

論文

# 傳統鐵路電車線系統可靠度之研究

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## 摘要

近年臺鐵西部幹線都會區鐵路捷運化之轉型，路線容量近趨飽和，設備故障所致之營運影響更顯重要，電車線系統可靠度直接影響營運安全與服務品質，故提高電車線系統可靠度是緊迫關鍵的問題。

本研究依歐洲標準EN50126之原則，以故障樹分析法對臺鐵西部幹線(含山線與海線)電車線系統進行可靠度定性及定量分析，結果顯示主吊線是電車線系統最薄弱的環節，必須進行改善工作；每百公里之電車線系統平均故障間隔時間MTBF約為198日，對於系統保養週期訂定提供重要參考。本研究也探討電車線系統可維修度、妥善率，闡述RAMS之內在關聯性，並提出營運階段可靠度改善方案，如下：採用較高可靠度的組件；採用較易更換、模組化的組件；培養訓練有素且經驗豐富的檢修人員。

**關鍵字：**電車線系統、故障樹分析、可靠度、可維修度、妥善率

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## Research Articles

# A Study on Reliability of Conventional Railway Overhead Catenary System

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## Abstract

In recent years, the Western Line of Taiwan Railway Administration (TRA) in the metropolitan areas have been rapid transit systematized. At the same time, the line capacity is near saturation. Therefore, the impact from electromechanical equipment failures on the operation is becoming more significant. The reliability of the overhead catenary system affects the operational safety and service quality directly, so the improvement of the overhead catenary system reliability is definitely an important and urgent issue.

In accordance with the principles of the European Standard EN50126, both the qualitative and quantitative analyses of reliability on the overhead catenary system of the TRA Western Line (both the Mountain Line and the Coast Line are included) were conducted with the fault tree analysis method. The results show that the messenger wires are the weakest link in the overhead catenary system, and therefore the improvement work is needed. The mean time between failures (MTBF) of the overhead catenary system per hundred kilometers is about 198 days, which provides an important reference for setting up the system maintenance cycle. In the study, it also explored the overhead catenary system maintainability and availability, and explained the inherent correlation of the RAMS. Meanwhile, it also proposed solutions to improve the reliability of the operational phase as the follows: adopting high reliability components, adopting easier-to-replace and modularized components, and fostering trained and experienced maintenance personnel.

**Keywords:** Overhead catenary system, Fault tree analysis, Reliability, Availability, Maintainability

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## INTRODUCTION

### 1. Safety Concerns for the Taiwan Railway Administration Overhead Catenary System

The conventional railway services in Taiwan are provided by the Taiwan Railway Administration of the Ministry of Transportation and Communications (TRA). As of June 2014, the business mileage of electrified sections totals 874.4 km. The passenger number reached 227 million and 290 thousand in 2013, a new record high.

The government is now devoted to construct a transportation environment that is more secure, reliable, efficient and of green energy; and meanwhile, it continues to promote the works of the ordinary-speed railways to be elevated, undergrounded, and rapid transit systematized. In response to the need of railway rapid transit systematization in metropolitan areas, the line capacity will become more saturated, the frequency of the use of mechanical and electrical equipment will increase, and the impact on the operations from the failures caused by electrical and mechanical equipment will be more serious. It is described in the European Standard EN50126:1999 that the reliability, availability, maintainability and safety (RAMS) of the railway has a clear influence on the quality with which the service is delivered to the customer. Service quality is also influenced by other characteristics concerning safety, functionality and performance[1]. Not only is railway system reliability an important influence factor on service quality, but more reliable service quality is also

highly desirable by the society.

Recently, several TRA incidents related to failure of the overhead catenary system (OCS), affecting the operational safety and service quality. The lack of reliability on the overhead catenary system, which would be a weak link in an electrified railway system, has become one of the important factors affecting the development of electrified railway. More importantly, the overhead catenary system has no backup arrangements, like series systems, and in case of failure it will immediately lead to operational interruption, which has a serious impact on service quality. Therefore, how to increase the reliability of the overhead catenary system is an urgent and key issue faced in the construction of the electrified railway.

### 2. Objectives, Scope and Methodology of the Study

The scope of the study was limited to the overhead catenary system of the TRA Western Line (including both the Mountain Line and the Coast Line), of which the traffic density is higher. Besides, the study analyzed statistically based on the TRA power accident data between years 2000 and 2013 to examine the reliability of the ordinary-speed railway overhead catenary system.

Using Fault Tree Analysis (FTA), the study conducted qualitative and quantitative analyses on the overhead catenary system, to identify fault links with low reliability index. And with reliability engineering theory, effective improvement measures were proposed to control the risk of system failure

within tolerable range, in order to improve the reliability of the overhead catenary system to ensure the safe operation of the system, increase the service quality of electrified railway operations, and improve economic benefits of operations.

## Literature Review

### 1. Reliability Theory

European standard EN50126 defines reliability as: "The probability that an item can perform a required function under given conditions for a given time interval." According to researches with large numbers of data for different types of component failures, for a component during the effective life cycle the failure rate  $\lambda(t)$  is nearly a constant, and its reliability  $R(t)$  is an exponential distribution, as shown in the equation below:

$$R(t) = e^{-\lambda t} \dots\dots\dots (1)$$

In the theory of reliability, the most likely time of failure in repairable systems or components is called the mean time between failures (MTBF) [2-6]. If the failure rate  $\lambda(t)$  of a system or a component is a constant, then

$$MTBF = \int_0^{\infty} R(t)dt = \int_0^{\infty} te^{-\lambda t} dt = \frac{1}{\lambda} \dots (2)$$

Maintainability means the probability of completing a repair in a given condition within a given time, and is usually denoted by  $M(t)$ . If the maintainability is of the exponential distribution, then

$$M(t) = 1 - e^{-\mu t} \dots\dots\dots (3)$$

In Equation (3),  $\mu$  is called the repair rate. If it is a constant, the mean time to repair (MTTR) of repairable systems or components can be expressed as

$$\mu = \frac{1}{MTTR} \dots\dots\dots (4)$$

In the reliability analysis of power system, there are three important indices, namely, the failure rate  $\lambda$ , the mean time to repair  $r$ , and the unavailability  $U$ , where  $U$  is the product of the failure rate  $\lambda$ , and the mean time to repair  $r$ [2-6].

The reliability indices of a series system are shown in the Equations (5) to (7) as follows:

$$\lambda_s = \sum_{i=1}^n \lambda_i \dots\dots\dots (5)$$

$$r_i = \frac{\sum_{i=1}^n \lambda_i r_i}{\sum_{i=1}^n \lambda_i} \dots\dots\dots (6)$$

$$U_s = \sum_{i=1}^n \lambda_i r_i \dots\dots\dots (7)$$

### 2. Fault Tree Analysis

The most unwanted system failure state is taken in Fault Tree Analysis (FTA) as the target for the fault analysis, and the selected system failure state is called the top event. The analyses are then taken place to find all the possible factors that lead to a failed state. The tracing ends at the factors that are not necessary for any analysis[4-5].

The so-called fault tree qualitative analysis is to identify all the possible failure modes that lead to the top events, and which means to identify the minimal cut set (MCS) of the fault tree[4-5].

At the fault tree quantitative calculations, the general hypotheses are that the basic events are independent from each other, and only two states

are considered for the top events and the basic events, normal or fault.

Assuming the fault tree top event T are combined in series by n events, namely,  $x_1, x_2, \dots, x_n$ , which means

$$T = x_1 \cup x_2 \cup \dots \cup x_n \dots \dots \dots (8)$$

The minimal cut sets of T are  $\{x_1\}, \{x_2\}, \dots, \{x_n\}$ , then the probability that T occurs is

$$P(T) = 1 - \{ 1 - P(x_1) \} \cdot \{ 1 - P(x_2) \} \dots \dots \{ 1 - P(x_n) \} (9)$$

Due to the influences from each basic event of the Fault Tree on the system failures being different, an importance measure method must be used to measure the degree of importance affecting the occurrence probability of the fault tree top events. Birnbaum importance measure used in this study can be expressed as:

$$I_{X_i}^B = \frac{\partial P(T)}{\partial P(X_i)} \dots \dots \dots (10)$$

Where  $I_{X_i}^B$  : Birnbaum importance measure of the basic event  $X_i$

$P(X_i)$ : Occurrence probability of the basic event  $X_i$

$P(T)$ : Occurrence probability of the top event T

### Fault Tree Analysis

#### 1. Overhead Catenary System Components

The study defines the overhead catenary system as a series composition formed by eight sub-systems, including the contact suspension, suspension subsidiary, support device, registration device, terminal device, pole, power equipment

and insulation device, as show in Figure 1. The reliability of the overhead catenary system is relevant not only to every single component, but also to the way they are composed or how they match each other. Thus, every single component failure will affect the normal operation of the overhead catenary system[4-5],[8-11] .

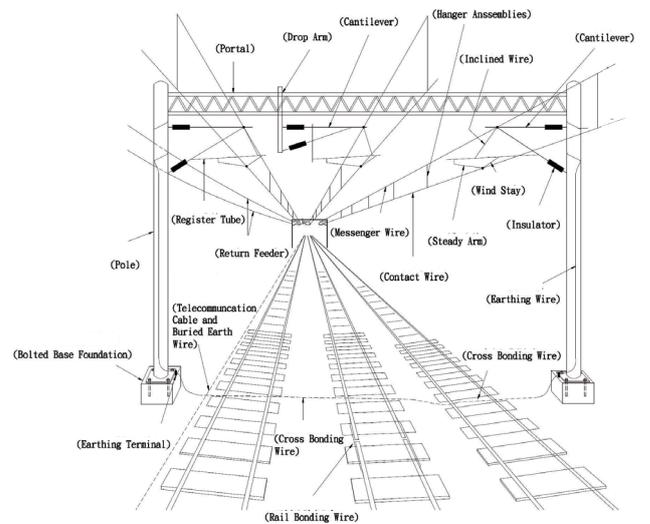


Figure 1 The components of the overhead catenary system[12]

#### 2. Construction of Fault Tree

The fault tree is a model reflecting the causal relationship among the system faults. To identify the causes for the overhead catenary system failures, the study summed up the key failure factors leading to the overhead catenary system failures based on data of a total of 217 overhead catenary system accidents during the period of interest [13]. And that provided a data base for the overhead catenary system reliability analysis.

With these statistical results, the overhead catenary system failure is the top event of the fault tree, helping the system to find the possible factors for the failure, of the system until all the causes of

system failure are identified. The basic principles of constructing the overhead catenary system fault tree were as follows: only the system's critical components were considered; neither the substations nor the power supply equipment were considered; the events with lesser impact on the system were not considered to simplify the model; the events

that had not investigated were taken as basic events. According to the above principles, the overhead catenary system fault trees can be shown as in Figure 2. The top fault tree is the overall overhead catenary system fault tree, where more details of  $\Delta$  -  $\Delta$  are further expanded in the following figures.

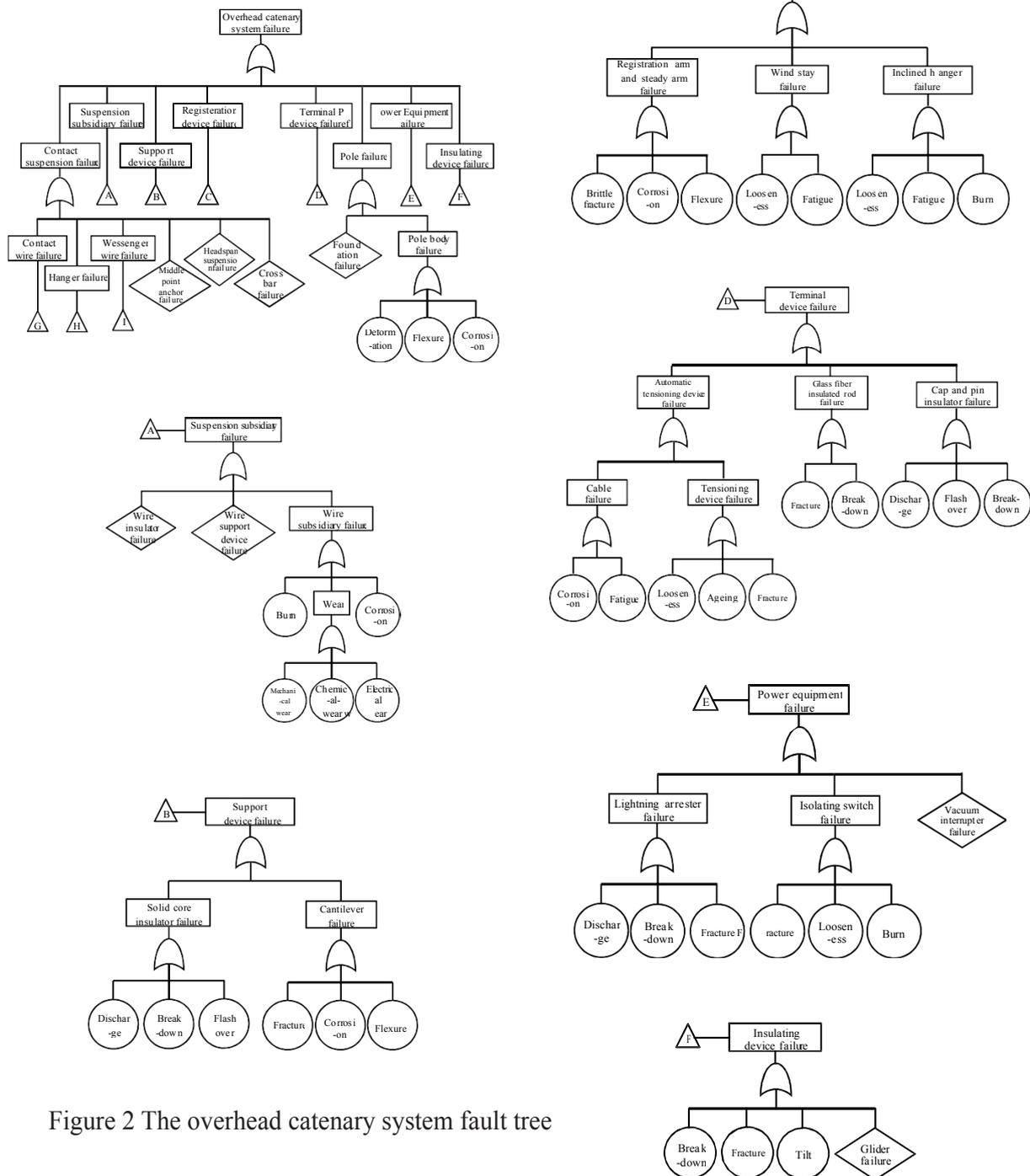


Figure 2 The overhead catenary system fault tree

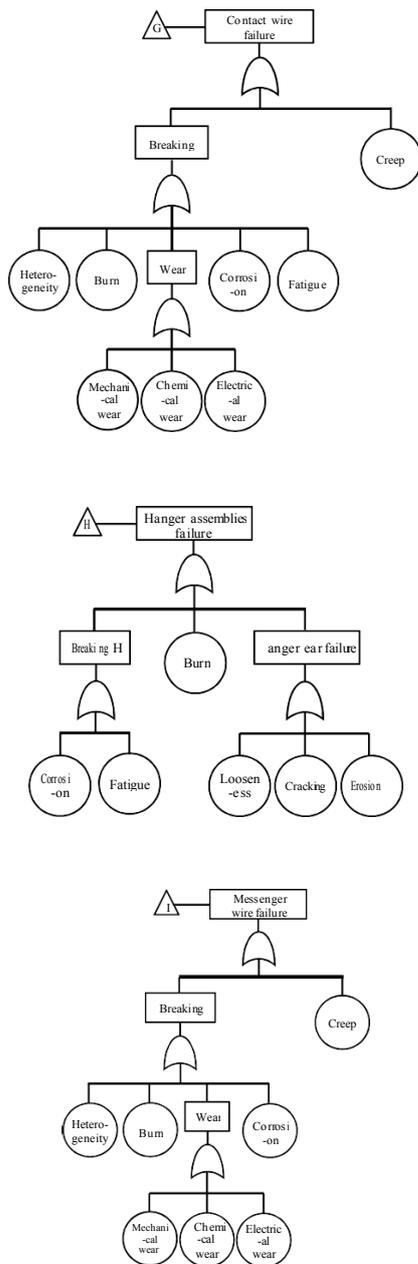


Figure 2 The overhead catenary system fault tree

### 3. Minimal Cut Sets

The main purpose of fault tree analysis was to find the logical relationship among the events that lead to system failures, and that is to find the minimal cut sets of the fault tree. In order to conduct the qualitative analysis with the overhead catenary

system fault tree, the individual basic events of the overhead catenary system fault tree were labeled with symbols[4],[8-11],[14-15], as shown in Table1.

Table 1 The basic events that lead to the failures of the OCS

Basic events	Deformation	Tilt	Corrosion	Burn	Mechanical wear	Chemical wear
Symbols	$x_1$	$x_2$	$x_3$	$x_4$	$x_5$	$x_6$
Basic events	Electrical wear	Electric discharge	Breakdown	Flash over	Fracture	Flexure
Symbols	$x_7$	$x_8$	$x_9$	$x_{10}$	$x_{11}$	$x_{12}$
Basic events	Brittle fracture	Looseness	Fatigue	Ageing	Heterogeneity	Creep
Symbols	$x_{13}$	$x_{14}$	$x_{15}$	$x_{16}$	$x_{17}$	$x_{18}$
Basic events	Cracking	Middle point anchor failure	Headspan suspension failure	Cross bar failure	Foundation failure	Wire insulator failure
Symbols	$x_{19}$	$x_{20}$	$x_{21}$	$x_{22}$	$x_{23}$	$x_{24}$
Basic events	Wire support device failure	Vacuum interrupter failure	Glider failure			
Symbols	$x_{25}$	$x_{26}$	$x_{27}$			

A bottom-up method was used to find the solutions of the minimal cut sets of the fault tree based on the fault tree model in Figure 1 and the symbols of the basic events leading to failures in Table 1. And the minimal cut sets of the contact suspension fault tree of the sub-systems can be obtained as  $\{x_3\}$ ,  $\{x_4\}$ ,  $\{x_5\}$ ,  $\{x_6\}$ ,  $\{x_7\}$ ,  $\{x_{14}\}$ ,  $\{x_{15}\}$ ,  $\{x_{17}\}$ ,  $\{x_{18}\}$ , and  $\{x_{19}\}$ . Similarly, the minimal cut sets that lead to the overhead catenary system failures are as follows:

$\{x_1\}$ ,  $\{x_2\}$ ,  $\{x_3\}$ ,  $\{x_4\}$ ,  $\{x_5\}$ ,  $\{x_6\}$ ,  $\{x_7\}$ ,  $\{x_8\}$ ,  $\{x_9\}$ ,  $\{x_{10}\}$ ,  $\{x_{11}\}$ ,  $\{x_{12}\}$ ,  $\{x_{13}\}$ ,  $\{x_{14}\}$ ,  $\{x_{15}\}$ ,  $\{x_{16}\}$ ,  $\{x_{17}\}$ ,  $\{x_{18}\}$ ,  $\{x_{19}\}$ ,  $\{x_{20}\}$ ,  $\{x_{21}\}$ ,  $\{x_{22}\}$ ,  $\{x_{23}\}$ ,  $\{x_{24}\}$ ,  $\{x_{25}\}$ ,  $\{x_{26}\}$ , and  $\{x_{27}\}$

### 4. Qualitative Analysis

The causes of the system failures can be classified based on the minimal cut sets of the overhead catenary system fault tree: heterogeneity

is the failure led by material factors; wear, fatigue, deformation, looseness, fracture, cracking, brittle fracture, flexure, tilting, and creep are failures arising during operational use; corrosion and ageing are failures arising in operational environments; electrical burns, discharge breakdown and flashover, etc., are failures caused by electrical factors[8-11],[14-15].

With analysis of causes of system failures, specific arrangements to improve the reliability of the system can be obtained as shown below:

- (1) High quality materials that are high-strength, corrosion resistant, and anti-fatigue, should be chosen, and installation techniques of the overhead catenary system should be improved. For example, contact lines that are high-strength, corrosion resistant, anti-fatigue, and homogeneous should be adopted.
- (2) For the components that are easily failed during operational process should be listed as key items for preventive maintenance and patrolling frequency should be increased.
- (3) For the components that are easily failed by electrical factors during operational use, the lightning arrester facilities should be strengthened to prevent short circuits caused by lightning from happening, and highly quality insulation equipment should be used.
- (4) Discharge, breakdown, and flashover are the main causes of failures of insulators, and it will directly lead to the overhead catenary system failure. To reduce the occurrence of these basic events, it is necessary to select appropriate insulators according to the operating environments. In addition, insulators should be cleaned regularly.

- (5) The basic events of wear, fatigue, deformation, looseness, fracture, cracking, brittle fracture, flexure, creep, erosion and ageing are related to operating environment and usage conditions. While the operating environments cannot be altered, the components' failure rate can only be reduced by regular maintenance, selecting highly reliable components, and replacing damaged components in time.

## **Reliability Analysis**

### **1. Statistical Analysis of Failure Data**

In the study, every 100 kilometers of the railway mainline are used for the statistical analysis of the overhead catenary system failure data. Calculating with the operating mileages of 511 kilometers of TRA Western Line (including the Mountain Line and the Coast Line), the statistical failure data of key components according to the failure information of the overhead catenary system during the period of interest. And applying the Equation (2), Equation (3), Equation (4), and Equation (5), the reliability index data can be obtained as shown in Table 2.

### **2. System Reliability Analysis**

The hypothesis that failure rate  $\lambda(t)$  for each component of the overhead catenary system obeys the exponential distribution was given in the study. By using the repairable system series Equation (5), Equation (6), and Equation (7), the reliability index data of the failure rate  $\lambda$ , mean time to repair  $\gamma$ , and unavailability  $U$  of the overhead catenary subsystem as shown in Table 3.

Table 2 Failure statistics of key components

Component type	Number of failures	Total time to repair (h)	Failures rate $\lambda$ (1/y)	Mean time to repair $r$ (h)
Messenger wire	97	376.35	0.8217	3.8799
Contact wire	24	158.55	0.2033	6.6063
Hanger assemblies	3	24.85	0.0254	8.2833
Middle point anchor	2	7.0667	0.0169	3.5333
Headspan suspension	1	9.0333	0.0085	9.0333
Cross bar	2	5.8333	0.0169	2.9167
Return feeder	1	1.9667	0.0085	1.9667
Feeder wire	2	3.8	0.0169	1.9
Jumpers	7	27.2667	0.0593	3.8952
Earthing wire	1	3.6167	0.0085	3.6167
Solid core insulator	17	50.8833	0.144	2.9931
Cantilever	12	46.8333	0.1017	3.9028
Inclined hanger	2	10.75	0.0169	5.375
Wind stay	1	9.1833	0.0085	9.1833
Register arm and steady arm	2	4.2833	0.0169	2.1417
Automatic tensioning device	4	14.4	0.0339	3.6
Cap and pin insulator	2	8.1667	0.0169	4.0833
Glass fiber insulated rod	4	15.4833	0.0339	3.8708
Pole	12	286.2167	0.1017	23.8514
Lightning arrester	3	8.9833	0.0254	2.9944
Main motorized isolator	6	11.3167	0.0508	1.8861
Vacuum interrupter	1	1.25	0.0085	1.25
Section insulator	6	27.8	0.0508	4.6333
Neutral section equipment	5	12.0167	0.0424	2.4033

Table 3 Reliability indices of each sub-system

Sub-system	Failures rate $\lambda$ (1/y)	Mean time to repair $r$ (h)	MTBF (y)	Unavailability $U$
Contact suspension	1.0928	4.5092	0.9151	5.6252E-04
Suspension subsidiary	0.0932	3.3318	10.7313	3.5443E-05
Support device	0.2457	3.3695	4.0705	9.4498E-05
Registration device	0.0424	4.8433	23.6088	2.3419E-05
Terminal device	0.0847	3.805	11.8044	3.6797E-05
Pole	0.1017	23.8514	9.837	2.7679 E-04
Power Equipment	0.0847	2.155	11.8044	2.084E-05
Insulating device	0.0932	4.0833	10.7313	3.8505E-05

Applying again the repairable system series Equation (5), Equation (6), and Equation (7), the reliability

index data of the failure rate  $\lambda_s$ , the mean time to repair  $\gamma_s$ , and the unavailability  $U_s$  of the overhead catenary system can be obtained as shown below:

$$\begin{aligned} \lambda_{System} = & \lambda_{Contact\ suspension} + \lambda_{Suspension\ subsidiary} \\ & + \lambda_{Support\ device} + \lambda_{Positioning\ device} + \lambda_{Terminal\ device} \\ & + \lambda_{Pole} + \lambda_{Power\ Equipment} + \lambda_{Insulating\ device} = \\ & 1.838297584(1/100km \cdot year) \dots\dots\dots (11) \end{aligned}$$

The unavailability  $U_s$  of the overhead catenary system per hundred kilometers can be calculated as follows:

$$\begin{aligned} U_{System} = & U_{Contact\ suspension} + U_{Suspension\ subsidiary} \\ & + U_{Support\ device} + U_{Positioning\ device} + U_{Terminal\ device} \\ & + U_{Pole} + U_{Power\ Equipment} + U_{Insulating\ device} \\ & = 0.001088809(1/100km \cdot year) \dots\dots\dots (12) \end{aligned}$$

The mean time to repair  $\gamma_s$  of the overhead catenary system can be calculated as follows:

$$\gamma_s = \frac{U_s}{\lambda_s} \times 8760 = 5.188479263(\text{hours}) \quad (13)$$

The hypothesis that failure rate  $\lambda(t)$  for each component of the overhead catenary system obeys the exponential distribution was given in the study, and thus the system reliability  $R_s(t)$  per hundred kilometers can be obtained as below, and the function graph can be shown in Figure 3.

$$R_s(t) = e^{-1.838297584t} \dots\dots\dots (14)$$

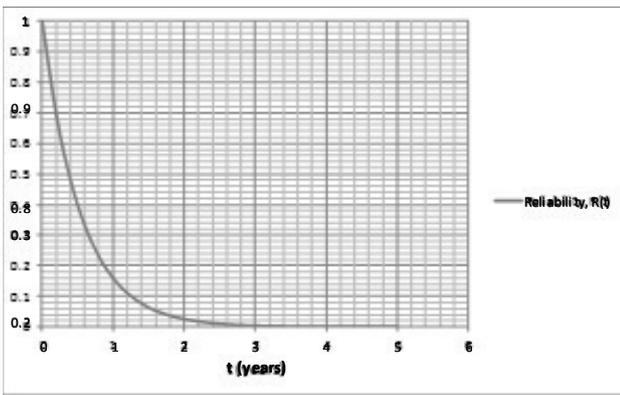


Figure 3 System reliability function  $R_s(t)$

The mean time between failures (MTBF) for the overhead catenary system per hundred kilometers can be calculated with the use of the equation below, and the value is 0.543981566 year, approximately equal to 198 days.

$$MTBF = \frac{1}{\lambda_s} = 0.543981566(\text{year}/100\text{km}) \quad (15)$$

Looking at similar cases abroad, literature [11], the reliability analyses on the overhead catenary system of the Beijing–Tianjin Intercity Railway were also conducted with the fault tree analysis method. The results show that the MTBF of the overhead catenary system per hundred kilometers

equals to 155 days. Since equipment levels, construction quality, climate, environment, and operating conditions are different, it will be difficult to compare with each other.

Although the mean time between failures (MTBF) of the overhead catenary system may not be used to predict accurately the probable failure time of the system in the future, it helps the arrangements of the preventive maintenance works. It provides an important reference for setting up the system maintenance cycle.

### 3. Importance Measure

The importance measure is the focus of Fault Tree Analysis. The main purpose is to determine weak links of the system in order to improve the design, or as an important reference for maintenance.

Based on the overhead catenary system of Fault Tree Analysis, the unreliability of the system  $F_s$  can be obtained. It is the probability of the top event's occurrence in Fault Tree, and can be shown as follows.

$$F_{\text{System}} = 1 - (1 - F_{\text{Contact suspension}})(1 - F_{\text{Suspension subsidiary}})(1 - F_{\text{Support device}})(1 - F_{\text{Positioning device}})(1 - F_{\text{Terminal device}})(1 - F_{\text{Pole}})(1 - F_{\text{Power Equipment}})(1 - F_{\text{Insulating device}}) \dots\dots\dots (16)$$

$$F_{\text{Contact suspension}} = 1 - (1 - F_{\text{Messenger wire}})(1 - F_{\text{Contact wire}})(1 - F_{\text{Hanger assemblies}})(1 - F_{\text{Middle point anchor}})(1 - F_{\text{Cross catenary}})(1 - F_{\text{Cross bar}}) \dots\dots\dots (17)$$

Similarly, the unreliability for any other subsystem can be obtained. To show the degree of the impact from the failure rates of the components

of the overhead catenary system on the failure rate of the system, it can be calculated the Birnbaum importance measure of each component based on Equation (10). Sorted with the order of the importance measure for all the components, it can be then shown as in Table 4.

Table 4 The importance measure of each component

Sequence	Component type	Birnbaum's importance
1	Messenger wire	$e^{-1.006570093t}$
2	Contact wire	$e^{-1.634983565t}$
3	Solid core insulator Cantilever	$e^{-1.694283488t}$ $e^{-1.736640575t}$
4	Pole	$e^{-1.736640575t}$
5	Jumpers Main motorized isolator	$e^{-1.778997662t}$ $e^{-1.787469079t}$
6	Section insulator	$e^{-1.787469079t}$
7	Neutral section equipment Automatic tensioning device	$e^{-1.795940497t}$ $e^{-1.804411914t}$
8	Glass fiber insulated rod Hanger assemblies	$e^{-1.804411914t}$ $e^{-1.812883332t}$
9	Lightning arrester Middle point anchor Cross bar Feeder wire	$e^{-1.812883332t}$ $e^{-1.821354749t}$ $e^{-1.821354749t}$ $e^{-1.821354749t}$
10	Inclined hanger Register arm and steady arm Cap and pin insulator	$e^{-1.821354749t}$ $e^{-1.821354749t}$ $e^{-1.821354749t}$
11	Headspan suspension Return feeder Earthing wire Wind stay Vacuum interrupter	$e^{-1.829826167t}$ $e^{-1.829826167t}$ $e^{-1.829826167t}$ $e^{-1.829826167t}$ $e^{-1.829826167t}$

#### 4. Maintainability

Maintainability is the ability of a system returning to the normal working condition through repairs in a short time from the moment the system fails. It is noticed from the previous analysis that the overhead catenary system structure is complex and failure rate is high. To ensure good operating condition, the maintainability demand of the overhead catenary system is also high. It needs to repair instantly for the defective parts when the

equipment fails to resume normal operation.

Substituting the system's mean time to repairs from Section 4.2 into Equation (4), it can be obtained that  $\mu_s = 0.192734701(1/hour)$ .  $\mu_s$  then substituted in Equation (3), and the maintainability of the overhead catenary system  $M_s(t)$  can be obtained as shown as follows, and the function graph is shown as Figure 4.

$$M_s(t) = 1 - e^{-\mu_s t} = 1 - e^{-0.192734701t} \quad (18)$$

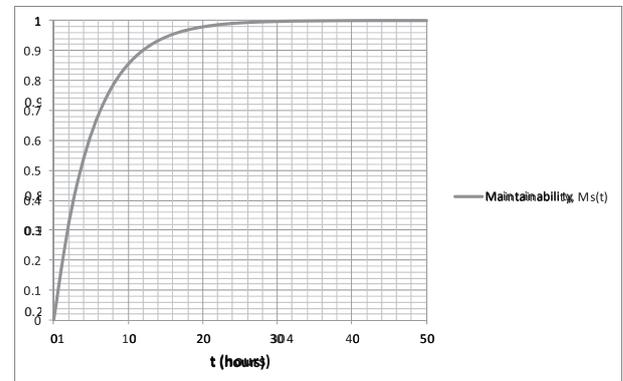


Figure 4 System maintainability function  $M_s(t)$

#### 5. Proposals for Improving System RAMS

Based on the analysis for reliability of the overhead catenary system in the section above, it shows that the reliability of the system is decreasing rapidly as time increases. It is suggested that effective improvements should be proposed to increase the reliability of the system according to engineering theory of reliability, and to reduce the impact on operational interruptions caused by system failures. Specific suggestions are proposed as the follows[8-11],[14-15]:

- (1) Using components with higher reliability to minimize the probability of failures to ensure the system safety.
- (2) Using components that are easier to replace

and modulated, so that the repair time can be reduced at failures, which means the condition of operational interruption can be reduced; Using failure positioning devices, with the use of advanced high-performance maintenance equipment, to shorten the maintain time as much as possible; using more strict maintenance strategy and more advanced inspection equipment in order to discover failures in time before they occur for a prompt process.

- (3) Fostering well-trained and experienced maintenance personnel to shorten the time needed for equipment checkup, maintenance, and replacement.

### Conclusion

In recent years, the transformation of the TRA Western Line being rapid transit systematized in the metropolitan areas has highlighted the importance of railway electromechanical equipment's reliability, while the reliability of the overhead catenary system affects directly the safety of railway operations.

In accordance with the principles of the European standard EN50126, the study investigated the reliability of the overhead catenary system of the TRA Western Line, including the Mountain Line and the Coast Line, conducted with the deductive approach of Fault Tree Analysis (FTA). And the major conclusions are then proposed as follows.

1. The number of accidents and the mean time to repair (MTTR) of the overhead catenary system between 2008 and 2013 decreases significantly compared to between 2000 and 2007; the components with higher failure rate

are messenger wire, contact wire, and solid core insulator.

2. Qualitative analysis was conducted on the system by Fault Tree Analysis (FTA), and the failures of the system were classified as factors of material, operational use, operational environment, and electricity, etc. The reliability of the system can increase by means of using components with higher reliability or by means of strengthening maintenance.
3. Quantitative analysis was conducted on this system with the fault tree model, and three important indices, including the failure rate  $\lambda_s = 1.838297584(1/100\text{km}\cdot\text{year})$ , the unavailability  $U_s = 0.001088809(1/100\text{km}\cdot\text{year})$ , and the mean time to repair  $\gamma_s = 5.188479263(\text{hours})$ . In addition, the MTBF of the overhead catenary system per hundred kilometers equals to 198 days, and it provides an important reference for setting up the system maintain cycle.
4. The messenger wire is the weakest link of the overhead catenary system. Thus the improvement work of strengthening messenger wire will be a critical and urgent issue. Although the failure rate of poles is not high, it has the longest mean time to repair; therefore, it contributes the most serious impact of all on the transportation services quality.
5. The improvement works of increasing the system reliability should be taken, and the impact on operational interruption caused by the system failures could be decreased. Specific actions are proposed as follows :
  - (1) Using components with higher reliability

to minimize the probability of failures to ensure the system safety. Such as the use of high strength, corrosion resistance, and anti-fatigue catenary materials.

- (2) Using components that are easier to replace and modulated, so that the repair time can be reduced at failures, which means the condition of operational interruption can be reduced.
- (3) Fostering well-trained and experienced maintenance personnel to shorten the time needed for equipment checkup, maintenance, and replacement.

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