Quality Control in Construction and Maintenance Process of Highway Mechanical and Electrical System Based on Weibull Distribution Model

Zhu Liwei\textsuperscript{1*}, Wang Liqing\textsuperscript{2} and Li Jianping\textsuperscript{3}

\textsuperscript{1}Research Institute of Highway Ministry of Transport, Beijing, 100088, China
\textsuperscript{2} Xi’an Highway Research Institute, Xi’an, Shanxi, 710065, China
\textsuperscript{3} Transportation Engineering Quality Supervision Bureau of Shanxi Province, Xi’an, Shanxi, 710075, China
\textsuperscript{*}Corresponding author’s e-mail: lw.zhu@rioh.cn

Abstract. The quality of Highway Mechanical and Electrical System (HMES) in construction and maintenance process is considered as the key link to ensure the highway operational safety and service level. In this paper, the quality control model in the construction and maintenance of HMES based on Weibull distribution model is provided and the quality control procedure which includes the data collection, parameter estimation, key devices/equipment and indexes determination, and quality control, is provided. In the end, the cameras of CCTV system in the surveillance and control subsystem of HMES is employed to verify the effectiveness of the proposed quality control model.

1. Introduction
Highway Mechanical and Electrical System (HMES) is the key subsystem of highway transportation system to ensure its operation efficiency and safety. In general, HMES includes the surveillance and control subsystem, communication subsystem, tolling subsystem, lighting system, fire control subsystem[1]. And further, the above subsystems are composed of vehicle detectors, CCTVs, changeable message signs, communication devices, etc. Therefore, in order to realize the mentioned functions of HMES, these devices should be constructed and maintained in good operation status. That is to say, the quality of these devices should be well controlled in the construction and operation process.

At present, the studies in quality control of construction and maintenance process are mainly focused on quality control standard [2], quality control [3], quality process organization [4] et al. However, as mentioned above, the HMES is composed of large qualities of device or equipment, the quality control of these devices or equipment is very difficult. Therefore, in order to improve the efficiency and effect, it is necessary to firstly focus on the key equipment, key links and key indicators in the construction and maintenance process of HMES.

For the determination of key equipment, key links and key indicators of devices or equipment in HMES, the quality control model based on Weibull Distribution Model is proposed, the quality control procedure is provide and an example is given in this paper.
2. Quality control model based on Weibull distribution model

As one of the most important life distributions in the field of reliability engineering, Weibull distribution has been concerned by researchers in mechanical engineering, statistics, economics, medicine and biology [5][6]. In HEMS, the devices or equipment are mainly electronic products, and its reliability curve is bathtub curve in large sample statistics. As the Weibull Distribution Model can fit the bathtub curve well, it was widely applied in the reliability estimation of electronic products [8]. In this paper, the 3-parameter Weibull distribution model is adapted in the proposed quality control model to determine the key devices, key links and key indexes in the construction and maintenance process of HMES.

Suppose that the random variable \( t \) obeys 3-parameter Weibull distribution, and then its probability density function \( f(t) \) is given as follows:

\[
f(t) = \frac{\beta}{\eta} \left( \frac{t-\gamma}{\eta} \right)^{\beta-1} \exp \left[ - \left( \frac{t-\gamma}{\eta} \right)^{\beta} \right] \quad t \geq \gamma
\]  

(1)

And the cumulative failure probability function \( F(t) \) can be calculated in the following:

\[
F(t) = P(T \leq t) = 1 - \exp \left[ - \left( \frac{t-\gamma}{\eta} \right)^{\beta} \right] \quad t \geq \gamma
\]  

(2)

where, \( \beta \) is the shape parameter (\( \beta > 0 \)), \( \eta \) is the scale parameter (\( \eta > 0 \)), \( \gamma \) is the position parameter (\( \gamma > 0 \)).

According to the literature [7], if the life cycle of many products and materials obeys Weibull distribution, their shape parameters are mostly between 0.5 and 5.0. And furtherly, because Weibull distribution can not only describe the product life cycle with increasing failure rate, but also describe the product life cycle with decreasing failure rate, Weibull distribution is considered as a statistical model suitable for describing the law of life distribution in reliability engineering, and can effectively describe the bathtub curve of product reliability.

For the specific device or equipment, to obtain the bathtub curve which should be applied in the determination of the key device, key link and the key index, the parameters (\( \beta, \eta \) and \( \gamma \)) in equation (1) and (2) should be firstly estimated.

There are many methods to estimate the above parameters such as Maximum Likelihood Estimation Method (MLEM), Regression Method (RM) etc [7]. In this paper, the Linear Regression Analysis method (LRAM) is adapted to estimate the shape parameter \( \beta \), scale parameter \( \eta \), and position parameter \( \gamma \).

LRAM is an optimization process, which the objective function is to minimize the deviation between the regression estimated value and the observed value. Suppose the linear relations between variables \( X \) and \( Y \) is expressed as follows:

\[
Y = b + wX
\]  

(3)

where, \( X \) is the input parameter (such as the time), \( Y \) is the output parameter (such as the failure status), \( w \) and \( b \) are the regression parameters should be obtained according to the observed data.

Suppose \( \hat{w} \) and \( \hat{b} \) is the estimation value of \( w \) and \( b \) respectively. And \( \hat{w} \) and \( \hat{b} \) can be obtained by the observed data \((x_1,y_1), (x_2,y_2), \ldots, (x_n,y_n)\) in the reliability experiment of HMES device. That’s to say, for each \( x_i \) (\( i=1,2,\ldots,n \)), the estimation value \( \hat{y}_i \) can be calculated in the following equation:

\[
\hat{y}_i = \hat{b} + \hat{w}x_i \quad (i = 1,2,\ldots,n)
\]  

(4)

Therefore, the deviation of the estimation value \( \hat{y}_i \) and the fact value \( y \) can be expressed as:

\[
y_i - \hat{y}_i = y_i - \hat{b} - \hat{w}x_i \quad (i = 1,2,\ldots,n)
\]  

(5)

The above equation is called loss function, which describe the deviation between the regression value and the observed value. Supposed \( Q(w,b) \) is the degree of the mentioned deviation, which is calculated in the following:
\[ Q(w, b) = \sum_{i=1}^{n} (y_i - b - wx_i)^2 \]  \hspace{1cm} (6)

Where the Least Square Method (LSM) can be used to calculate the \( \hat{w} \) and \( \hat{b} \), which to enable Equation (6) get the minimum value:

\[ Q(\hat{w}, \hat{b}) = \min(w, b) \]  \hspace{1cm} (7)

If we find the partial derivative of \( Q \) with respect to \( w \) and \( b \), and let it be zero, then we have:

\[
\begin{align*}
\frac{\partial Q}{\partial w} &= -2 \sum_{i=1}^{n} (y_i - b - w x_i) x_i = 0 \\
\frac{\partial Q}{\partial b} &= -2 \sum_{i=1}^{n} (y_i - b - w_i) = 0
\end{align*}
\]  \hspace{1cm} (8)

Solving the above equations, the following results can be obtained as:

\[
\begin{align*}
\hat{b} &= \bar{y} - \bar{x} \hat{w} \\
\hat{w} &= \frac{\sum_{i=1}^{n} x_i y_i - n \bar{x} \bar{y}}{(\sum_{i=1}^{n} x_i^2 - n \bar{x}^2)}
\end{align*}
\]  \hspace{1cm} (9)

where,

\[
\begin{align*}
\bar{x} &= \frac{1}{n} \sum_{i=1}^{n} x_i \\
\bar{y} &= \frac{1}{n} \sum_{i=1}^{n} y_i
\end{align*}
\]  \hspace{1cm} (10) \hspace{1cm} (11)

According to the Equation (9)-(11), the parameters of \( \hat{w} \) and \( \hat{b} \) can be estimated, and subsequently the parameters of the Weibull distribution model can be estimated based on the reliability experiment data of HMES devices or equipment in by LRAM. Therefore, the quality control data can be obtained according to the equation (1) and (2).

That is say, according to the operation data or reliability experiment data of HMES devices or equipment, the reliability performance (failure rate or life cycle) can be obtained based on the Weibull distribution model. And this reliability performance can be considered the quality performance of HMES devices or equipment. Form these reliability performance, the lower reliability devices and the more frequency failure can represent the key device and key indexes that should be focused in the quality control of construction and maintenance process.

### 3. Quality control procedure of HMES construction and maintenance process

The procedure of HMES quality control of construction and maintenance process based on Weibull distribution model is proposed is illustrated in Figure 1.

---

Figure 1. Quality control procedure of HMES in the construction and maintenance process
3.1. Data Collection of HNES Devices/Equipment
As given in Figure 1, the first step is to collect the data which can be used to evaluate the reliability of HNES Devices/equipment. There are two types of data: one is the operation data of the HNES, and the other is the reliability experiment data, where the collected data is mainly includes the failure data or running status data.

3.2. Estimation of the parameters of the quality control model based on Weibull distribution model
After the collection of the HNES devices/equipment, the parameters of the quality control model based on Weibull distribution model according to the Equation (1)-(11), and subsequently, the reliability and quality performance are analysed.

3.3. Determination of the key devices/equipment and key indexes of HMES
Based on the analysis result of the reliability and quality performance, the key devices/equipment can be determined in the lower reliability and the more frequency failure devices/equipment. And the key indexes can be collected by the analysis on the failure types and the performance indexes which can cause the failure of HMES devices/equipment.

3.4. Quality control of the construction and maintenance of HMES
After the key devices/equipment and key indexes of HEMS have determined, the quality characteristics of the indexes and devices are focused and the quality control technique should be determined according to the specifications and standards of the related devices/equipment.

4. Verification of the proposed quality control model
In order to verify the proposed quality control model of the HEMS construction and maintenance process, the quality control software is developed by python. According to the running data of HMES, the cameras are the more frequency failure devices in the devices/equipment HMES, therefore the cameras of CCTV system in the surveillance and control subsystem of HMES are the key devices in the quality control model based on Weibull distribution model. Therefore, the cameras are employed to verify the effectiveness of the proposed quality control model.

4.1. Data Collection on the Reliability Experiment of Cameras
The reliability experiments results of 30 cameras are are given in the Table I.

| Serial Number | Failure Time | Failure Type | Indexes               |
|---------------|--------------|--------------|-----------------------|
| 1             | 1034         | Power Supply Failure | Insulation Resistance |
| 2             | 2771         | Surveillance Image Loss | Cable Failure |
| 3             | 3050         | Surveillance Image Fuzzy | Transfer Channel Indexes |
| 4             | 2397         | Pan-Tilt Failure | Horizontal Rotation Angle of Pan-Tilt |
| 5             | 1945         | Power Supply Failure | Insulation Resistance |
| 6             | 2395         | Surveillance Image Fuzzy | Transfer Channel Indexes |
| 7             | 2464         | Surveillance Image Fuzzy | Transfer Channel Indexes |
| 8             | 1683         | Power Supply Failure | Insulation Resistance |
| 9             | 2296         | Power Supply Failure | Insulation Resistance |
4.2. *Estimation of the parameters of the quality control model*

Based on the experiment data, the parameters of the quality control model are estimated in the proposed software and the results are illustrated in Figure 2, Figure 3. As illustrated in Figure 4, in the reliability experiment data of cameras, there are 5 indexes which cause the cameras’ failures such as insulation resistance, grounding resistance, communication cable failures, transfer channel indexes, and horizontal rotation angle of pan-tilt. The probability of these indexes are 40%, 13%, 23%, 17% and 7%.

| 10   | 1883 | Surveillance Image Fuzzy | Transfer Channel Indexes |
| 11   | 2645 | Surveillance Image Fuzzy | Transfer Channel Indexes |
| 12   | 2015 | Power Supply Failure     | Insulation Resistance    |
| 13   | 2924 | Surveillance Image Loss  | Cable Failure            |
| 14   | 2126 | Surveillance Image Loss  | Cable Failure            |
| 15   | 1984 | Surveillance Image Loss  | Cable Failure            |
| 16   | 1815 | Surveillance Image Loss  | Cable Failure            |
| 17   | 1436 | Power Supply Failure     | Insulation Resistance    |
| 18   | 2634 | Pan-Tilt Failure         | Horizontal Rotation Angle of Pan-Tilt |
| 19   | 1012 | Power Supply Failure     | Insulation Resistance    |
| 20   | 2556 | Power Supply Failure     | Insulation Resistance    |
| 21   | 2210 | Power Supply Failure     | Insulation Resistance    |
| 22   | 2950 | Power Supply Failure     | Insulation Resistance    |
| 23   | 3095 | Power Supply Failure     | Insulation Resistance    |
| 24   | 2412 | Surveillance Image Loss  | Cable Failure            |
| 25   | 1955 | Surveillance Image Loss  | Cable Failure            |
| 26   | 1798 | Power Supply Failure     | Insulation Resistance    |
| 27   | 902  | Power Supply Failure     | Grounding Resistance     |
| 28   | 1930 | Power Supply Failure     | Grounding Resistance     |
| 29   | 868  | Power Supply Failure     | Grounding Resistance     |
| 30   | 2443 | Power Supply Failure     | Grounding Resistance     |
Figure 2. Fit Curve of the reliability experiment data of Cameras

Figure 3. Prediction curve of the proposed quality control model (fault distribution, fault density, reliability and failure rate)

Figure 4. The Frequency of the Indexes of Cameras

4.3. Determination of the key indexes of HMES

According to the operation data of HMES, we use cameras as the key devices in surveillance and control subsystem of HMES to verify the effectiveness of the proposed quality control model. And further, the key indexes are the insulation resistance, communication cable failure, transfer channel indexes and grounding resistance, which determined by the probability of these indexes.
4.4. Quality control of the construction and maintenance of HMES
Based on the key devices/equipment and key indexes, the quality control of these devices and key indexes should be focused to improve the quality level according to the specifications or standards in the construction and maintenance process of HMES in the given highway of Shanxi Province.

5. Conclusion
The quality control model in the construction and maintenance of HMES based on Weibull distribution model is provided in this paper. According to the quality control model, the key devices/equipment and key indexes can be determined. Based on the proposed quality control model, the quality control procedure which includes the data collection, parameter estimation, key devices/equipment and indexes determination, and quality control, is provided. In the end, the cameras of CCTV system in the surveillance and control subsystem of HMES are employed to verify the effectiveness of the proposed quality control model.

Acknowledgments
This paper was supported by the Science and Technology Project of the Department of Transport in Shanxi Province (No. 17-47X).

References
[1] Zhang Zhiyong, Zhu Liwei, et al, “New Technology and Application of Highway Mechanical and Electrical System”, Beijing: China Communication Press, 2008.
[2] Ministry of Transport of the People’s Republic of China, “Quality Inspection and Evaluation Standards for Highway Engineering Section 2 Electrical and Mechanical Engineering (JTG F80/2-2004)”, China Communication Press, Beijing, 2004.
[3] Wang Liang, “The Research of SD highway Mechanical and Electrical Engineering Quality Control”, Shandong University, 2016.
[4] Zhu Liwei, “Real-time Operational Risk Assessment of Highway Tunnel Mechanical and Electrical System,” Highway, vol. 62, pp. 176–181.
[5] Mann N R. Warranty periods based on three ordered sample observations from a Weibull population. IEEE Transactions on Reliability, 1970, 19(4): 167-171.
[6] Kuntman A, Ardali A, Kuntman H, Kaçar F. A Weibull distribution-based new approach to represent hot carrier degradation in threshold voltage of MOS transistors. Solid-State Electronics, 2004, 48(2): 217-223.
[7] Abbasi B, Hamid A, Hahromi E, et al. Estimating the parameters of Weibull distribution using simulated annealing algorithm. Applied Mathematics and Computation, 2007, 183(1): 85-93.