RATIONAL PLACEMENT OF REPAIR FACILITIES TAKING INTO ACCOUNT FAILURES OF RAILWAY WAGONS

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ABSTRACT

Current technical condition of railway freight wagons evaluated through the assessment of the residual life of their elements, according to many specialists, is a priority criterion for choosing a guiding strategy for repair activities. Meanwhile the current repair should be carried out as current uncoupling repair at the mechanized points of car repair (MPCR). The article, using the theory of probability, the theory of mass service and the theory of integral equations, substantiates the method for selecting location of the MPCR within the railway network, considering reliability of one of the most critical and potentially dangerous elements of the design of a freight car which is roller axle box. The research suggests a local criterion for finding right site for repair points, it is defined through minimum number of freight wagons with faults in the axle box, left unrepaired, during the day when maximum number of wagons entered the workshop for current uncoupling repair because of that fault.

Keywords: *railway, freight car, roller axle box, reliability, maintenance, placement of repair points.*

Background. *Operation of potentially dangerous units of wagon rolling stock and low technological level of the actors of railway cars/ repair market have been highlighted in recent years among the main problems that JSC Russian Railways experiences with regard to its network. In particular, this concerns a roller axle box, which is one of the most crucial elements of the design of a freight car, and safety of train traffic depends on its reliability.*

According to experts, to solve the problem of safe operation of potentially hazardous products, it is necessary to repair freight cars according to the evaluation of their current technical condition based on assessment of the residual life of the elements of their design. At the same time, the current uncoupling repair must be carried out at the mechanized points of car repair (MPCR) [1].

The location of the repair points has an undoubted effect on organization of the current uncoupling repair. And it is not just about distances, one should also take into account the different technological and resource levels of different MPCR:

- *the number of places in wagon accumulation section of MOCRs is limited;*
- *it is possible that spare parts and materials for repairing at a given MPCR are almost completely missing at the time of uncoupling the car;*
- *a situation is likely when there are no free repair teams at MPCR at the time of uncoupling of a car.*

Those situations can cause decrease of customers' applications for repair of railway cars either a need for an emergency job at MPCR, resulting in an increase in the number of cars that were not repaired during the day and their unproductive idle time.

Objective. *The objective of the author is to suggest an approach to rational location of mechanized points of car repair within the railway network taking into account reliability of a roller axle box.*

Table 1

Once censored sample of operating time of a roller box of a freight car

No.	i	t_i	j	τ_j
1	1	0,7333333	–	–
2	2	0,5666667	–	–
3	3	0,5666667	–	–
4	4	0,3666667	–	–
5	5	0,7333333	–	–
6	6	0,8333333	–	–
7	7	0,6333333	–	–
8	8	0,6666667	–	–
9	9	0,8333333	–	–
10	10	0,7	–	–
......	......	....	–	–
......	....	......	–	–
927	927	19,98	–	–
....	–	–	1	20
....	–	–	2	20
....	–	–	3	20
......	....	....	......	......
18373	–	–	17446	20

Notations: l – index for numbering, i, j – index of operating time before occurrence of failure and trouble-free operating time; t_i, τ_j – the value in the months of time between failure and failure-free operating time.

Methods. *The author uses general scientific methods, mathematical methods, comparative analysis, evaluation approach.*

Results.

1.

Let's consider the issue of reliability of the elements of the design of a freight car. The probability of an event consisting in the fact that the residual service life of a structural element until a resource failure occurs (the moment of transition of movement of a roller bearing from the rolling friction mode to the sliding friction mode [2] (random value ξ_t)), will be no less than the required operation period y (for example, until the next current uncoupling repair), provided that it was used for its intended purpose and worked flawlessly until time t, is determined as follows:

$$P\{\xi_t \geq y\} = \frac{\overline{F}(t+y)}{\overline{F}(t)}, \qquad (1)$$

where $\bar{F}(t)$ – probability of failure-free operation of the design element of the freight car during time t; $\bar{F}(t+y)$ – probability of failure-free operation of the same element over time (t + y).

To estimate the residual life of the component of the freight car that has worked for a certain period of time t, it is necessary to solve the inverse problem: to find such a value of the operation period y, during which a failure will not occur with the required probability.

It has been proved with mathematical precision that the operating time of the roller axle box before failure obeys to the Weibull–Gnedenko distribution law [3]:

$$F(t) = 1 - e^{-\left(\frac{t}{a}\right)^b}. \qquad (2)$$

An experiment was conducted using a centralized number-specific metering system for cars. The observation was carried out for operation of freight cars of various types built in 2005–2007 before the first uncoupling using fault codes 150 (axle box heating) and 151 (axle box shift). Taking into account the fact that the observed car during the experiment should not get into the first depot repair after construction, at which parts of the axle box can be replaced with new ones, the observation period T_a was assumed to be 20 months. According to the regulatory and technical documentation [4], NUT test plan corresponds to such observation conditions. The sample size (the number of cars uncoupled because of heating and shifting of the axle box) was N = 18373. During the observation, a one-time censored sample was obtained, which includes the number of operating time to failure n = 927 and the number of reliable running times m = 17446 (Table 1).

Using the maximum likelihood method, point estimates of the distribution law parameters $\hat{b}$ = 1,68, $\hat{a}$ = 133,3 months were obtained.

Using the criterion of A. N. Kolmogorov the correctness of the hypothesis about proximity of the obtained model of operating time of the roller axle box of the freight car to failure and the statistical distribution function, the values of which are obtained by the Johnson method, was proved. Therefore, the resulting model of roller axle box failure can be used in predicting reliability indicators, in particular, the residual resource with an error probability not exceeding 5 %.

Thus, taking the value of the required probability of no failure of the roller axle box for period y as 0,99 and taking into account the operational data for freight cars built in 2005–2007, using the failure model (2) and formula (1), we obtain the expression for the residual life of the roller axle box, after 20 months of trouble-free operation:

$$y^{RAB} = \sqrt[\hat{b}]{\left(\left(\frac{20}{\hat{a}}\right)^{\hat{b}} - \ln 0{,}99\right)\hat{a}^{\hat{b}}} - 20. \qquad (3)$$

At the expiration of the period determined by formula (3), it will be necessary to carry out a deep diagnostics of the roller axle box and to perform a similar assessment of the residual service life.

2.

In [5], it was established that for a trouble-free movement of a freight car to the place of repair, it is necessary to preserve a certain amount of the residual life of its construction elements i. e. safety margin. Speaking about the accident of a freight car due to the failure of the roller axle box, it is required to describe the process of formation of a finite set of fatigue damage to bearing parts resulting from transfer of the rollers from rolling friction to sliding friction and resulting in destruction of bearing parts with subsequent fracture of the axle neck [6].

Considering the need to ensure the safety margin, let us imagine the process of setting the repair at an abstract MPCR of cars detached at the moment of detecting a malfunction of the roller axle (pre-failure condition), as follows: n cars arrive at the repair point, with n >> 1; one of the detached cars is put in service, and the rest (n – 1) cars are queuing for repair; MPCR has a section of accumulation of cars with a limited number of places and n service channels (repair crews) are in operation. At the same time, no more than n cars can be repaired at the same time, and the stock of parts and materials is limited with respect to that condition. The process of accepting of cars to MPCR continues until the n-th detached car is taken into operation.

We believe that the cars arrive at MPCR with some fixed intensity and without any priorities, as the queue moves, and the order of repair of cars is arbitrary. In this case, the amount of time already spent on waiting does not affect the amount of time that still needs to be spent.

Based on the conditions for occurrence of an accident due to the failure of the roller axle box and of arrival of cars to MPCR, to describe the process of destruction of bearing parts and the arrival of applications for repair of cars it is appropriate to use the expression of the probability density of the gamma distribution:

$$f(t) = \frac{\lambda^n}{G(n)} t^{n-1} e^{-\lambda t}, \text{ at } t > 0 \text{ and } n > 0, \qquad (4)$$

where λ, n – distribution parameters, G(n) – tabulated gamma function.

Since n – integer, the expression for the distribution function of a random variable t is:

$$F(t) = \sum_{k=0}^{n-1} \frac{(\lambda t)^k}{k!} e^{-\lambda t}. \qquad (5)$$

At the same time, the operating time of the roller axle box of a freight car before detection of a malfunction and frequency of receipt of detached cars at MPCR can be interpreted as the sum of independent terms, each of which has an exponential distribution, which is a particular case of the Weibull–Gnedenko distribution. With exponential distribution, we increase the probability of failure of the roller axle box in the period from the start of operation of the freight car to the current uncoupling repair (interval (0; T), T –

average value of the operating time of the roller axle box until a malfunction is detected), providing a safety margin.

From the expression (5) it also follows that:

$$P\{v(t)=k\}=\frac{(\lambda t)^k}{k!}e^{-\lambda t}. \qquad (6)$$

where $v(t)$ – number of cars (repair applications) received during time t; $\lambda = 1/T$ – intensity of the flow of applications for MPCR.

That is, incoming requests for repair of cars at MPCR at random times form an extraordinary Poisson stream.

Using the maximum likelihood method and the data in Table 1, it is possible to determine the point estimate of the parameter λ in accordance with NUT test plan:

$$\hat{\lambda}=\frac{n}{\sum_{i=1}^{n} t_i+(N-n)T_a}. \qquad (7)$$

Let X – be the railway network of the considered site for operation of freight cars. Let divide it into n parts and denote by $L_1, L_2, \ldots, L_n$. Each zone L_j should be served by its MPCR H_j. However, if necessary, cars can be sent to the repair point of the adjacent zone. The quality of current repairs at all enterprises of the site is considered the same. All linear enterprises receive faulty cars, forming in time a flow of type (6). In this case, the pre-failure state of each car is characterized not only by the time point t, but also by the coordinates of the location of the car $(x_1, x_2) \in X$.

Considering the low technological level of MPCR, when determining the distances in each zone of the site between MPCR that is planned to be located and the technical service points of cars (TSP), it is necessary to choose the distances in the way that the number of cars that were not repaired during the day should be minimal.

3.

We will forecast the change in the number of cars that were not repaired during the day, taking into account the distance between MPCR planned for placement and TSP.

Using the formula (6) with $k = 0$, the mathematical expectation of the number of cars (unserved applications) that are at a certain distance from the randomly chosen MPCR at a random time t can act as a functional that is the product of the probability that a certain number of faulty cars will not be repaired at this address due to the significant distance between MPCR and the point of their detection and the number of unrepaired cars depending on this distance.

This means that to predict the process of changing of quantity of unrepaired cars during the day, it is possible to use the Fredholm equation [7]:

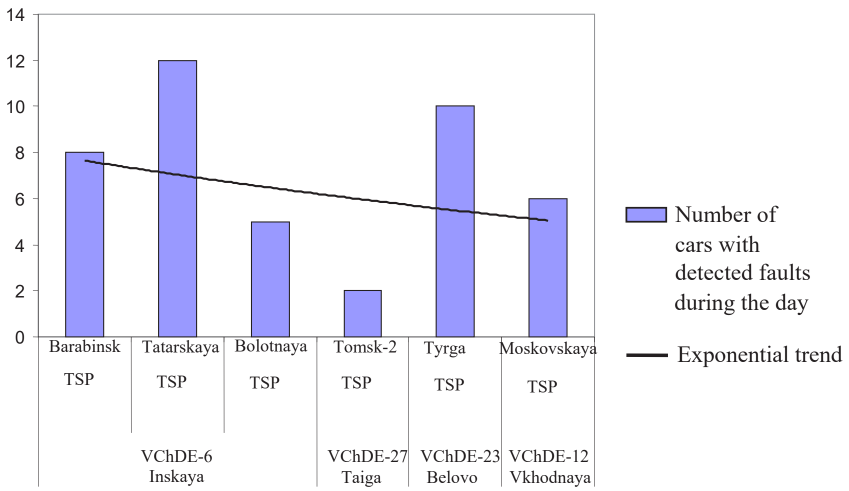
$$N(\mu)=f(\mu)+\int_{s_1}^{s_n} e^{-\hat{\lambda}M(\mu,s)}N(s)ds. \qquad (8)$$

Here μ – number of cars uncoupled due to a malfunction of the roller axle box during the previous day; $N(\mu)$ – function describing the dependence of the mathematical expectation of the number of cars that were not repaired during the day on the number of detected defective cars μ in the area of their operation polygon (the parameter of the current uncoupling repair under study); $f(\mu)$ – function describing the pattern of detection of defective cars μ in the area of operation (trend); $e^{-\hat{\lambda}M(\mu,s)}$ – function that determines the probability that some average number of cars M, depending on the number of uncoupled cars μ and distance s between them and the planned MPCR at time t, will not be repaired (the original core of this integral equation); $N(s)$ – function describing the dependence of the mathematical expectation of the number of cars not repaired during the day on the distance between their detection points and MPCR; s_1 – minimum distance between TSP and the planned MPCR; s_n – maximum distance between TSP and the planned MPCR.

To solve the integral equation, we use the method of successive approximations (iterations).

We define the first core:

$f(\mu) = 8{,}3066e^{-0{,}0829\mu}$



Pic. 1. Example of determination of the expression of the function f(μ). Notations: coordinate x_1 – TSP, on which freight cars are uncoupled due to malfunction of the roller axle box; coordinate x_2 – operational depot to which TSP belongs.

Table 2

The matrix of values of the function N(μ)

Probability of occurrence of rush job								
		p_{11}	p_{12}	p_{13}	p_{14}	p_{14}	p_{15}	p_{16}
Probability of application loss	p_{21}	36,7	28,7	30,1	33,3	22,4	34,9	40,4
	p_{22}	35,4	40,3	20,4	22,7	34,4	25,8	30,5
	p_{23}	28,3	30,6	33,9	34,5	24,9	24,7	41,7
	p_{24}	29,6	42,2	35,1	26,5	42,5	20,3	19,8
	p_{25}	26,8	32,1	40,8	29,3	22,7	19,5	23,5
	p_{26}	23,6	30,4	35,2	42,8	18,3	26,9	15,5

$K_1(\mu,s) = e^{-\hat{\lambda}\mathrm{M}(\mu,s)} = e^{-\hat{\lambda}\mathrm{M}(\mu)} \bullet e^{-\hat{\lambda}\mathrm{M}(s)}$.

We define the second core:

$K_2(\mu,s) = \int_{s_1}^{s_n} e^{-\hat{\lambda}\mathrm{M}(\mu,\theta)} \bullet e^{-\hat{\lambda}\mathrm{M}(\theta,s)} d\theta$. *We get:*

$$K_2(\mu,s) = e^{-\hat{\lambda}[\mathrm{M}(\mu)+\mathrm{M}(s)]} \int_{s_1}^{s_n} e^{-\hat{\lambda}\mathrm{M}(\theta)} d\theta =$$

$$= e^{-\hat{\lambda}\mathrm{M}(\mu)} \bullet e^{-\hat{\lambda}\mathrm{M}(s)} \bullet (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)}).$$

We define the third core:

$$K_3(\mu,s) = \int_{s_1}^{s_n} e^{-\hat{\lambda}\mathrm{M}(\mu,\theta)} \bullet e^{-\hat{\lambda}\mathrm{M}(\theta)} \bullet e^{-\hat{\lambda}\mathrm{M}(s)} \bullet (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)}) d\theta = e$$

$$= ^{-\hat{\lambda}[\mathrm{M}(\mu)+\mathrm{M}(s)]} \bullet (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)}) \int_{s_1}^{s_n} e^{-\hat{\lambda}\mathrm{M}(\theta)} d\theta.$$

We get: $K_3(\mu,s) = e^{-\hat{\lambda}\mathrm{M}(\mu)} \bullet e^{-\hat{\lambda}\mathrm{M}(s)} \bullet (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)})^2$.

We define the fourth core:

$K_4(\mu,s) = e^{-\hat{\lambda}\mathrm{M}(\mu)} \bullet e^{-\hat{\lambda}\mathrm{M}(s)} \bullet (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)})^3$.

Analyzing the obtained results, we find out that the resolvent of an integral equation is the product of $e^{-\hat{\lambda}\mathrm{M}(\mu)}$ and the sum n of the first members of the geometric progression $K_1(\mu, s)$, $K_2(\mu, s)$, $K_3(\mu, s)$, $K_4(\mu, s)$,..., $K_n(\mu, s)$. The denominator of this geometric progression is a binomial $e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)}$.

We obtain the solution of the integral equation:

$$N(\mu) = f(\mu) + e^{-\hat{\lambda}\mathrm{M}(\mu)} \int_{s_1}^{s_n} \frac{e^{-\hat{\lambda}\mathrm{M}(s)}[(e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)})^n - 1]}{e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)} - 1} ds .$$

Thus, in accordance with the equation (8), we determine the criterion for rational placement of MPCR on the railway network when estimating the likelihood of a rush job and of the loss of an application for a repair point:

$$f(\mu) + (e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)}) \bullet \bullet \frac{e^{-\hat{\lambda}\mathrm{M}(\mu)}[(e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)})^n - 1]}{e^{-\hat{\lambda}\mathrm{M}(s_1)} - e^{-\hat{\lambda}\mathrm{M}(s_n)} - 1} = = \min_N \max_\mu N(\mu). \quad (9)$$

4.

Since the operating time of the roller axle box before detecting a failure has an exponential distribution, using criteria (9) in calculations, the expression of the function f(μ) can be determined using the exponential trend obtained when constructing a histogram, each column of which, displaying the number of faulty cars (μ), has its own coordinates (x_1, x_2)∈X. The value of the function M(μ), reflecting the dependence of the mathematical expectation of the total number of defective freight cars sent from all TSP at MPCR, on the number of cars (μ), found on each TSP, can be found as the value of the Lebesgue integral from the function f(μ) on some numerical segment [μ_1; μ_n] [8]:

$$\mathrm{M}(\mu)=\int\limits_{[\mu_1;\mu_n]} \begin{matrix} f(\mu)d\mu = f(\mu_1)\cdot\mu_1 + f(\mu_2)\cdot\mu_2 + \\ + f(\mu_3)\cdot\mu_3 + \ldots + f(\mu_n)\cdot\mu_n \end{matrix}. \qquad (10)$$

At the same time, a certain number of cars M(μ) will be located at a distance sÎ[s_1; s_n] from MPCR. Considering the need for a safety margin when moving a faulty car to MPCR and varying the values of the distances s_1 and s_n, as well as taking into account the formula (3) and the average daily mileage of the freight car l_{dm} = 500 km/day, we accept the condition:

$$s < \frac{30 y^{RAB} l_{dm}}{n}, \qquad (11)$$

where n – number of inspections of the freight car within the maximum interval between the deep diagnostics, including the assessment of the residual life of the roller axle box, which is also a solution to the quadratic equation [9]:

$$cP^2n^2 + cP(2-P)n + 2(c - PVy^{RAB}) = 0, \qquad (12)$$

where P – probability of detecting a malfunction of the roller axle box, determined by taking into account the exponential distribution of its operating time until the malfunction is detected;

$c = 0{,}16\dfrac{S}{N}$ *– cost of one control of the technical condition of the car;*

S – average cost of maintaining TSP;

N – average number of cars that passed through TSP;

$V = \dfrac{L}{y^{RAB}}R$ *– average loss from the stay of the car in a latent emergency state per unit of time;*

L – expected damage from the crash;

R – risk of an accident with the car through fault of railway car division.

<u>Let's consider an example.</u> Let the area of operation of freight cars is within the West-Siberian railway (a subsidiary to JSC Russian Railways). It is planned to locate MPCR, at which freight cars will be received from several points of maintenance for carrying out current uncoupling repairs. Based on the data of the Main Computing Center of JSC Russian Railways on uncoupling freight cars due to malfunction of roller axle boxes for the previous day, we determine the expression for the function f(μ) (Pic. 1).

Using the formula (10), we find the value of M(μ) for a certain number of cars sent from TSP – μ_1, μ_2, μ_3, μ_4, μ_5, μ_6.

Using the average statistical data on costs and risk levels to be put in place, expressions (3), (7), conditions (11), and equations (8) and (12), we obtain the matrix of values of the function N(μ) when estimating the likelihood of rush job at an MPCR $p_1 = e^{-\hat{\lambda}\mathrm{M}(s_1)} \equiv e^{-\hat{\lambda} s_1}$ and probability of loss of the application with n = 6 (Table 2) [10].

Based on the criterion (9) we determine: N(μ) = 15,5 at s_1 = 105 km and s_n = 210 km.

Conclusion. *The method of rational allocation of MPCR on the railway network is shown, taking into account failure level of the roller axle box of the freight car.*

Been considered in the framework of the method, the criterion for determining the distance between TSP and the planned repair point takes into account the influence of the real technological level of MPCR.

MPCR is the simplest car-repair enterprise, and in further research on organization of the system of maintenance and repair of freight cars, the basic principles of the developed method can also be applied to substantiate the rational parameters of much larger production facilities – depots and car-repair plants.

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