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ALGORITHM FOR MAKING THE OPTIMAL DECISION FOR FURTHER OPERATION OF FREIGHT CARS

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Resume

The article deals with the methodology of selecting the optimal decision for the maintenance and operation of freight cars.

The statistics of failures for the main units of freight cars has been collected. A hypothesis has been proposed about the method of selecting a decision based on the optimality criterion, i.e. the maximum profit. The optimality criterion is the difference between the income and the costs and is the function of the frequency of certain operations on each of the car units.

An algorithm has been developed that allows for the effective optimization of the processes of operating, repairing, and writing-off the cars, ensuring an increase in the competitiveness of rail transport due to the rational use of resources and optimization (reduction) of costs.

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1 Introduction

Rail freight transport plays the key role in global logistics due to its cost-effectiveness and ability to transport large volumes over long distances. In recent years, there has been a significant increase in demand for freight cars, especially in such countries as India, China, the United States and Russia [1].

The increase in demand for cars is caused by the global economic recovery, the growth in trade and industrial production. In addition, the strict environmental standards and the desire to reduce carbon emissions have contributed to the transition from road to rail transport in several regions [2]. This has strengthened the position of rail freight as an environmentally friendly and cost-effective mode of transportation.

The global freight car market growth forecast presented in the SCI Verkehr report (2024) indicates an annual increase of 2.6% until 2028 [3].

The growth in demand for freight cars in the railway industry of Kazakhstan is caused by several key factors that are related to the economic, infrastructural and geographical features of the country: increasing the volume of exports of raw materials, developing the transit potential, depreciation of the existing rolling stock, investments in the railway infrastructure modernization, the growth of agricultural production, and increasing the volume of domestic transportation.

The data of analytical research show that the rolling stock fleet of Kazakhstan owned by state railways has decreased by half, while the fleet of private companies has increased more than sevenfold. Private companies need an approach to operation that leads to increased profits [4].

A significant portion of the current rolling stock has been in operation for more than 10-15 years. This causes a high level of wear and tear and an increase in maintenance costs [5-6]. A significant portion of the cars that have been in operation for over 25 years require either major repairs or write-offs, which leads to additional costs and possible disruptions in transportation.

Before each trip, freight cars undergo mandatory maintenance, including checking their main components and mechanisms [7-11].

Modern diagnostic technologies are used to identify faults: thermal imagers, acoustic systems and automated control systems [12-18]. However, it is necessary to develop and to implement methods of predicting the condition of cars. The existing forecast methods, including extrapolation, expert assessments and modelling, have a number of limitations [19-20]. As researchers note, such approaches do not completely eliminate the risk of malfunctions and emergency situations.

The main difficulties of the freight car market are related to high capital expenditures for servicing and upgrading the fleet [20-21]. Despite advances in diagnostics and maintenance, the issues of increasing reliability of cars remain relevant. This requires developing the new systems for predicting the technical condition of cars, which will reduce downtime and increase operational efficiency.

The hypothesis of the study is the possibility of increasing profitability of car operation by optimizing the decision for technical maintenance, repair and their operation, taking into account the costs of various activities and the relative frequency of failures.

The aim of the work was to develop and to justify the methodology of optimizing the processes of operating, repairing and writing-off the cars, aimed at increasing their reliability and economic efficiency.

The main criterion for assessing the effectiveness of the proposed methodology is profit maximization, which emphasizes its importance for increasing the competitiveness of rail transport.

The scientific novelty consists in the development of an algorithm graph for making an optimal decision for the operation of freight cars based on the probabilistic analysis of failures and economic efficiency.

The practical significance lies in the possibility of minimizing the costs of servicing the cars, increasing reliability of their operation and optimizing the use of resources.

2 Materials and methods

The use of the criteria approach to selecting the optimal decision for the operation of railway rolling stock (freight cars) can significantly improve the efficiency of operation. Based on this assumption, the analysis of gondola cars as the most popular and widely used type of freight cars was carried out [22]. Their versatility and significant share in the total wagon fleet determine the feasibility of selecting this object for research.

The proposed hypothesis forms the methodology that, despite being focused on gondola cars, can be adapted to any type of railway rolling stock, which significantly expands its scope of application and confirms its versatility.

Table 1 *Collected statistical data of the availability and repair of faulty freight cars (F. CA-31)*

			Last repair type			Time of admission to the faulty ones		Time of dispatch for repair	
No.	Car No.	Year of manufacturing	Marking stamp	Date	Fault code	Date	Time	Date	Time
1	53788485	1990	608	09.01.2020	445	22.04.2013	5h 41min.	26.04.2023	20:55
2	94752219	1988	1181	21.05.2018	571	12.01.2020	6h 42min.	15.02.2020	07:08
3	53784518	1991	608	30.11.2019	571	12.01.2020	18h 19min.	14.01.2021	02:37
4	24023988	1975	721	06.01.2017	570	17.01.2020	15h 59min.	22.01.2020	22:36
5	94752912	1988	1181	19.01.2018	571	04.02.2020	16h 45min.	15.02.2020	07:08
6	94305364	1988	697	16.07.2017	571	04.02.2020	16h 45min.	16.02.2020	10:45
7	94343217	2008	698	03.03.2018	572	10.02.2020	17h 55min.	17.02.2020	01:53
8	94283850	2011	612	16.02.2018	572	10.02.2020	17h 55min.	17.02.2020	01:53
9	60262052	2005	691	30.04.2016	572	12.02.2020	23h 20min.	17.02.2020	01:55
10	60259587	2010	745	09.04.2018	572	12.02.2020	2h 50min.	13.02.2020	04:20
11	50256239	1980	697	29.12.2016	570	14.02.2020	12h 03min.	28.02.2020	06:50
12	57302887	1986	697	13.12.2016	570	14.02.2020	12h 03min.	28.02.2020	06:50
13	62217567	1985	220	27.02.2017	571	15.02.2020	11h 10min.	21.02.2020	06:50
14	52052693	2011	1016	20.07.2017	572	28.02.2020	13h 15min.	02.02.2020	23:54
15	24344442	1989	692	10.03.2017	570	01.03.2020	02h 10min.	02.03.2020	23:54
16	63912646	1998	695	15.10.2018	571	07.03.2020	21h 50min.	21.03.2020	05:18
17	94504404	2009	900	29.10.2017	572	09.03.2020	02h 05min.	11.03.2020	12:35
18	60358983	2005	220	22.10.2018	572	13.03.2020	12h 35min.	13.03.2020	13:05
19	28025104	2006	720	25.11.2017	107	13.03.2020	04h 25min.	17.03.2020	07:59
20	55303788	2010	341	22.06.2017	572	15.03.2020	04h 57min.	18.03.2020	07:40
21	90887647	1979	608	19.02.2019	571	28.03.2020	22h 55min.	05.04.2020	06:09

At the first stage of the research work, a summary of statistical information of freight car defects was carried out, based on the data for the period from 2022 to 2024. The main sources of information were the automated wagon fleet database (AWFDB), the automated system for operational management of transportation at the road level (ASONM), and the book of records of the presence and repair of faulty wagons of the freight fleet (form of Carriage accounting-31 (F.CA-31)) [23-24]. The information of freight cars uncoupled for repair work is presented in Table 1.

When analyzing the data on faulty freight cars, parameters recording the technical condition and repair history of the rolling stock were used. Here is provided an explanation of some columns, such as "brand" and "malfunction code" indicated in Table 1.

Brand is a conventional designation (digital or alphanumeric code) assigned to a car by a repair enterprise or depot where the last major or depot repair was performed.

Malfunction code is a numeric identifier corresponding to the classifier of typical failures and defects of freight cars included in the Commonwealth of Independent States (CIS), as well as Latvia, Lithuania and Estonia. Each code reflects a certain type of technical malfunction. For example, code 445 may mean wear of the side frame, 571 - an axle crack, 570 - a defect in the car body, etc [25]. During the study, certificates (Appendix A) of various forms were requested for each freight car, which made it possible to determine the number of times the car was uncoupled, when it was sent for repairs during its service life, the year the car was manufactured, the manufacturer of the car, etc.

When analyzing the data of defective freight cars, the parameters were used that provided the technical condition and the repair history of the rolling stock. Here is an explanation of some of the columns, such as the "a stamp" and "fault code" listed in Table 1.

The stamp is a symbol (a numeric or an alphanumeric code) assigned to a car by a repair company or depot where the last major or depot repairs were performed [26].

Additionally, the Karaganda operational wagon depot of the NC KTZh JSC (Republic of Kazakhstan) collected the information of the technical condition of wagons and their operation for the period 2022-2024 at the Karaganda branch of the railway.

The analysis of the presented data revealed the most common types of freight car malfunctions and the main components that cause their uncoupling for routine uncoupling repairs (RUR). Based on the collected information, the classification of malfunctions was performed, including the following units: wheel pairs, automatic brake equipment, automatic coupling devices, body, etc.

As an example, Figure 1 shows in detail the main types of malfunctions (deformations) of the gondola car body.

The faults of covered cars include damage to the roof (a, b), weakening or absence of doors (c, d, e), presence of holes, cracks and dents in the skin (e, g, h, i), damage to the floor with holes (k), as well as malfunction or absence of locking devices (l, m) (Figure 2).

The collected data of the Karaganda operational wagon depot of the NC KTZh JSC (Republic of Kazakhstan) are presented in graphic form, which made it possible to visualize the share of each category of faults (Figure 3).

The analysis of the data for 2022-2024 shows that in 2023, the number of faulty cars uncoupled for repairs increased significantly compared to 2022. Uncoupling for trailer equipment increased by 993 units, for the body by 3,106 units, and for the "other" categories by 1,321 units.

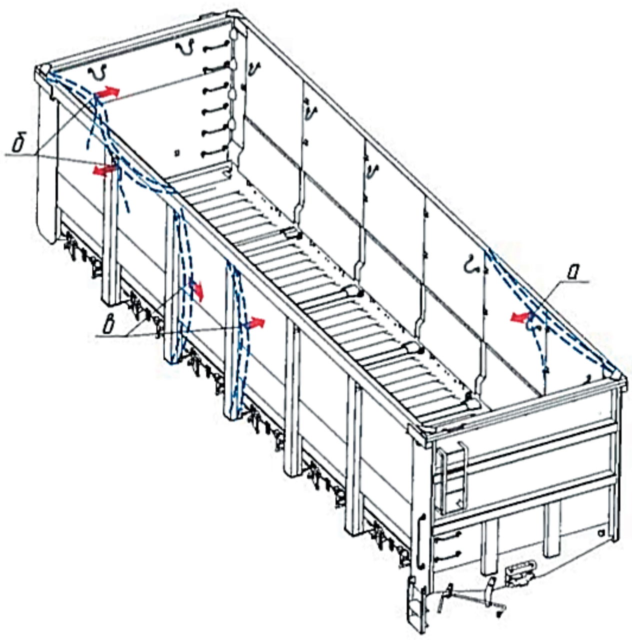

Figure 1 *Types of deformations of gondola car bodies: a - widening of the body; b - body skew; c - deflection, dent of pillars*

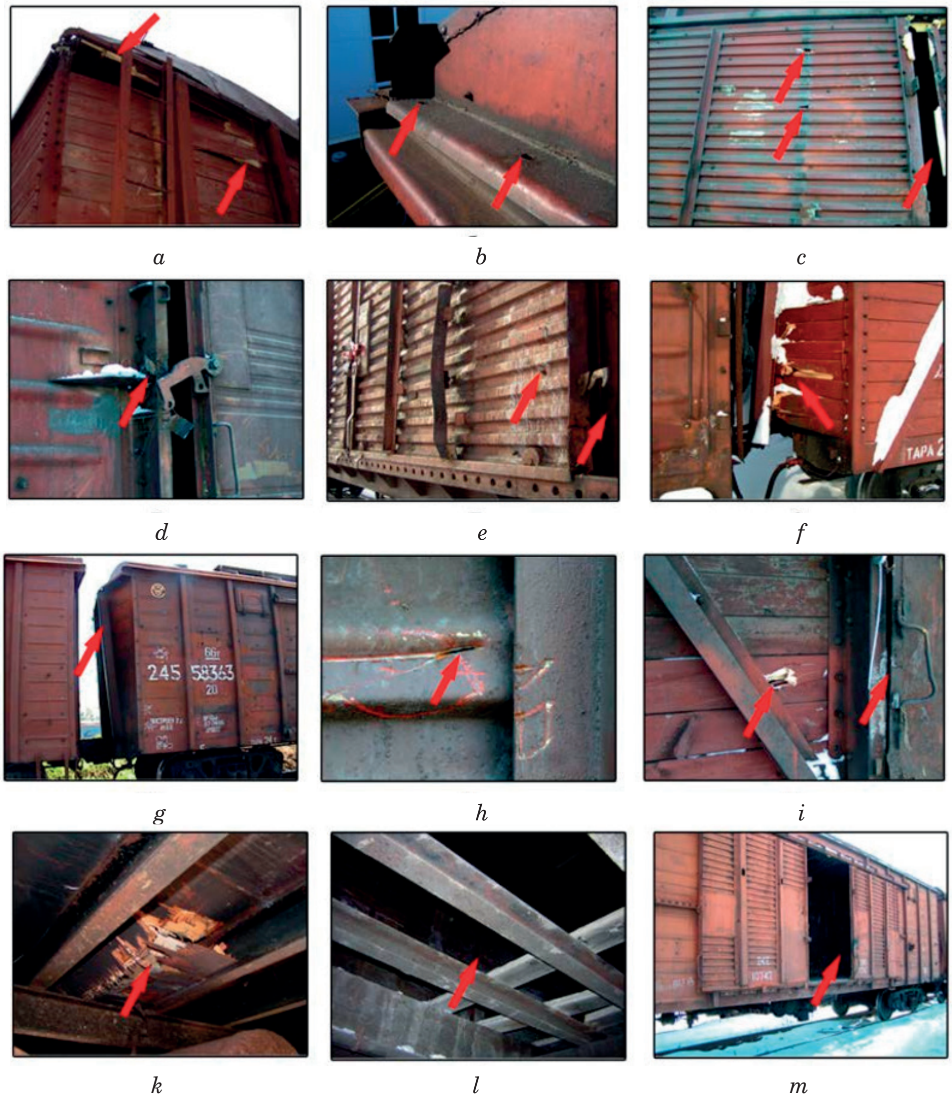

***Figure 2** Main types of covered cars faults*

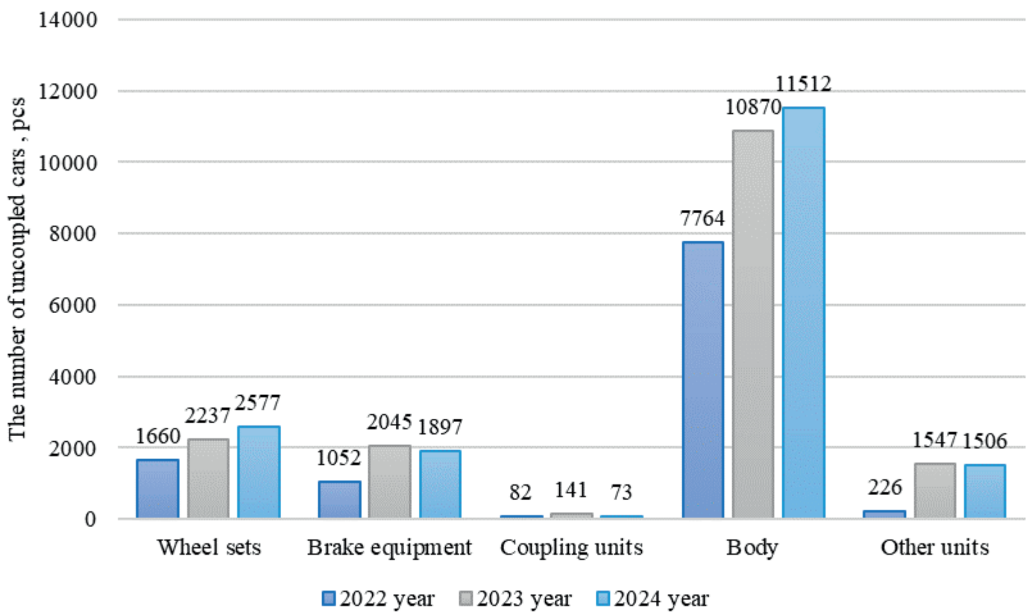

***Figure 3** Number of technically faulty cars uncoupled at the technical maintenance points (TMP) of the Karaganda branch (Republic of Kazakhstan) in 2022-2024*

Significant growth was also observed for wheel sets and automatic coupling devices.

In 2024, the situation changed, as the number of uncoupling decreased for some units, but for critical elements such as wheel sets and the body, the growth continued by 340 and 642 units, respectively. This indicates that the problem remains relevant and requires the adoption of correct, effective measures.

Statistics confirm the need for an optimal selection of decision-making on the operation of freight cars. To correctly select the decision, it is necessary to develop a decision-making algorithm. A graph of the algorithm for making a decision on the operation of a freight car has been developed. The algorithm is presented in Figure 4 and is implemented using the example of gondola cars, the most universal and popular type of freight cars, which are widely used in various types of transportation and also make up the largest share in the car fleet of the Republic of Kazakhstan (42.6%) [27].

The algorithms for choosing the optimal solution for wheelsets, car brakes, bodywork, and the other components and parts are similar to the algorithm for maintenance of auto couplers. For the sake of brevity, these graphs are given in appendix B.

The graph defines a sequence of steps for selecting the optimal scenario based on the technical condition of the car and economic indicators. Changes in economic conditions, associated with the fact that most of the car fleet is privately owned, made it possible to formulate the optimality criterion as the maximum profit. To establish the maximum optimality criterion, it is necessary to analyze the costs of repairs and potential income from further operation of the freight car.

To make the optimal decision on further operation of the freight car, a detailed analysis of its condition is carried out, which begins with a technical inspection upon arrival or during the formation of a train at the technical maintenance points (TMP) of the station. As a part of the initial inspection, the condition of the main units is assessed. Based on the inspection results, the degree of wear and tear and the need for repair are determined. Then, a decision is made to put the car in for repair in accordance with one of the three key rules of technical maintenance given in Table 2.

The graph includes the following main scenarios:

- initial inspection of the technical condition of the car: assessment of the units (wheel pairs, trailer equipment, automatic coupling devices, body and other elements) and determination of the degree of wear and the need for repair;

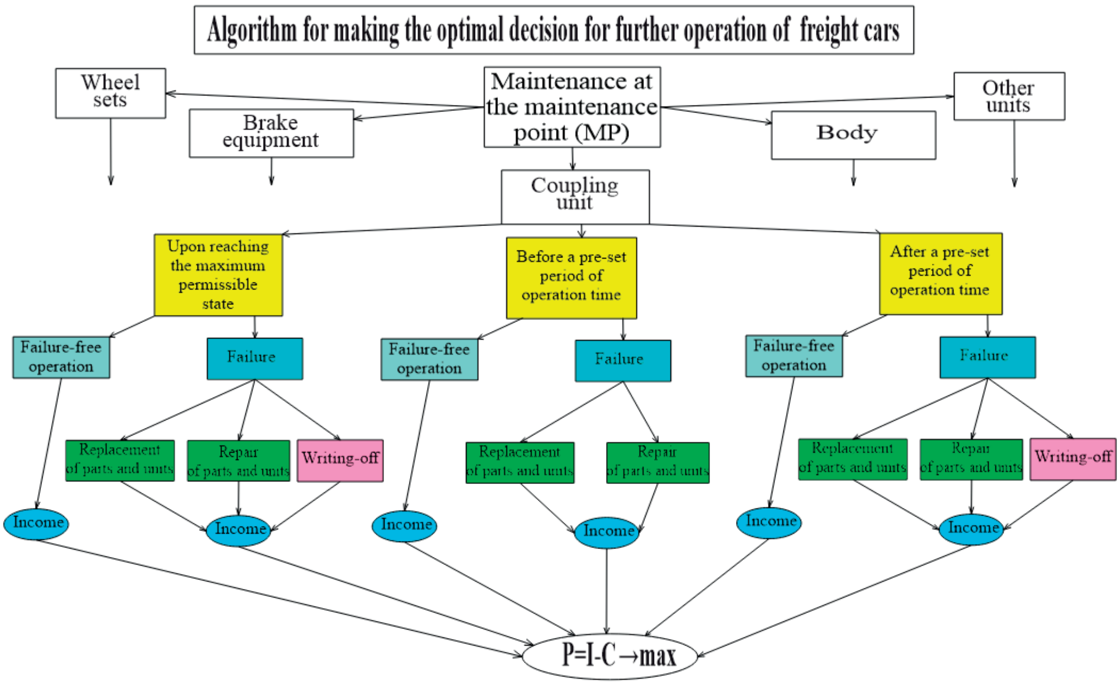

***Figure 4** The decision-making algorithm for the further operation of the freight car*

***Table 2** Freight car technical maintenance guidelines [28-29]*

No.	Technical maintenance rule	Description
1	Limit state rule	Repairs are carried out when a unit or part reaches a set wear limit or technical condition.
2	Calendar term rule	Maintenance and repairs are carried out after a predetermined period of time, regardless of the condition of the car.
3	Mean time between failures rule	Repairs are carried out upon the occurrence of a malfunction or complete failure of a unit or part.

- decision making based on the condition of the units: the malfunction is not critical, i.e. the car is allowed for further operation with minimal costs. A moderate malfunction is possible, which requires routine repairs, after which the car is returned to operation, or a critical malfunction, when the car is subject to major repairs or write-off;
- assessment of the economic feasibility of repairs: comparison of the repair costs to the projected income from the remaining service life of the car. If the repair is justified, then the repair work is carried out and the car is returned to operation. If the repair is unprofitable, it is necessary to consider options for writing off the car or selling it on the secondary market;
- optimization of the decision based on the income and cost analysis: selection of the scenario with the maximum profit, if the income from operation exceeds the costs of repairs and maintenance, the car remains in operation.

3 Decision-making algorithm

1. The car undergoes a technical inspection, worn-out wheel sets are identified.
2. The costs of their replacement and the potential income from operating the car after repair are analyzed.
3. If the replacement of parts or units will cost an amount comparable to the income from operation, a decision is made to repair.
4. If the repair costs exceed the income, the car is written off.

Selecting the optimality criteria depends on the priorities and goals, as well as on the specifics of the activities, external conditions. Depending on the goals and conditions of operation, various criteria can be selected. In the case, to assess the efficiency of operating freight cars, the key criterion is profit maximization.

The profit maximization is the main indicator of the economic efficiency of any transport system in the context of modern commodity-money relations. The basis of this approach is the objective function of the optimality criterion, aimed at achieving maximum profit at minimum costs. Profit maximization is the difference between income from operation and the sum of all the costs:

$$\max(P) = I_{rso} - \sum C_i ; \quad (1)$$

where $\sum C_i$ consists of the following:
C_{repl} are costs for replacing units and parts;
C_{rep} are costs for repairing units and parts;
C_{wof} are costs for writing-off the car loss of residual resource;
max(P) is the maximum profit;
I_{rso} is the income from the rolling stock operation (or form selling its units and parts when written-off) per unit of time or run.

To make an optimal decision, it is necessary to meet the optimality condition that consists of maximizing the profits, while minimizing costs, which allows selecting the most profitable option for the operation, repair or decommissioning of rolling stock:

$$C_{opt} = \min\left(\sum C_j\right) \text{ at this } I_{rso} - \sum C_i ; \quad (2)$$

This condition means that the minimum costs should ensure a positive income from further operation of the car.

Efficient management of freight car operation requires analyzing the probabilities of failures and failure-free operation of their main units. These are the key indicators to predict the repair costs, to assess reliability of the system and to make informed decisions aimed at increasing the economic efficiency of rolling stock operation.

To analyze the economic efficiency of car operation and to develop an optimal decision-making algorithm, an example of calculating the probabilities of failures for the main units of the rolling stock is given. The analysis is based on statistical data from the Karaganda branch of the railway (Republic of Kazakhstan) for 2023, presented in Figures 1, 2. Based on these data, as well as on the given formulas, the probabilities of failures are included in the calculation of profits and costs. This allows determining the optimal decision-making algorithm for further operation of the rolling stock.

The probability of a unit or system failure shows the frequency of malfunctions over a certain period of time. It is determined based on the statistical data that allow predicting which units require more attention. It is calculated using the formula:

$$F(t) = 1 - e^{-\lambda t} ; \quad (3)$$

where λ is the failure rate;
t is the operation time.

The uptime P(t) probability reflects the ability of a component to function without failure for a given period. The higher this probability, the lower the repair and replacement costs. It is determined by the formula:

$$F(t) = e^{-\lambda t} ; \quad (4)$$

where λ is the failure rate;
t is the unit operation time.

Determining the probability of failure is directly related to the processing of large volumes of statistical data, which in some cases can be complicated. In this study, to simplify the calculations, the failure rate (relative failure frequency) was used, which allows for a high-precision reflection of the share of failures of each unit relative to the total number of recorded faults. This approach ensures sufficient reliability of the results and allows for their effective integration into subsequent analysis of the operational reliability of rolling stock.

The failure rate (λ) characterizes the frequency of failures per unit of operating time:

$$\lambda = \frac{n_i}{N \cdot t}; \tag{5}$$

where $n_{i\ fail}$ is the number of failures of a certain i-th unit $n_{i\ fail\ unit}$;
$n_{1\ fail\ unit}$ is the total number of wheel set failures per year;
$n_{2\ fail\ unit}$ is the total number of brake equipment failures per year;
$n_{3\ fail\ unit}$ is the total number of the coupling unit failures per year;
$n_{4\ fail\ unit}$ is the total number of the body failures per year;
$n_{5\ fail\ unit}$ is the total number of the other units failures per year;
N is the total number of the processed cars;
t is the tile of operation (the year time).

The calculated failure rates, failure probabilities and failure-free operation probabilities serve as the basis for assessing the economic efficiency of car operation. Those indicators are included in the calculation of profits and maintenance costs, which allows making informed decisions on optimizing operation and repair processes. This approach allows developing an optimal decision-making algorithm aimed at reducing costs and increasing reliability of car operation.

The current state of operation or downtime of cars is taken into account by introducing the existence coefficient (α_i). This coefficient reflects the current operating status of each unit or rolling stock as a whole:

- if the car is idle on the tracks without work, the existence coefficient $\alpha_i = 1$;
- if the car is in operation, the existence coefficient $\alpha_i = 0$.

The calculation formula is as follows:

$$P > I - \alpha_0 \cdot C_{id} - \sum_{i=1}^{5} \alpha_i \cdot p(t)_i \cdot З_i; \tag{6}$$

where I is the income from the rolling stock operation (tg);
α_0 is the existence coefficient of the idle costs;
C_{id} is the idle costs (tg);
α_i is the existence coefficient of the costs for repairing units (ifthe repair was made, $\alpha_i = 1$, if not, $\alpha_i = 0$);
$p(t)_i$ is the failure-free operation of the unit i;
C_i is the costs for repairing or replacing unit i.

In this case, Equation (6) has the form:

$$\begin{aligned} P > I - \alpha_0 \cdot C_{\pi p} - \alpha_1 \cdot p(t)_1 \cdot C_1 + \\ + \alpha_2 \cdot p(t)_2 \cdot C_2 + \alpha_3 \cdot p(t)_3 \cdot C_3 + \\ + \alpha_4 \cdot p(t)_4 \cdot C_4 + \alpha_5 \cdot p(t)_5 \cdot C_5; \end{aligned} \tag{7}$$

where I is the income from the rolling stock operation (tg);
α_0 is the existence coefficient of the idle costs;
C_i is the idle costs (tg);
α_1 is the factor of necessity to repair wheel sets (if repair was made, $\alpha - 1$, if not, $\alpha - 0$);
α_2 is the factor of necessity to repair brake equipment (if repair was made, $\alpha - 1$, if not, $\alpha - 0$);
α_3 is the factor of necessity to repair coupling units (if repair was made, $\alpha - 1$, if not, $\alpha - 0$);
α_4 is the factor of necessity to repair the body (if repair was made, $\alpha - 1$, if not, $\alpha - 0$);
α_5 is the factor of necessity to repair the other units (if repair was made, $\alpha - 1$, if not, $\alpha - 0$);
$p(t)_1$ is the probability of failure-free operation of the wheel set;
$p(t)_2$ is the probability of failure-free operation of the brake equipment;
$p(t)_3$ is the probability of failure-free operation of the coupling units;
$p(t)_4$ is the probability of failure-free operation of the body;
$p(t)_5$ is the probability of failure-free operation of the other units;
C_1 is costs for repair or replacement of a wheel set;
C_2 is costs for repair or replacement brake equipment;
C_3 is costs for repair or replacement coupling units;
C_4 is costs for repair or replacement of the body;
C_5 is costs for repair or replacement of the other units.

The novelty of the proposed dependences in Equations (6) and (7) is the introduction of the existence coefficient of costs, which can be equal to 0 or 1. The introduction of this coefficient allows combining all the existing decision options into one formula.

The probability addition is used if the failure of one unit itself leads to the failure of the entire system. This is typical for a series connection of elements, where the failure of any unit causes the failure of the entire car.

For a freight car, it is logical to apply the probability addition formula, since the failure of even one critical unit (brakes or wheel pairs) makes operation impossible and unsafe.

$$P_{car} = 1 - \prod_{i=1}^{n} (1 - P_i), \tag{8}$$

where P_{car} is the probability of failure of the whole system (car);
P_i is the probability of failure of each unit;
n is the total number of units.

If the failure of any of the car systems (brakes, wheel sets or body) leads to the failure of the car as a whole, then this formula is suitable.

4 An example of selecting the optimal decision for maintenance and operation of freight cars

To calculate the failure rate, the data on the number of cars processed per year is required. Figure 5 shows the quantitative indicators of cars processed at maintenance points (MP) for the Karaganda branch of the railway (Republic of Kazakhstan).

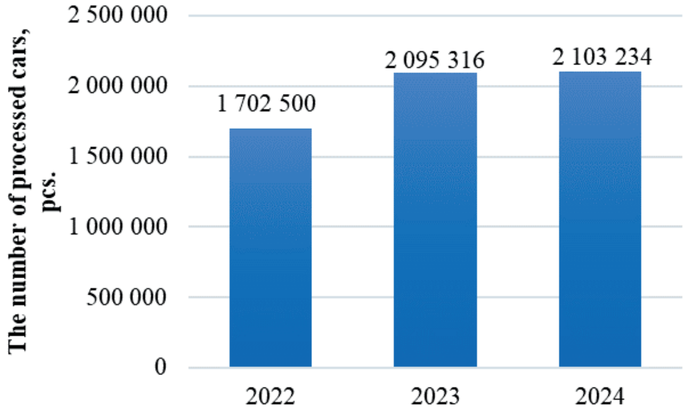

Figure 5 *The number of processed cars at the Karaganda branch of the road for 2022-2024*

Table 3 *Failure rate (λ) for units*

No.	Unit	Failure rate (λ) for 2022	Failure rate (λ) for 2023	Failure rate (λ) for 2024
1	Wheel sets	0.000975	0.001067	0.001225
2	Brake equipment	0.000618	0.000976	0.000902
3	Coupling devices	0.000048	0.000067	0.000035
4	Body	0.004562	0.005188	0.005472
5	Other	0.000133	0.000738	0.000716

Table 4 *Failure probability (q(t)) for units*

No.	Unit	Failure probability ($q(t)$) for 2022	Failure probability ($q(t)$) for 2023	Failure probability ($q(t)$) for 2024
1	Wheel sets	0.6843	0.7022	0.7340
2	Brake equipment	0.4661	0.6017	0.5874
3	Coupling devices	0.0491	0.0626	0.0344
4	Body	0.9822	0.9934	0.9952
5	Other	0.1074	0.5077	0.5057

Table 5 *Failure-free operation probability (p(t))*

No.	Unit	Failure-free operation probability ($p(t)$) for 2022	Failure-free operation probability ($p(t)$) for 2023	Failure-free operation probability ($p(t)$) for 2024
1	Wheel sets	0.3157	0.2978	0.2660
2	Brake equipment	0.5339	0.3983	0.4126
3	Coupling devices	0.9509	0.9374	0.9656
4	Body	0.0178	0.0066	0.0048
5	Other	0.8926	0.4923	0.4943

The calculation of the failure rate (λ), failure probability (q(t)) and failure-free operation probability (p(t)) for the units was made based on the data presented in Figures 1 and 2 for 2023, in accordance with the data given in Tables 3, 4 and 5.

The highest failure probability is for the car body (0.9934), which indicates its high wear and tear and the need for regular maintenance. The wheel pairs and brake equipment also require special attention, as their failure probability is 0.7022 and 0.3017, respectively. At the same time, automatic coupling devices have demonstrated the highest reliability (0.0626), which makes them the least expensive to operate.

Calculation of the costs is done for each unit by substituting the conditional values according to Table 6:

1. For the wheel sets:

$\alpha_1 \cdot p(t)_1 \cdot C_1 = 1 \cdot 0.2978 \cdot 313 = 93.2$ Euro;

***Table 6** Initial data for calculations*

Parameter	Value, Euro
Income (I)	2 083
Idle costs (C_{id})	417
Repair costs	
Wheel sets (C_1)	313
Brake equipment (C_2)	208
Coupling units (C_3)	104
Body (C_4)	625
Other units (C_5)	146
Failure probability (v_i)	
Wheel sets (v_1)	0.133
Brake equipment (v_2)	0.121
Coupling units (v_3)	0.008
Body (v_4)	0.646
Other units (v_5)	0.092
Existence coefficients (α_i)	
Cost existence coefficients (α_0)	1
Wheel sets (α_1)	1
Brake equipment (α_2)	0
Coupling units (α_3)	0
Body (α_4)	1
Other units (α_5)	1

2. For the brake equipment:
   $\alpha_2 \cdot p(t)_2 \cdot C_2 = 0 \cdot 0.3983 \cdot 208 = 0$ Euro;
3. For the coupling units:
   $\alpha_3 \cdot p(t)_3 \cdot C_3 = 0 \cdot 0.9374 \cdot 104 = 0$ Euro;
4. For body:
   $\alpha_4 \cdot p(t)_4 \cdot C_4 = 1 \cdot 0.0066 \cdot 625 = 4.13$ Euro;
5. For the other units:
   $\alpha_5 \cdot p(t)_5 \cdot C_5 = 1 \cdot 0.4923 \cdot 146 = 71.89$ Euro;
   The total costs for repair:
   93.2 + 0 + 0 + 4.13 + 71.89 = 169.22 Euro.
   The probable profit:
   P = 2083 – 1 · 147 – 169.22 = 2083 – 417 – 169.22 = = 1496.78 Euro.

Calculation of the total failure probability is done according to Equation (9):

$$P_{car} = 1 - [0.2978 \cdot 0.3983 \cdot 0.9374 \cdot 0.0066 \cdot \cdot 0.4923] \approx 0.999. \quad (9)$$

The total probability of car failure was 99.9%, which significantly exceeds the critical level of 0.5. This fact emphasizes the need for immediate technical intervention, including major repairs or decommissioning of the car.

Based on the presented calculations and analysis of the failure probabilities, the technical condition of the units and the total costs, the following decision to decommission the car was made based on the optimal decision-making graph (Figure 1), since the total probability of failure is 99.9%, which significantly exceeds the critical level of 0.5. This means that the car is in a state of high accident rate and its further operation is impossible without significant interventions, and the main unit requiring repair - the body, has a critically high probability of failure (0.9934). This indicates its high wear, which makes restoration extremely ineffective, since the cost of replacing the body is actually approaching the cost of a new car.

It is not economically feasible to carry out a major overhaul of the car in the case if:

- the total cost of the repair is 169.22 Euro, but this does not include the replacement of the body, which is the main problem.
- after the repair, there is a high probability of new failures, which will lead to additional costs in the future.
- the car downtime during the repair increases operational losses, reducing the economic efficiency of the restoration.

According to the decision-making column, if the probability of failure exceeds the permissible level and a major overhaul is not economically viable, the car is subject to writing-off.

Based on the above, as well as on the analysis of the technical condition and economic efficiency, the optimal decision is to write-off the car, since further operation is impossible without significant costs, and a major overhaul does not justify the invested funds.

5 Results and discussion

Thus, the analysis confirms that the car body is the most vulnerable unit that requires careful monitoring and timely repair. Automatic coupling units on the contrary show the lowest failure rate, which makes them the most reliable.

Having analyzed possible scenarios of operation and failure of freight cars, there can be drawn the following conclusions:

- The greatest number of failures occurs in the body, which requires development of new approaches to its maintenance and repair.
- It is economically advantageous to pay attention to the restoration of automatic coupling units, since their probability of failure is minimal.
- The probability of failure-free operation of brake equipment and wheel sets is at the level of about 87-88%, which requires regular preventive maintenance.

The use of this algorithm for making decisions on the operation of freight cars allows minimizing the financial costs for maintenance and repair, ensuring the maximization of profits and operational reliability of the rolling stock. Based on the data provided, the probability of profit is 1496.78 Euro. This approach takes into account the probability of failure-free operation of units, minimizes costs and helps to make an informed decision for the efficient operation of wagons.

Based on the analysis and calculations of the failure rate, failure probabilities and failure-free operation of freight car units, the following data were obtained (presented in Figures 6-8).

The highest probability of failures is for the car body (0.9934), which indicates the significant wear or high load on this unit. For automatic brake equipment, other

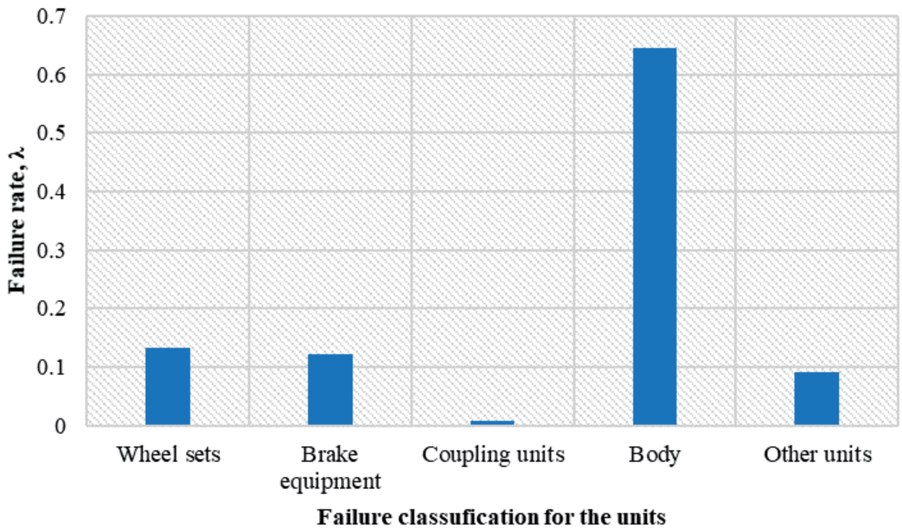

Figure 6 *Failure rate of freight car units on the Karaganda branch of the railway for 2023*

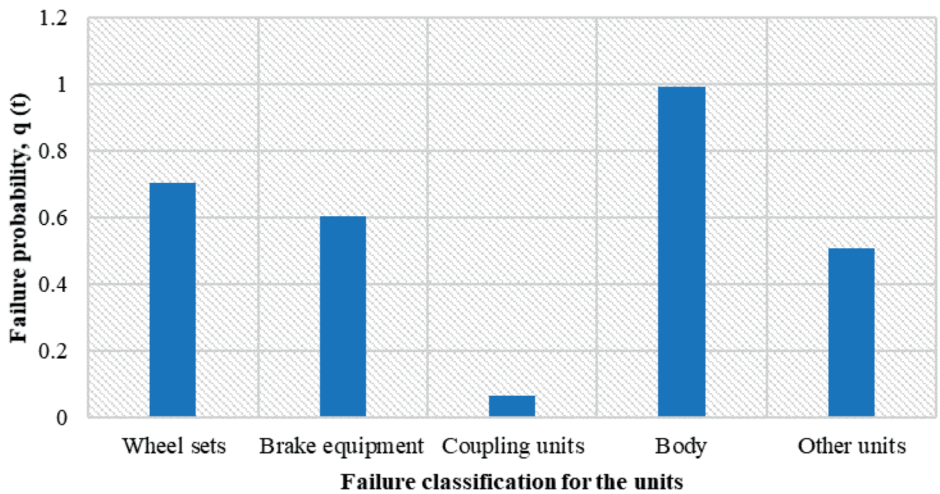

Figure 7 *Probability of failure of freight car units on the Karaganda branch of the road for 2023*

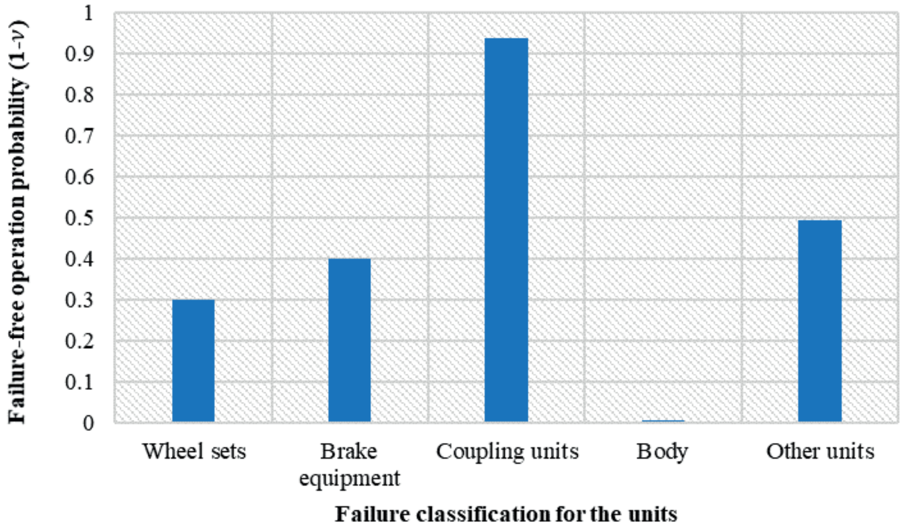

Figure 8 *Probability of failure-free operation of freight car units on the Karaganda branch of the road for 2023*

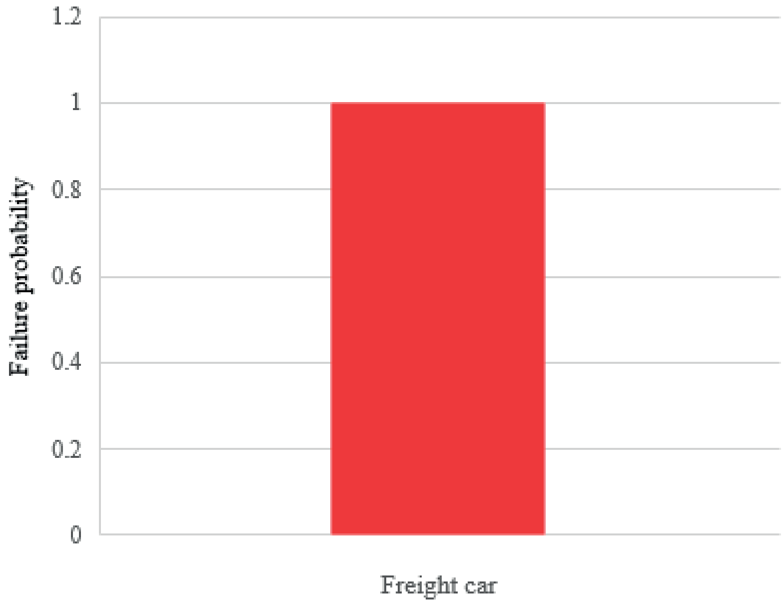

Figure 9 *Total probability of the freight car failure*

units and wheel pairs, the probability of failures is lower (from 0.0626 to 0.7022, respectively), which indicates a lower intensity of their failures. Automatic coupling devices showed the minimum probability of failures (0.008), which indicates their high reliability.

Automatic coupling devices demonstrate the highest probability of failure-free operation (0.9374), followed by the other components (0.4923) and automatic brake equipment (0.3983). Wheel sets have the failure-free operation probability of 0.2978, and the body has the lowest indicator (0.0066).

Figure 9 shows the total probability of freight car failures, which is 99.9%. This figure significantly exceeds the critical level of 50% and indicates an unacceptable level of risk for further operation of the cars. With the total probability of failure above 0.5, operation of the cars becomes economically inexpedient and potentially unsafe, so it is recommended to immediately carry out major repairs or to consider writing off the cars.

6 Conclusion

The study confirmed that the application of the decision-making algorithm for operation of the freight cars according to the developed graph allows significant reducing of the costs and increasing the efficiency of the resource use.

The study allows drawing the following conclusions and coming to the following algorithm for selecting the optimal decision regarding the operation of freight cars based on the optimality criterion, i.e. the profit maximization:

- assessing the current technical condition of the cars;
- analyzing the costs for all scenarios;
- assessing the profitability of continued operation;
- making a decision on the repairing of units and parts, and/or replacing the components, and/or writing-off the car, which maximizes the profit and takes into account the resource of units and parts.

Regardless of the country, engineering and rail transport follow the same patterns. The working conditions of railway transport and the patterns of wear do not depend on the country in which it is used. Therefore, the proposed algorithm for making the optimal decision for the further operation of freight cars can be used in the other countries, as well.

Implementation of this approach helps to free up the financial resources that can be directed to modernizing the infrastructure and improving the quality of service. This makes the car operation management system more flexible and resilient to changes in the market conditions, and applicable in the other industries.

The application of the developed methodology reduces the risks associated with the inefficient use of the rolling stock. The results of the study provide railway companies with effective tools for optimizing the processes of technical maintenance, repair and decommissioning of the cars, which ultimately allows for a significant reduction in costs and increasing the profitability of transportation.

Thus, the versatility of the proposed method makes it applicable not only in the railway industry but also in the other areas where the management of operational resources plays the key role. This emphasizes the relevance of the study and its significance for a wide range of specialists.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A - Reference 2653 Information of the last executed repair

```
REPORT 2653. THURSDAY FEBRUARY 22, 2024 13:44
**********************************************************
(AFTER THE CAR NUMBER THERE CAN BE SET THE NUMBER OF THE REPAIRS (3 BY DEFAULT)

**********************************************************
REPORT ON THE REPAIRS MADE ON CAR 28807352  ON 22.02.24 13:44:18.4
NO REPAIR TYPEOE  DATE                 ROAD              REPAIR DEPOT
--- ----------- ------------------- ----------------- -----------------
 1  RUN-1       DECEMBER 15,  2012   68 KAZAKHSTAN R/W 4048 the depot car part
(DCP)DCP-34 CDC BOROVOYE
                (220 - SLIDER CLEARANCE INCOMPLIANCE)
 2  RUN-1       APRIL 13,  2014      68 KAZAKHSTAN R/W 4042 DCP-19 KOSTANAI
                (212 - CAP SLIDER CRACK)
 3  RUN-2       MAY 25,      2014   80 SOUTH-URAL RAILWAY 4102 SECTION TOP ST.
MAGNITOGORSK CDCE-5 KARTALY OF THE Joint-stock Company Russian Railways (hereafter
RR JSC)
                (117 - IRREGULAR RUNNING ON THE CIRCLE RIDING ABOVE THE NORM)
 4  DEP.        -- -------- ---- Y. 68 KAZAKHSTAN R/W     4154 DCP-24
                (570 - DEPOT MAINTENANCE CALENDAR SCHEDULE EXPIRED)
 5  DEP.        OCTOBER 29,  2014   68 KAZAKHSTAN R/W  745 Ust-Kamenogorsk Car
repair depot (hereafter CRD)
                (7600 - PLANNED REPAIR WITH STENCIL PLACING)
                (3108 - MOUNTING DURABLE TROLLEYS MODEL 18-100 )
                (2158 - MODIFICATION OF THE FIXATION UNIT, BRAKE SHOE)
                (1213 - MODERNIZING THE LOCK OF THE COVERED CARS DOORS)
 6  INSPECTION  DECEMBER 04, 2016   92 EAST-SIBERIAN R/W   4126 DCP-13 TAISHET RR
JSC
                (102 - THIN RIB)
                (107 - SHELLING OF THE DRIVING WHEEL)
 7  INSPECTION  JANUARY 07,   2017  92 EAST-SIBERIAN R/W   4126 DCP-13 TAISHET RR
JSC
                (574 - ADVANCED DELIVERY TO DEPOT REPAIR DUE TO TECHNICAL CONDITION)

 8  INSPECTION  FEBRUARY 09,  2017  92 EAST-SIBERIAN R/W   4126 DCP-13 TAISHET RR
JSC
                (107 - SHELLING OF THE DRIVING WHEEL)
                (219 - RAISING/LOWING THE FRICTION WEDGE RELATIVE TO SUPPORTING
SURFACE)
 9  INSPECTION  FEBRUARY 17,  2017  92 EAST-SIBERIAN R/W   4126 DCP-13 TAISHET RR
JSC
                (574 - ADVANCED DELIVERY TO DEPOT REPAIR DUE TO TECHNICAL CONDITION)

10  RUN-2       FEBRUARY 17,  2017  92 EAST-SIBERIAN R/W   4126 DCP-13 TAISHET RR
JSC
                (107 - SHELLING OF THE DRIVING WHEEL)
11  RUN-2       SEPTEMBER 14, 2017  61 VOLGA R/W           4129 DCP-10 ASTRAKHAN
R/W
                (211 - CAP SLIDER CRACK)
12  DEP.        -- -------- ----    68 KAZAKHSTAN R/W      4035 DCP-3 UTALSK
                (570 - EXPIRED CALENDAR SCHEDULE)
13  DEP.        OCTOBER 27,  2017   68 KKAZAKHSTAN R/W/    684 DCP URALSK -
KAZNEMIRTRANS JSC BRANCH
                (7600 - PLANNED REPAIR WITH STENCUL PLACING)
                (3108 - MOUNTING DURABLE TROLLEYS MODEL 18-100 )
14  RUN-2       OCTOBER 05,  2018   85 CRIMEAN R/W         1507 DCP JANKOI R/W
                (214 - SPRING DAMAGE )
                (912 - COMPLAINTS OF THE QUALITY OF THE DEPOT REPAIR )
15  RUN-1       -- -------- ---- Y. 68 KAZAKHSTAN R/W      4046 DCP-30 ARYS
                (214 - SPRING DAMAGE )
16  RUN-1       MAY 27,2019         68 KAZAKHSTAN R/W     4281 ARYSSHPALZAVOD LLP
17  RUN-1       SEPTEMBER 19, 2019  68 KAZAKHSTAN R/W      4047 DCP-26
                (539 - DAMAGE TO THE HATCH COVER AND HINGES)
18  INSPECTION  OCTOBER 08,  2020   68 KAZAKHSTAN R/W      4045 DCP-27 JAMBYL
                (214 - SPRING DAMAGE )
19  DEP.        -- -------- ---- Y. 68 KAZAKHSTAN R/W      613 DCP-8 ASTANA
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```
                (570 - EXPIRED CALENDAR SCHEDULE )
20  DEP.        OCTOBER 16,  2020   68 KAZAKHSTAN R/W      608 DCP BURABAI CRD
                (7600 - PLANNED REPAIR WITH STENCUL PLACING)
                (3108 - MOUNTING DURABLE TROLLEYS MODEL 18-100 )
21  RUN-2       DECEMBER 23,  2022  28 NORTH R/W           4120 DCP-7 LOSTA R/W
OJSC
                (107 - SHELLING OF THE DRIVING WHEEL)
                (537 - DOOR LOCK FAILURE )
                (912 - COMPLAINTS OF THE QUALITY OF THE DEPOT REPAIR)
22  INSPECTION  SEPTEMBER 05, 2023  68 KAZAKHSTAN R/W      4045 DCP-27 JAMBYL
                (537 - DOOR LOCK FAILURE )
23  RUN-1       SEPTEMBER 06, 2023  68 KAZAKHSTAN R/W      4045 DCP-27 JAMBYL
                (537 - DOOR LOCK FAILURE )
                (411 - FAILURE OF THE AUTO PRESS BEAM OR EE MOUNTING)
24  INSPECTION  OCTOBER 03,  2023   68 KAZAKHSTAN R/W      1019 DCP-13 KARAGANDA
                (537 - GOOR LOCK FAILURE )
25  DEP.        -- -------- ----    68 KAZAKHSTAN R/W      1019 DCP-13 KARAGANDA
                (570 - EXPIRED CALENDA SCHEDULE OF THE DEPOT REPAIR )
26  DEP.        OCTOBER 06,  2023   68 KAZAKHSTAN R/W      612 KAMKOR WAGON CRD
BRANCH
                (3108 - MOUNTING DURABLE TROLLEYS MODEL 18-100 )
                (7600 - PLANNED REPAIR WITH STENCUL PLACING)
--- ----------- ------------------- ------------------ ------------------
  INFORMATION OF THE LAST REPAIRS OF CAR NO 28807352
*** REPAIR 26 *** 06.10.23 19:10   ** LAST *****************
     C A R  NO          28807352
DATE OF COMMISSIONING       OCTOBER 06, 2023 16:11
OWNER                       27 KAZAKHSTAN
ROAD                        68   KAZAKHSTAN R/W
REPAIR DEPOT                0612 KAMKOR WAGON CRD BRANCH
TROUBLES                 --
PLANNED REPAIR WAS ASSIGNED BY THE 1 DEPOT ON OCTOBER 16, 2023
TYPE OF THE REPAIR MADE     1 DEPOT
EXCHANGE STATION VU-23      --
NOTIFICATION NUMBER VU-23   --
DATE-TIME OF TROUBLESHOOT    --
REPAIR START                OCTOBER 06,  2023 08:00 EMPTY RUNNING 33329 KM
REPAIR END                  OCTOBER 06,  2023 19:10 LOADED RUNNING 65910 KM
NOTIFICATION NUMBER VU-36   22 f68      (44 6813 8)00
MODERNIZATIONS              3108 MOUNTING DURABLE TROLLEYS MODEL 18-100
                            7600 PLANNED REPAIR WITH STENCUL PLACING
   REPORT 1353 IS ABSENT
*** REPAIR 25 *** 03.10.23 10:42   ** NEAREST TO LAST *************
     C A R  NO              28807352
DATE OF COMMISSIONING       OCTOBER 03,  2023 07:43
OWNER                       27  KAZAKHSTAN
ROAD                        68 KAZAKHSTAN R/W
REPAIR DEPOT                1019   CDC-13 KARAGANDA
TROUBLES                    570 EXPIRED CALENDAR SCHEDULE OF THE DEPOT REPAIR
TYPE OF REPAIR              1 DEPOT
EXCHANGE STATION VU-23      67307
NOTIFICATION NUMBER VU-23   30 F68      (44 6813 8)00
DATE/RIME OF TROUBLE        OCROBER 03,  2023 10:42
REPAIR START        --
REPAIR COMPLETION             --
NOTIFICATION NUMBER VU-36     --
NO MODERNIZATIONS
   REPORT 1354 IS ABSENT
*** REPAIR 24 *** 03.10.23 10:39   ******************************
     C A R  NO              28807352
DATE OF COMMISIIONING       OCTOBER 03,  2023 07:40
OWNER                       27    KAZAKHSTAN
ROAD                        68    KAZAKHSTAN R/W
REPAIR DEPOT                1019    CDC-13 KARAGANDA
TROUNLES                    537 DOOR LOCK DAMAGE
TYPE OF REPAIR              9 INSPECTION
EXCHANGE STATION VU-23      67386
NOTIFICATION NUMBER VU-23   1 F68      (44 6813 8)07
```

```
DATE-TINE OF TROUBLE        OCTOBER 01,  2023 17:49
REPAIR START                OCTOBER 03,  2023 10:38 EMPTY RUNNING 33329 KM
REPAIR END                  OCTOBER 03,  2023 10:39 LOADD RUNNING 65910 KM
NOTIFICATION NUMBER VU-36   0 F68      (44 6813 8)07
NO MODERNIAZATIONS
*********************** REPORT END ***********************
```

Appendix B - The decision-making algorithm for the further operation of the freight car