CONSTRUCTION OF A PROBABILISTIC MODEL OF AXLE BOX RELIABILITY

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ABSTRACT

In operation freight car axle box is subject to considerable dynamic forces that determine its relatively low durability and, as a consequence, a rapid transition to a latent state of emergency. The method for constructing a probabilistic model of axle box reliability allows to determine a moment of axle box transition in the state of failure and to prevent the emergence of a number of negative consequences for cars being on the line: derailment, train accidents, unproductive idle hours of cars, etc. The article found out that distribution law used by the author when checking the axle box life length to failure does not contradict experimental data and performed calculations.

Keywords: railway, axle box, safety, accident rate, reliability, distribution law, life length to failure.

Background. *The level of reliability in existing operation conditions, as well as its desired value determined by general transport tasks and conditions of safety, have a special meaning in organization, and choice of rational parameters of maintenance and repair system. Axle equipment is one of important nodes in the car's design, due to the failure of which more than half of all failures in rail transport occur. However, studies have shown that the efficiency of the use of information about axle box failures remains low, despite the implementation of electronic networking technologies.*

The development of a probabilistic model of axle box reliability, to which we refer distribution law of time between failures, and determination of its parameters based on collected statistical information can be a basis for modeling and forecasting failures [1], justifying calculation of parameters of car's maintenance and repair system.

Now in the railway network system of centralized number-specific accounting of freight cars is functioning, on the basis of which MCC of JSC «Russian Railways» in real time monitors technical condition of each car. From all over the service range of the network statistical information is collected on all identified faults, including axle boxes. This information may be material for a probabilistic model of axle box reliability. Methods of its obtaining include several fundamentally important stages. It is necessary to justify a form of distribution law of life length to failure (failure model), to determine a standard plan for testing reliability and its parameters, to obtain statistical information (sample), to process experimental results and to provide point estimates of model's parameters, to verify their quality.

Objective. *The objective of the author is to demonstrate construction of a probabilistic model, which can be applied for assessment of axle box reliability.*

Methods. *The author uses general scientific methods, probability theory, mathematical statistics methods, simulation, evaluation approach.*

Results.

Selection of axle box failure model

A study [2] by constructing an axle box fault tree contains a generalized expression of distribution law of axle box life length to failure. However, now collected statistical information is not sufficient for its reproduction. However, there is a fairly large list of classical reliability laws used in the simulation of failures of various structural elements. Each of them has a certain specificity and scope.

For example, the exponential law describes patterns of sudden failure occurrence during normal operation [1], that is, those failures that have no external signs of approaching an inoperable state. Axle box failure is not sudden, in addition, there is an indirect sign of failure – increase in the operating temperature of an axle box. Another frequently used law is the law of normal distribution. It is assumed that all factors that influence the appearance of a device's failure are independent, and none of them is dominant. But this property cannot be used for characterizing factors affecting the axle box transition in inoperable state [2].

In [3] there is a justification of the fact that axle box life length to failure is distributed according to Weibull – Gnedenko law:

$$F(t)=1-e^{-\left(\frac{t}{a}\right)^{b}}, \qquad (1)$$

where a and b are respectively parameters of scale and form.

This law is universal and generalized, since for certain values of parameters it is «transformed» into other described theoretical laws.

Plan of reliability tests

Such a plan is rules under which primary statistical information is collected. Violation of these rules does not allow correctly applying the methods of probability theory and mathematical statistics. The plan defines a sample size, a criterion of experiment's end and how to deal with a failed node. The experiment is simultaneously the start of monitoring over multiple identical items (to be exact – which are in the same state).

It should be noted that existing information technology, using database that collects and stores information about detected failures of cars in operation, allows organizing experiments based on the information archive that is retrospective information. Thanks to them, it is possible to start tracking similar objects, produced at various times, believing that monitoring over them started simultaneously. On the basis of collected statistical data an experiment is possible according to a standard plan of reliability tests of the type [NUT]. As an example, our direct experiment included cars, produced in 2005-2007 at one of domestic car-building factories. The number of cars in experiment N (sample size) is 22888. The duration of observation T is selected considering the fact that the car during the experiment must not get into the first post-construction depot repair, in which wheel sets with axle boxes can be replaced. The minimum period for the selected object is 20 months.

Receiving statistical information

Axle box failure is the event consisting in the transition of a car into a faulty state (in uncoupling) by heat or shear of axle box. The detection of axle box failure by car inspectors is executed in a prescribed

Table 1

An example of an ordered series of life length

Through index l	Index of life length to failure i	Life-length to failure τ_i , months	Index of failure-free life length j	Failure- free life length t_j, months
1	1	2,4	-	-
2	2	3,5	-	-
3	3	4,8	-	-
....	....	....	-	-
927	927	19,97	-	-
928	-	-	1	20
929	-	-	2	20
930	-	-	3	20
....	....	....	....	....
22888	-	-	21961	20

manner and transmitted to an information center via communication form 1353 with a car fault code 150 or 151, respectively (according to the current classifier of freight cars faults). Since the most critical elements of the car's design, which include axle box, highly reliable products, and their failures have a direct impact on traffic safety, the resulting sample is incomplete and heavily censored. This is an important feature of the model for the failure of critical parts and units [4]. According to the gathered statistical information in the sample there are 927 life lengths to failure and almost 22 thous. of failure-free life lengths. An example of an ordered series of life length of resulting sample is shown in Table 1.

The mathematical processing of experimental results

At this stage, it is necessary to determine point estimates of parameters of the previously selected model of failure a and b. To find them, we use a maximum likelihood method, which allows us to get effective, unbiased, consistent estimates. The likelihood function for a incomplete sample is as follows:

$$L=\sum_{i=1}^{m}\ln f_{\tau_i}(t)+\sum_{j=1}^{n}\ln\left(1-F_{t_j}(t)\right), \qquad (2)$$

where $f_{\tau_i}=\frac{b}{a}\left(\frac{t}{a}\right)^{b-1}e^{-\left(\frac{t}{a}\right)^{b}}$ *is expression of distribution density of life length to failure, corresponding to the selected model (1); m is a number of life length to failure; n is a number of failure-free life length;* F_{t_j} *is a distribution function of life length to failure, expression (1).*

After the procedure for searching the extremes of the maximum likelihood function, we obtain an expression for determining point estimates of the parameters a and b:

$$\hat{a}=\frac{\left(\sum_{i=1}^{m}\tau_i^{\hat{b}}+\sum_{j=1}^{n}t_j^{\hat{b}}\right)^{\frac{1}{\hat{b}}}}{m^{\frac{1}{\hat{b}}}}; \qquad (3)$$

$$\frac{m}{\hat{b}}=-\sum_{i=1}^{m}\ln\tau_i+m\frac{\sum_{i=1}^{m}\tau_i^{\hat{b}}\ln\tau_i+\sum_{j=1}^{n}t_j^{\hat{b}}\ln t_j}{\sum_{i=1}^{m}\tau_i^{\hat{b}}+\sum_{j=1}^{n}t_j^{\hat{b}}}. \qquad (4)$$

From the expression (4) it is not possible to obtain a point estimate of the parameter b in explicit form. For this we use the most intuitive graphical method. Denoting in the expression (4), the left side as f_1, the right side as f_2, we construct graphs of these functions (Pic. 1). At the point of intersection of the graphs the value of the estimate of the parameter b is determined.

Thus, the value of the point estimate of the parameter b we take as 1,68.

Substituting the obtained value in (3), we obtain the value of the point estimate of the scale parameter:

a = 133,3 months ≈ 11,1 years

That is, we obtain a theoretical distribution function of time to failure – the required model (an expression of the law of distribution of life length of the car to failure):

$$F(\tau_i)=1-e^{-\left(\frac{\tau}{133,3}\right)^{1,68}}. \qquad (5)$$

Quality check of point estimates

To confirm the hypothesis that the resulting failure model (5) describes the obtained sample it is necessary to check the consistency of the theoretical distribution function (5) and the experimental curve (empirical function). Verification will be carried out using Kolmogorov criterion. For this it is required to determine the maximum difference between theoretical and empirical functions and to compare it to the maximum permissible value. By using Johnson function based on an ordered series (Table 1) were obtained ordinates of empirical function:

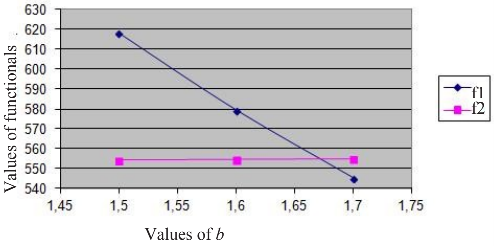
$$\hat{F}_{\partial}(\tau_i)=\frac{r_i}{v+1}, \qquad (6)$$

where $r_i=r_{i-1}+\frac{v+1-r_{i-1}}{v+2-l}$ *is auxiliary factor; ν is a number of elements in the sample; in determining r_1 the value of r_0=0.*

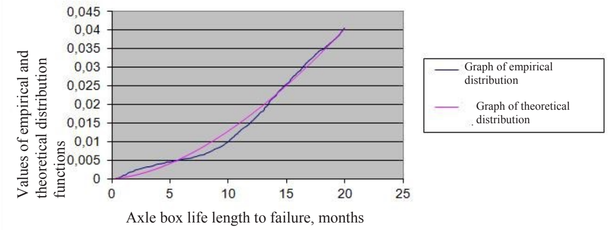
To confirm the validity of the proximity hypothesis of received theoretical distribution law of axle box life length to failure and function F_{∂} using Kolmogorov fitting criterion it is required to check conditions:

if $D\cdot\sqrt{n}<t_{\alpha}$ *– the hypothesis of the distribution of operating time to failure of the axle box according to Weibull-Gnedenko law does not contradict experimental data;*

if $D\cdot\sqrt{n}>t_{\alpha}$ *–the difference between theoretical and empirical distributions should be recognized essential: the hypothesis of the distribution of operating time to failure of the axle box according to Weibull-Gnedenko law contradicts experimental data. Here D is the maximum difference between values of theoretical and empirical distribution functions of the time*



Pic. 1. Determination of point estimate of the shape parameter of the distribution law of Weibull-Gnedenko for axle box.



Pic.2. Comparison of theoretical and empirical distributions of life length of axle box to failure.

to failure; n is sample size; t_α *is quantile of the distribution of Kolmogorov-level* α.

As can be seen from the graphs of functions (Pic. 2), the largest difference between theoretical and empirical distribution is achieved at the point-10 months and is D = 0,00298.

The corresponding value of distribution quintile at a error significance level of 5% is t_α *= 1.44. Therefore it is possible with a probability of not less than 95% assume that the chosen theoretical distribution law of axle box life length to failure does not contradict experimental data [1].*

Conclusions. *These point estimates of parameters of the law of distribution of time to axle box failure can be used to solve practical problems, failure modeling, simulation and statistical modeling, as well as assessing the impact of reliability indices of axle box on parameters of system of maintenance and repair of freight cars. In addition, the present technique can be a basis for a centralized automated system for assessing reliability and safety of structural elements of car structures at the stage of direct intended use of cars which allows more efficient use of existing information system of monitoring the technical condition of rolling stock fleet.*

REFERENCES

1. Ustich, P.A., Karpychev, V.A., Ovechnikov, M. N. Reliability of non-tractive railway rolling stock [*Nadezhnost' rel'sovogo netjagovogo podvizhnogo sostava*]. Moscow, UMC MPS RF, 2004, 416 p.

2. Kruglikov, E. P. Reliability Analysis of the Journal-Box: Event Tree Construction. *World of Transport and Transportation*, 2014, Vol.12, Iss.2, pp. 82-89.

3. Martynov, I. E. Development of scientific bases and the development of a set of measures to improve the reliability of axle units of cars [*Razvitie nauchnyh osnov i razrabotka kompleksa meroprijatij po povysheniju nadezhnosti buksovyh uzlov vagonov*]. Kharkiv, 2007, 297 p.

4. Tikhov, M. S. Evaluation of quality indicators for incomplete samples [*Ocenivanie pokazatelej kachestva po nepolnym vyborkam*]. *Nadezhnost' i kontrol' kachestva*, 996, Iss. 11, pp. 16-24.

5. Fedotkin, M. A. Fundamentals of applied theory of probability and statistics. Textbook [*Osnovy prikladnoj teorii verojatnostej i statistiki. Uchebnik*]. Moscow, Vysshaya shkola publ., 2006, 368 p.

6. Fedotkin, M. A. Models in probability theory. Textbook [*Modeli v teorii verojatnostej. Uchebnik*]. Moscow, Nauka– Fizmatlit publ., 2012, 608 p.

7. Polovko, A.M., Gurov, S. V. Fundamentals of reliability theory [*Osnovy teorii nadjozhnosti*]. St.Petersburg, BHV-Peterburg publ., 2006, 702 p.

8. Polovko, A.M., Gurov, S. V. Fundamentals of reliability theory. Practicum [*Osnovy teorii nadjozhnosti. Praktikum*]. St.Petersburg, BHV-Peterburg publ., 2006, 560 p.

9. Ryabinin, I. A. Reliability and safety of structural complex systems [*Nadezhnost' i bezopasnost' strukturno-slozhnyh system*]. St.Petersburg, St.Petersburg University, 2007, 278 p.

10. Fedotova, G. A. International scientific seminar «Methodical research questions of reliability of large-scale power systems» [*Mezhdunarodnyj nauchnyj seminar «Metodicheskie voprosy issledovanija nadezhnosti bol'shih sistem energetiki»*]. Prospekt – Irkutsk, ESI SB RAS, 2009.

11. Reliability Model Selection // Proceedings of the 28th Annual International Computer Software and Applications Conference (COMPSAC'04), 2004, pp. 534-539.

12. Mironov, A.A., Volkov, V. M. The statistical approach to the estimation of required control volume of welded joints of large metal structures [*Statisticheskij podhod k ocenke trebuemogo ob'ema kontrolja svarnyh soedinenij krupnogabaritnyh metallokonstrukcij*]. *Privolzhskij nauchnyj zhurnal*, 2013, Iss. 1, pp. 12-16.

13. Bansiya, J., Davis, C. A Hierarchical Model for Object-Oriented Design Quality Assessment. IEEE Transactions on Software Engineering, 2002, V. 28, Iss. 1, pp. 4-17.

14. Volkov, V.M., Mironov, A.A., Mironov, N. A. Model of service life calculation of cylindrical shells under wear of thick walls [*Model' rascheta resursa cilindricheskih obolochek v uslovijah iznosa tolshhiny stenki*]. *Bulletin of Volga State Academy of Water Transport,* 2008, Vol. 25, pp. 108-117.

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