintenance cost.

$$\min C_{op} = \sum_{i=1}^{N}\left[M_o^{(i)} C_p^{(i)} + (C_p^{(i)} + C_f + C_e) M_p^{(i)}\right] \tag{9}$$

where C_{op} is the total maintenance cost of catenary under preventive opportunistic maintenance, N is the total number of parts of catenary, $C_p^{(i)}$ is the cost of preventive maintenance for part i, $M_o^{(i)}$ is the opportunistic maintenance number of part i, C_f is the regular maintenance cost due to manpower, tools and other inputs for each maintenance, C_e is the loss caused by outage of catenary maintenance, $M_p^{(i)}$ is the preventive maintenance number of part i, the relationship between $M_p^{(i)}$ and the life of part T is as follows when regardless of opportunistic maintenance

$$M_p^{(i)} = T / T_p^{(i)} \tag{10}$$

The constrains of the preventive opportunistic maintenance of catenary is

1. Reliability constraint

$$\begin{cases} R_o^{(i)} \geqslant R(T_o'^{(i)}) \geqslant R_p^{(i)} \\ R(T_p'^{(i)}) \geqslant R_p^{(i)} \end{cases} \tag{11}$$

It refers to the reliability of the catenary at opportunistic maintenance, and preventive maintenance should meet the requirement of catenary operation. When we perform preventive maintenance at time $T_p^{\prime(i)}$, the time $T_p^{\prime(i)}$ should satisfy $R(T_p^{\prime(i)})\geqslant R_p^{(i)}$, which means that the preventive maintenance should be performed before the reliability falls to $R_p^{(i)}$, and also the opportunity maintenance time $T_o^{\prime(i)}$ should make $R_o^{(i)}\geqslant R(T_o^{\prime(i)})\geqslant R_p^{(i)}$ satisfied, which means the opportunity maintenance time $T_o^{\prime(i)}$ can be a time within the interval $[T_o^{(i)},T_p^{(i)}]$.

2. Opportunistic maintenance interval constraint

$$T_p^{\prime(i)} - T_o^{\prime(i)} - \frac{\Delta_R}{k_R^{(i)}} \leqslant \varepsilon \tag{12}$$

where ε is an infinitesimal quantity. Equation (12) refers to the optimized $T_o^{\prime(i)}$; it should be near $T_p^{\prime(i)}$ and it should satisfy the changing rule of reliability.

Since equation (9) is not an explicit function of opportunistic maintenance margin Δ_R, in order to avoid solving Jacobian matrix and Hessian matrix, quadratic interpolation method can be used as an optimization algorithm.[23] For each Δ_R, calculate a C_{op}, then serveral points can be obtained to fit an interpolation polynomial approximated to the objective function. Based on the principle of interval elimination, the optimal point is determined by gradually reducing the search interval, and the optimal solution of this polynomial can be used as the approximate optimal Δ_R^*.

Case study

One section of the catenary is taken as an example; this section of the catenary is 46 km long and is managed by a work class; based on the fault statistics for the past three years, from 2008 to 2010, we can estimate the reliability parameters for the most key parts of the catenary as shown in Table 1.

According to statistical data, the fixed maintenance cost C_f of catenary is 17,000 CNY, and the power outage loss C_e caused by preventive maintenance is 35,000 CNY.[23]

Based on the R_p shown in Table 1, the slope k_R of the reliability curve at point (Tp, Rp) can be calculated first according to formula (8); then the opportunistic maintenance time margin Δ_T can be calculated by equation (7). Finally, the opportunistic maintenance interval can be obtained. The corresponding results are shown in Table 2.

Figure 4 shows the process of solving the optimal solution of reliability margin with quadratic interpolation method described in last paragraph of the 'Preventive opportunistic maintenance model for the catenary' section. The total maintenance cost for different reliability margins is shown in Figure 4.

Since $R_p+\Delta_R\leqslant 1$ and the standard R_p of reliability is large, usually Δ_R is very small. The maintenance cost decreases first and then increases when the reliability margin increases, because when Δ_R is small, the corresponding Δ_T is also small; that will lead to independent preventive maintenance, which is expensive. On the other hand, when Δ_R is too large, the corresponding opportunity interval is large, and the part will implement opportunistic maintenance easily;

Table 1. Reliability parameters and maintenance parameters for the parts of catenary.

Part of catenary	Scale parameter η	Shape parameter, m	Maintenance cost $C_p/(10^3\text{CNY})$	Standard for preventive maintenance, R_p
Contact line	1.67×10^6	0.37	12	0.988
Messenger wire	1.29×10^6	0.48	11	0.995
insulator	1583.57	0.86	8	0.972
Tension compensation device	6.54×10^4	0.43	5.5	0.968
Electrical connection device	4320.50	0.76	3.0	0.967

Table 2. Calculation results for opportunistic maintenance interval.

Part of catenary	k_R	$[R_p, R_o]$	Δ_T/month	$[T_o, T_p]$/month
Contact line	3.70×10^{-4}	[0.988, 0.989]	3.01	[9.01, 12.02]
Messenger wire	1.21×10^{-4}	[0.995, 0.996]	9.21	[10.46, 19.67]
insulator	9.60×10^{-4}	[0.972, 0.973]	1.16	[23.44, 24.60]
Tension compensation device	6.38×10^{-4}	[0968, 0.969]	1.75	[19.28, 21.03]
Electrical connection device	5.06×10^{-4}	[0.967, 0.968]	2.20	[46.33, 48.53]

Note: The unit for Δ_T, T_O, T_p is month, which is suitable to guide the on-site maintenance work.

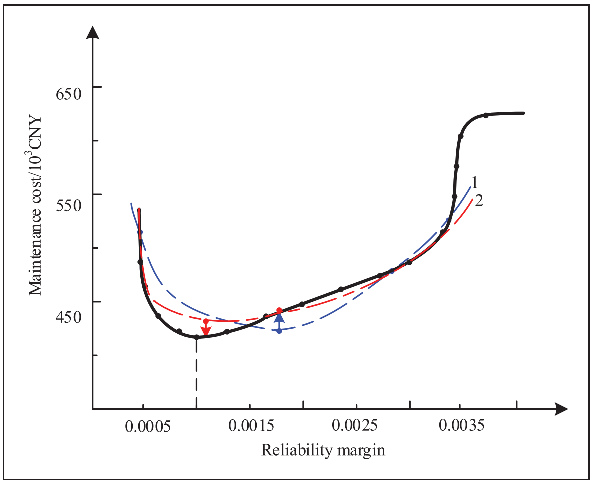

Figure 4. Relationship between maintenance cost and reliability margin.

Table 3. Maintenance times and cost in different maintenance modes.

Parts of catenary	Preventive maintenance		Preventive opportunistic maintenance		
	M_p	$C_p/10^3$CNY	M_p	M_o	$C_{op}/10^3$CNY
Contact line	12	2016	6	6	1269
Messenger wire	6		0	9	
Insulator	6		3	3	
Tension compensation device	6		6	0	
Electrical connection device	3		3	0	

too frequent maintenance will increase the maintenance cost.

The minimum maintenance cost can be calculated by quadratic interpolation, as shown with the dotted line in Figure 4, and its corresponding reliability margin is $\Delta_R^* = 0.001114$. Based on this reliability margin, opportunistic maintenance intervals can be calculated as shown in Table 2.

From Table 2, it can be seen that a maintenance cycle comprises 56 months. On the basis of these opportunistic maintenance intervals, the maintenance times and cost for different catenary parts in this section in 168 months (14 years' design life) are shown in Table 3, and the process of preventive opportunistic maintenance for different parts of catenary is shown in Figure 5.

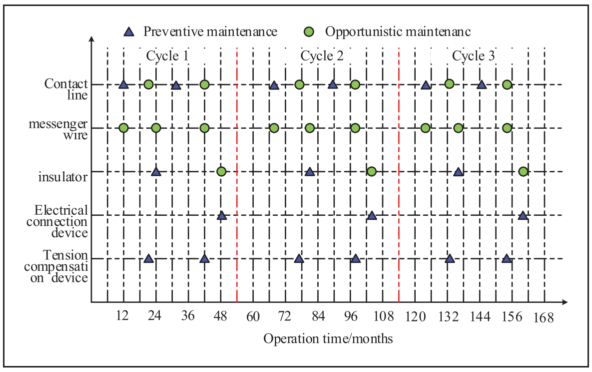

Figure 5. Process of preventive opportunistic maintenance of catenary.

It can be seen from Table 3 that, in the case of only preventive maintenance, the total number of maintenance is 33, while when the preventive opportunistic maintenance is taken into account, the total number of maintenance is 18, which is reduced by 45.5%. It is because in the case of preventive opportunistic maintenance, there are 18 opportunistic maintenance processes which reduce the number of preventive maintenance and save 747,000 CNY in maintenance costs; the cost reduction rate is up to 37.1%.

Conclusions

1. As a vital component that provides energy for locomotives, the catenary should always be in good condition. Reasonable maintenance is an important means to ensure good working condition of the catenary.
2. The catenary is a complex system consisting of multiple parts, which are interrelated and interact with each other; the maintenance schedule of catenary should consider the influence of the interrelationship.
3. Opportunistic maintenance can provide coordination chances for the maintenance of different parts of catenary, which can reduce the number of maintenance schedules and save the maintenance cost.
4. Reliability margin is a way to calculate opportunistic maintenance intervals; a reasonable reliability margin is the key to realize the balance between reliability and maintenance economy of the catenary.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported in part by National Rail Transit Electrification and Automation Engineering Center under Grant NEEC2018B10 and in part by Jiangxi Department of Education under Grant GJJ160498.

ORCID iD

Hongbo Cheng https://orcid.org/0000-0002-6859-1172

References

1. HE Z-Y and Cheng H-B. Research on health management and early warning system for traction power supply system of high-speed railway. *Power System Technol* 2012; 36: 259–264.
2. Grigoriev A, Van De Klundert J and Spieksma FCR. Modeling and solving the periodic maintenance problem. *Eur J Oper Res* 2006; 172: 783–797.
3. Tanarro F and Fuerte V. OHMS-real-time analysis of the pantograph-catenary interaction to reduce maintenance costs. In: *5th IET conference on railway condition monitoring and non-destructive testing (RCM 2011)*, Derby UK, 29–30 November 2011, pp.52–52.
4. Jimenez Redondo N, Bosso N, Zeni L, et al. Automated and cost effective maintenance for railway (ACEM–Rail). *Proc – Social Behav Sci* 2012; 48: 1058–1067.
5. Lopez-Pita A, Teixeira PF, Casas C, et al. Maintenance costs of high-speed lines in Europe state of the art. *Transport Res Record* 2008; 2043: 13–19.
6. Chen S-K, Wang X-D, Bai Y, et al. Lowest costs-based optimum maintenance scheduling model for catenaries of railways. *J China Railway Soc* 2013; 35: 37–42.
7. Chen S-K, Ho T-K, Mao B-H, et al. A bi-objective maintenance scheduling for power feeding substations in electrified railways. *Transport Res Part C: Emerging Technol* 2014; 44: 350–362.
8. Li X, Wu J-Y, Yang Y, et al. Research on optimization of catenary system maintenance schedule for high-speed railways. *J China Railw Soc* 2010; 32: 24–30.
9. Liu C, Chen M-W and Song Y-L. Research on optimization of maintenance plan for high-speed railway catenary system based on risk assessment. *J Railw Sci Eng* 2017; 14: 205–213.
10. Lidén T and Joborn M. An optimization model for integrated planning of railway traffic and network maintenance. *Transport Res Part C: Emerging Technol* 2017; 74: 327–347.
11. D'Ariano A, Meng L, Centulio G, et al. Integrated stochastic optimization approaches for tactical scheduling of trains and railway infrastructure maintenance. *Comput Ind Eng* 2019; 127: 1315–1335.
12. Soh SS, Radzi NHM and Haron H. Review on scheduling techniques of preventive maintenance activities of railway. In: *IEEE 2012 4th international conference on computational intelligence, modelling and simulation*. New Jersey: IEEE, pp.310–315, 2012.
13. Stenström C, Per N, Parida A, et al. Preventive and corrective maintenance–cost comparison and cost–benefit analysis. *Struct Infrastruct Eng* 2016; 12: 603–617.
14. Liu H, Liu Z-G and Jiang J. Optimization research of preventive maintenance strategy on the catenary system based on reliability constraints. *J Mech Strength* 2016; 38: 74–79.
15. Min LX, Wu JY, Yang Y, et al. Multiobjective optimization of preventive maintenance schedule on traction power system in high-speed railway. In: *IEEE* 2009 *annual reliability and maintainability symposium*. New Jersey: IEEE, 2009, pp.365–370.
16. Guan J-F, Wu J-Q, Wang X-D, et al. Study on optimized maintenance strategy of overhead contact line system based on RCM technology. *Railw Standard Des* 2013; 7: 97–101.
17. Ho TK, Chi YL, Ferreira L, et al. Evaluation of maintenance schedules on railway traction power systems. *Proc IMechE, Part F: J Rail and Rapid Transit* 2006; 220: 91–102.
18. Zhao H-S and Zhang L-P. Preventive opportunistic maintenance strategy for wind turbines based on reliability. *Proc CSEE* 2014; 34: 3777–3783.
19. Moon JF, Kim JC, Lee HT, et al. Reliability evaluation of distribution system through the analysis of time-varying failure rate. In: *IEEE power engineering society general meeting*. New Jersey: IEEE, 2004, pp.668–673.
20. Wang L-Z, Xu Y-G and Zhang J-D. Research on reliability analysis model for key components and parts of railway equipment and its application. *J China Railw Soc* 2008; 30: 93–97.
21. Cheng H-B, He Z-Y, Wang Q, et al. Fault diagnosis method based on Petri nets considering service feature of information source devices. *Comput Electr Eng* 2015; 46: 1–13.
22. Hung P. *Optimization theories and methods*. China: Tsinghua University Press, 2009, pp.76–78 (in Chinese).
23. Zhan G-Z. *The studies of OCS maintenance optimization based on its reliability*. Doctor of Thesis, Tsinghua University, Beijing, 2009.