Задавшись, например, исходными данными таблицы 1 с помощью формулы (11), оценим влияние указанных в ней факторов на величину $l_{гу}$.

Влияние на протяжённость гарантийного участка ПТО ($l_{гу}$) таких важных факторов, как брак в работе осмотрщиков вагонов ($1-P$) и затрат на контроль технического состояния вагона (C), представлено в виде матрицы гарантийных участков ПТО (таблица 2).

Из данных таблицы 2 следует, что при увеличении затрат на контроль технического состояния вагона с 2 до 4 руб. безостановочный пробег вагона при вероятности брака в работе осмотрщиков 0,55 может быть увеличен с 1281 до 1804 км, т. е. на 523 км. Расчёты показали, что при $l_{БД}$=20 мес. упомянутый пробег может вырасти с 854 до 1203 км, т. е. на 349 км. Тем самым улучшаются показатели маршрутной скорости поездов, уменьшается оборот вагона, а также сокращаются совокупные затраты вагонного линейного хозяйства за счёт уменьшения количества ПТО.

Следовательно, имеется возможность решить и немаловажную обратную задачу – определить, какие мероприятия следует провести и какими ресурсами требуется располагать на их реализацию, чтобы увеличить маршрутную скорость поездов, скажем, в 2–4 раза.

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CALCULATION OF THE WARRANTY SECTION OF A MAINTENANCE POINT OF FREIGHT CARS

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ABSTRACT

A verbal model of work of car inspectors and mathematical model of design-based justification of the warranty section of freight cars maintenance enterprise are considered. At the same time indicators of reliability and safety of the car, the acceptable crash risk level, likelihood that a car inspector will not find them inoperable (foozle in his work) are taken into account. A test example shows the effect of operating parameters on the frequency of the technical control.

Keywords: railway, warranty section of maintenance depot, frequency of monitoring the technical condition of the car, the probability of defect during the inspection, verbal model, mathematical model, security parameters of the car, design-basis justification.

Background. *The task of increasing the length of the non-stop running of trains is much more serious than it may seem at first glance.*

More than half a century ago, a professor of MIIT, L. A. Shadur and his students showed that increasing the weight of trains at the expense of increasing the linear loads of cars is the most appropriate in terms of slowing down the degradation of the most capital-intensive element of railways which is the track superstructure. In addition, this approach does not require elongation of station tracks.

Under the leadership of L. A. Shadur eight-axle tanks and gondola cars were developed, which became a means of implementing higher linear loads. So, a train, consisting of these eight-axle gondola cars, can carry 43% more coal, ore and other goods than a train of an equal length, formed of four-axle gondola cars.

A similar effect is achieved when eight-axle tanks, serial production of which has been carried out for a long time at the Zhdanov Carbuilding plant (today «Azovmash», Mariupol, the Ukraine), are used in the transportation process.

It should be noted that the power of locomotives is no longer a deterrent. Indicators of the quality of the track superstructure are not considered as a limitation, although the same cannot be said about the methods of organizing the transportation process.

In fact, there is a huge gap between the average speed of goods traffic (10–12 km/ h) and a service speed of freight trains (34 km / h) due to the fact that on average, every 140 km freight is processed at service station and after 450 km – at marshalling yard. That's why goods in the rail network are moving at a speed of animal-drawn transport.

The problem itself was realized in the late 80s of the last century. And then a task arose: to increase car-mileage without processing at stations up to 1000 km. For traffic service it is meant to develop new routing technologies, which would not require so often to resort to services of technical stations during the voyage, and for rolling stock department – to increase the length of the warranty section of maintenance depot (l_{ws}) in 4–5 times.

Such a complex task needs to be addressed with a great care, since at an arbitrary (not supported by science) change of l_{ws} in one or another direction a railway, as narrated in the famous Greek myth, certainly could be between Scylla and Charybdis. With increasing l_{ws} labor productivity due to the growth of average speed of trains will increase, but the level of safety on the road will be lower. If the value l_{ws} decreases, the traffic safety increases and the labor productivity declines. In other words, there are risks, respectively, on the one and the other sides.

It is clear that it is impossible to do without scientific justification of l_{ws}.

As a methodological basis to solve this problem it is advisable to have a verbal model of the organization to identify dangerous damage, i. e. verbal description of the operation of the current detection system of dangerous damage available on a particular train.

The mentioned system can be represented as a pair of car inspectors, acting at the location of the car at the maintenance depot, and (k–1) redundant pairs of their counterparts, each of which is located at own maintenance depot in the direction of travel. Reserve pair of car inspectors of the neighboring station is included in the process, if the foozle took place at the previous enterprise, where no dangerous damage to equipment was found.

The process continues as long as any one of the (k–1) pairs of car inspectors finds damage, or it is found during the diagnosis of technical condition of cars within the next scheduled maintenance, unless, of course, crash or train accident happens. Here k is a maximum possible number of attempts to detect existing dangerous damage to a car from the moment of its appearance to setting up the car in the next scheduled repairs (roundhouse servicing or overall repair).

We emphasize that the object of consideration and research within the required mathematical model should not be a separate maintenance depot, and many such companies, through which the car passes between scheduled repairs, which corresponds to the security settings of the car (l_{sec}) with the existing strategy for depot repair.

Note that we are interested in the optimal value of the length of the warranty section of the maintenance depot regarding the criterion of optimization, set in advance.

Objective. The objective of the authors is to investigate a verbal model of work of car inspectors and a mathematical model of design-based justification of the warranty section of freight cars maintenance enterprise.

Methods. The authors use mathematical methods, analysis, comparative method.

Results. As the object of optimization we use a so-called plan for monitoring the technical condition (TC) of the car on the interval (0; l_{sec}):

$$D_n = (x_1, x_2, ..., x_n), \quad (1)$$

where x_i is mileage of the car to the i-th ($i=\overline{1,n}$) control of its technical condition, counting it from scratch; l_{sec} is a car security parameter, i. e. a maximum mileage of the car between scheduled repairs.

An optimization problem will be solved within the framework of the following assumptions:

a) because the probability of detection of dangerous damage to the car in the conditions of maintenance depot is very low as compared with the probability of detection of the same damage in terms of planned maintenance, it is appropriate to assume that at roundhouse servicing or overall repair with almost one hundred percent probability dangerous damage is detected and working capacity of the car fully restores;

b) foozle in the work of car inspectors is possible, however, we assume that detected dangerous damage or failures are eliminated completely, i. e. only one function of the maintenance depot will be explored – timely identification of existing hazardous damage to the cars;

c) we take it for granted that the skill level of car inspectors at nearby maintenance depots is about the same.

An important part of the problem is the derivation of the objective function (hereinafter-OF). As such, we use a function of so-called operational losses (hereinafter-OLF), which, as will be shown below shall have two arguments:

ξ is a continuous random variable, which means the service hours of the car until appearance (not detection!) of a dangerous damage;

n_i is a discrete random variable, which is designed to assess the results of monitoring the technical condition in order to identify an existing dangerous damage to the car by a pair of car inspectors at the i-th maintenance depot; a law of distribution of this random variable can be conveniently represented in a tabular form:

n_i	1	0
	P_i	$1-P_i$

(2)

where P_i is a probability that a pair of car inspectors of the i-th maintenance depot finds an existing dangerous damage to the car and therefore the expression ($1-P_i$) means the probability of foozle in their work.

The probability P_i depends on the skills, technological and labor discipline of car inspectors,

Table 1

Initial data

Factor	Indication	Dimension	Value
Averaged value of the damage due to a train derailment	π	rub.	$360 \cdot 10^6$
Car safety parameter	l_{sec}	months	30
Acceptable risk of the train crash	R	-	10^{-4}
Daily average mileage of the car	$l_{daily\ aver.}$	km	400

Table 2

The matrix of warranty sections of maintenance depots, km

C, rub.	1–*P*, [–]							
	0,7	0,6	0,55	0,5	0,45	0,4	0,35	0,3
1	739	853	904	952	1000	1043	1087	1122
1,275	835	963	1020	1078	1128	1176	1228	1276
1,5	907	1045	1111	1169	1224	1278	1329	1379
2	1049	1208	1281	1348	1417	1476	1538	1594
3	1285	1181	1572	1659	1739	1809	1885	1954
4	1487	1714	1804	1914	2004	2093	2182	2258

time of day, weather conditions, and testability of car structures at the time of operation.

None of the railways of the world has an existing mechanism for an objective assessment of the probability (1–P_i), which would characterize the quality of control of the technical condition of the car during its intended use.

Meanwhile, a few years ago at MIIT a verbal model of the network-wide automated control system (hereinafter-ACS) was developed, which is a dual purpose system:

– Monitoring the performance of each car inspector;

– Obtaining the operational data on service hours of cars before the appearance (not detection) of dangerous damages.

Due to the mentioned arguments of required OF (ξ and n_i) it seems possible to simultaneously take into account the strength and reliability of car structures (using ξ), and the plurality of the factors affecting the value of foozle in the work of car inspectors (using n_i).

Nonrandom factors that affect the result of the solution of the problem should be considered using two parameters of OF.

Parameter C – costs of a single control of the technical condition of the car:

$$C = 0{,}16\frac{S}{N}, \qquad (3)$$

where S is average monthly costs of maintenance and support of operation of the maintenance depot of cars; N is a number of cars passes through the service station for a specified period; 0,16 is a share of labor costs for the control of the technical condition of cars.

Parameter h is an average value of economic losses of railways because of the car staying in stealth disrepair during a unit of time (or mileage of the car):

$$h = \frac{\pi}{l_{sec}} \cdot R, \qquad (4)$$

where π is an expected damage from the crash; R is an input risk (probability) of a train crash due to a foozle in the work of car inspectors. This value can be determined by the formula [2]:

$$R = 1 - K_{or}(l_{sec}^{opt}), \qquad (5)$$

where l_{sec}^{opt} is a value of l_{sec}, in which a ratio of operational readiness of cars $K_{or}(\cdot)$) becomes the largest.

An assumption that the competence level of car inspectors at neighboring maintenance depots is about the same, makes it possible to drop the index at the random value n_i, i. e.. $n_i \equiv \nu$ at any i.

Thus, the objective function, according to the dimension of its arguments, can be expressed in terms of the components of the mileage vector of the car (1), we denote it as $G_{D_n}(\upsilon, \xi)$.

The structure of OF is such that costs to compensate the consequences of accidents and derailments of trains are balanced by the costs of organizing the timely detection of dangerous damage to cars with their direct use in the transportation process. Therefore, the existence of an extreme of a desired OF is not in doubt.

Since the arguments of OF are random variables, then the function itself takes random values. In this form it cannot be used in an optimization task. Therefore OF should first be subject to averaging over the random variable ν, and then – over the random variable ξ.

As a result of these operations, described in [3], a mathematical expectation of OLF (or OF) is obtained as follows:

$$\mathrm{M}G_{D_n}(\xi) = \int_0^{l_{sec}} G_{D_n}(x)dF(x) + G_{D_n}(l_{sec}) \cdot \overline{F}(l_{sec}), \qquad (6)$$

where $\mathrm{M}G_{D_n}(\xi) \equiv \mathrm{M}_{\xi}\left[\mathrm{M}_{\upsilon}G_{D_n}(\upsilon,\xi)\right]$; F (x) is a distribution function of the service hours of the car until the dangerous damage appears; $\overline{F}(x) = 1 - F(x)$ is a probability of a failure-free work over the time x (reliability function).

The formula (6) refers to the desired expression for OF, or average value of operating losses in the period of use of the car in the transportation process between scheduled repairs, i. e. in the range (0, l_{sec}).

In [3] a method is given for determining the distribution function F (x) on the basis of a developed at MIIT verbal model of production of performance data on service hours of cars before hazardous damages appear.

Since currently on the railways of Russia (and other countries) there is no any working mechanism *of production of operational data to identify the distribution function of service hours of cars until dangerous damage emerge, at first, it is possible to use of (6) under the assumption that there is a lack of information about F (x).*

This assumption is facilitated by the fact that an increase in the security parameter of the car (l_{sec}), the first and the second terms in the equation (6) change monotonically in opposite directions. Consequently, there is a function $F^*(x)$, for which the maximum operating losses are achieved:

$$\max_F \mathrm{M}G_{D_n}(\xi). \qquad (7)$$

The resulting error in solving the problem will go to offset the guaranteed safety of the car. It now remains on the interval (0, l_{sec}) to choose such a mileage vector $D_n = (x_1, x_2, \dots, x_n)$, when the expression (7) reaches a minimum:

$$\min_{D_n} \max_F \mathrm{M}G_{D_n}(\xi), \qquad (8)$$

which, in fact, is the desired optimization criterion of the length of the warranty section of the maintenance depot of freight cars.

Methods of solving these minimax problems are known [4]. In this case, the optimal mileage x_i $(i=\overline{1,n})$, followed by a control of the technical condition of the car can be calculated according to the formula:

$$x_i = i \cdot P \cdot \left\{ \begin{matrix} \dfrac{l_{\sec}}{n^* \cdot P + 1} + \\ \dfrac{C}{2h}\left(\dfrac{n^*\left[\left(n^*+1\right)\cdot P + 2\right]}{n^* \cdot P + 1} - (i+1) \right) \end{matrix} \right\}, \qquad (9)$$

where P is a probability that a pair of car inspectors of the maintenance depot finds an existing dangerous damage to the car; n^* is the greatest n, for which the inequation is met

$$Cp^2n^2 + Cp(2-p)n + 2(C - phl_{\sec}) \le 0. \qquad (10)$$

As can be seen from the expression (9), the optimal frequency of monitoring the technical condition of the car is variable that, in principle, is possible to be used in practice with the help of «DISPARK» system that is, within the branch system of timely setting up of cars in the planned repairs on the mileage.

However, taking into account the minimax formulation of the task, it is permissible to use an approximate estimate of the length of the warranty section of the maintenance depot of cars, obtained by the formula:

$$l_{ws} = \frac{l_{\sec}}{n^*}. \qquad (11)$$

Conclusions. *The value of the formulas (10) and (11) for calculation of the optimal length of the warranty section of the maintenance depot of cars is as follows:*

– A link is found between frequency of deep diagnostics (l_{sec}) and the length of the warranty section of the maintenance depot (l_{ws});

– An explicit dependence of the length of warranty section of the maintenance depot from the probability of foozle in the work of car inspectors is found, and consequently, the level of organization of production at the enterprise.

Specified, for example, the original data in Table 1, using (11), we estimated the effect of these factors on l_{ws} value.

Impact on the length of the warranty section of the maintenance depot (l_{ws}) of such important factors as the foozle in the work of car inspectors (1–P) and the costs of technical inspection of the car (C), represented as a matrix of warranty sections of the maintenance depot (Table 2).

The data in Table 2 shows that an increase in the costs of monitoring the technical condition of the car from 2 to 4 rubles nonstop mileage of the car when the probability of foozle in the work of car inspectors 0,55 can be increased from 1281 to 1804 km, i. e. at 523 km. Calculations have shown that when l_{sec}=20 months the mentioned mileage may grow from 854 to 1203 km, i. e. at 349 km. Thereby parameters of the average speed of trains increase, and the turnover of the car, as well as total cost of rolling linear economy reduce by reducing the number of maintenance depots.

Therefore, it is possible to solve an important inverse problem – to determine what activities should be carried out and what resources need to be placed on their implementation, in order to increase the average speed of trains, say, by 2–4 times.

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