

Original article

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Evaluation of the Efficiency of the Use of Hopper Cars with Aluminum Alloy Bodies

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ABSTRACT The use of aluminium and its alloys in the world history of car building began in the 30s of the last century. The paper considers various types of cars made using aluminium alloys produced in different countries, as well as an assessment of the effect of the use of cars with bodies made of aluminium alloys in the Russian Federation. The effect was determined for three parties of the transportation process: car owners, the carrier and the consignor. The paper calculated the effect of using a hopper car made of aluminium alloys model 19-1299 with an axle load of 25 tf in comparison with hopper cars with steel bodies with an axial load of 25 and 23.5 tf. It is shown that for the consignor and the carrier, the use of a car with an aluminium body by reducing the tare weight and increasing the carrying capacity brings a significant economic effect, at the same time, as for the owner of the car, there is a reasonable increase in the price of the car by 25–30 %. The purchase of cars with aluminum bodies is more expensive for the owner, and therefore it is necessary to increase the rental rate to compensate for the costs or take measures for state support.

KEYWORDS: aluminium cars; car building; aluminium alloys; innovative cars, hopper car

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Научная статья

Оценка эффективности использования вагонов-хопперов с кузовами из алюминиевых сплавов

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АННОТАЦИЯ Применение алюминия и его сплавов в мировой истории вагоностроения началось в 30-х годах прошлого века. Рассмотрены различные типы вагонов, изготовленные с помощью алюминиевых сплавов производства разных стран. Проведена оценка эффекта от применения вагонов с кузовами из алюминиевых сплавов в РФ. Эффект определялся для трех сторон перевозочного процесса: собственников вагонов, перевозчика и грузоотправителя.

Представлен расчет эффекта от применения вагона-хоппера из алюминиевых сплавов модели 19-1299 осевой нагрузкой 25 тс в сравнении с вагонами хопперами с кузовами из стали с осевой нагрузкой 25 и 23,5 тс. Для грузоотправителя

и перевозчика применение вагона с алюминиевым кузовом за счет снижения веса тары и увеличения грузоподъемности приносит значительный экономический эффект в то время, как для собственника вагона имеется обоснованное увеличение цены вагона на 25–30 %. Приобретение вагонов с алюминиевыми кузовами обходится дороже для собственника, в связи с чем необходимо увеличить арендную ставку для компенсации затрат или принять меры по господдержке.

КЛЮЧЕВЫЕ СЛОВА: алюминиевые вагоны; вагоностроение; алюминиевые сплавы, инновационные вагоны, вагон-хоппер

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INTRODUCTION

Nowadays, aluminium and its alloys are widely used in various industries, including car building. This is due to the resumption of work on the development of cars with smaller containers through the use of new materials. Aluminium alloys have satisfactory strength characteristics with higher corrosion resistance and lower specific gravity compared to steels commonly used in car manufacturing [1–4].

In the world history of car building, they started to use aluminium in the USA in the 30s of the XX century together with the production of aluminium hopper cars. Then aluminium was used in the production of high-speed rolling stock, thanks to which it was possible to reduce the cost of traction of trains and reduce the weight of the car body. In the USSR, the production of aluminium passenger cars was limited to the ER200 train [5–7].

For freight traffic of the USSR in 1975 “Ural Car Works” manufactured a pilot gondola car with a load capacity of 66 t with a body made of aluminium alloys for transportation of coal, ore, timber and other bulk cargoes that do not require protection against atmospheric precipitation. The body and frame structure was made of special pressed profiles and panels of high-strength aluminium-magnesium alloy, hatch covers were made of steel. The catalogue-guidebook “Cars of the USSR” provides information about a 6-axle gondola with load capacity of 97 t with aluminium alloy body, but there is no information about their operation [8, 9].

In the Russian Federation, work on the creation of a car made of aluminium alloys began in the early 2000s with “Ural Car Works” producing a prototype gondola car of model 12-568 using aluminium alloys in the body structure. On the basis of aircraft building technologies of “Voronezh Joint Stock Aircraft Building Company” an attempt was made in 2005 to manufacture a gondola car from aluminium alloys, the side and end walls of which consisted of hollow pressed aluminium alloy panels [10, 11].

“Promtractor-Car”, CJSC developed a pilot hopper car made of alloy 1565h with load-carrying capacity of 80 tonnes, but serial production has not started.

At the moment the model range of cars with the use of aluminium alloys is limited. “United Car Company” has developed a hopper car with an aluminium alloy roof. “RM Rail” produced a pilot batch of model 19-1244 hopper cars made of 1565h alloy in 2017, and in 2023 developed a new model 19-1299 hopper car with a body made of 1584 aluminium alloy. “United Car Company” and “RM Rail” have developed aluminium alloy tank cars for the carriage of nitric acid, models 15-6901 and 15-1232-05. However, these developments are still unique in the “1520 area”.

At the same time, more than 200 thousand cars with aluminium alloy bodies are in operation in North America. Why are these cars profitable in America, but not in the 1520 Area?

Aluminium alloy cars manufactured in different countries are shown in the *figure* and their technical characteristics are shown in *Table 1*.

Analysing the data of *Table 1*, it can be concluded that the hopper car of model 19-1299, having steel frame and aluminium body, is somewhat inferior to all-aluminium foreign cars in terms of tare coefficient. The application of steel frame in production and operation, according to the developers, gives a number of advantages to such a car.

The task is to evaluate the effect of using cars with aluminium alloy bodies for three parties of the transportation process: car owners, carrier and consignor.

MATERIALS AND METHODS

Compared items and initial data

Three hopper cars of different models were chosen for efficiency calculations: 19-1299 — axle load of 25 tf, aluminium body; 19-9549 — axle load of 25 tf, steel body; 19-9814 — axle load of 23,5 tf, steel body (*Table 2*).



Fig. Aluminium alloy cars from different countries: a – Aluminum AutoFlood III (USA); b – Steel and Aluminum Triple Hopper Aggregate (USA); c – Small Cube Covered Hopper (USA); d – hopper car, model 19-1299 (Russian Federation); e – Aluminum BethGon II (USA); f – 1060 mm gauge C80H Aluminum Alloy Coal Gondola (PRC); g – tank car, model 15-6901 (Russian Federation); h – tank car, model 15-1232-05 (Russian Federation)

Table 1

Technical characteristics of aluminium alloy cars

Model (trade mark) of the car	Produced in	Type of car	Tare, t	Carrying capacity, t	Cubic capacity, m ³	Empty weight to carrying capacity ratio (tare coefficient)
Aluminum AutoFlood III	USA	Open hopper	22.40	107.32	118.93	0.21
Steel and Aluminum Triple Hopper Aggregate	USA	Open hopper	23.81	105.91	68.81	0.22
Small Cube Covered Hopper	USA	Closed hopper	23.50	106.23	92.94	0.22
19-1299	RF	Closed hopper	21.00	79.00	111.00	0.27
Aluminium BethGon II	USA	Gondola car	18.92	110.82	128.00	0.17
1060mm gauge C80H Aluminium Alloy Coal Gondola car	PRC	Gondola car	20.00	80.00	87.00	0.25
15-6901	RF	Tank car	24.50	75.00	54.78	0.33
15-1232-05	RF	Tank car	20.40	78.60	61.78	0.26

Table 2

Technical characteristics of the compared cars

Model, specific features	Axle load, tf	Carrying capacity, t	Tare, t	Tare coefficient
19-1299 aluminium body	25	79	21	0.265
19-9549 steel body	25	76	24	0.315
19-9814 steel body	23.5	70	24	0.343

Table 3

Guaranteed mechanical properties of the alloy 1581

Type of the item	Alloy	Thickness	Mechanical properties, minimum values	
			σ_n , MPa	$\sigma_{0.2}$, MPa
Flat stock	1581	1.5–6.0	345	205
		6.0–10.5	350	200
		10.5–50.0	350	190
Extruded section	1581	All dimensions	355	215

Table 4

Calculated strength characteristics

Strength class	Yield point σ_p , N/mm ²	Ultimate resistance σ_b , N/mm ²
345	345	490
375	375	510

The body of hopper car model 19-1299 is made of aluminium alloys 1581. Its mechanical properties are given in Table 3.

Car bodies of 19-9549 and 19-9814 models are made of high strength steels according to GOST 19281–2014 and GOST 19903–2015. Calculated characteristics of their strength are given in Table 4.

Evaluation of possible cost increases for the owner when purchasing cars with aluminium alloy structures

When purchasing new cars, the owner is faced with the question of the investment payback period and the

reasonableness of the car price increase when new materials are used.

To compare strength and stiffness materials, the characteristics of specific strength (ratio of strength to specific weight) and specific stiffness (ratio of modulus of elasticity to specific weight) are used. Table 5 summarises the specific strength and stiffness characteristics.

Analysing Table 5, we can conclude that aluminium alloy is 2.1 times more efficient than steel in terms of specific strength by time resistance, and 1.7 times more efficient than steel in terms of specific strength by yield strength. In terms of specific stiffness, the materials are approximately equal. Proceeding from the fact that when designing cars the main calculations are carried out on yield strength, it is possible to conclude that the elements of cars created from aluminium alloy 1581 should be about 1.7 times lighter than steel ones.

In the hopper car model 19-1299 steel body structures weighing 6.6 t were replaced by aluminium alloy structures weighing 3.6 t, i.e. the weight of the replaced structures decreased by 1.83 times. The increase in the price of material alone amounted to

$$C = 3.6t \cdot 340 \cdot 10^3 \text{ rubles/t} - 6.6t \cdot 66 \cdot 10^3 \text{ rubles/t} = 1\,224\,000 - 396\,000 = 828\,000 \text{ rubles.}$$

This is approximately 20 % of the cost of the car.

In addition, the production of aluminium structures requires the purchase of new equipment and the introduction of new welding and assembly technologies. Therefore, a reasonable increase in the price of the car should be estimated at 25–30 %, which should be paid by the owner of the car. To compensate for these costs, the owner should increase the fee for leasing the car to consignors.

Effect for the carrier from the reduction of train traction costs

In order to evaluate the effect, a comparative calculation of energy consumption and train traction costs was carried out when carrying out transport work of $3.6 \cdot 10^6$ net tonnes, which is approximately equal to the average annual work of a hopper car.

Table 5

Specific strength and stiffness values

Material	Density, t/m ³	Strength class, σ_b , MPa	Yield point, σ_p ($\sigma_{0.2}$), N/mm ²	Specific strength by ultimate tensile strength, $\sigma_b/\rho g$, km	Specific strength at yield point, $\sigma_{0.2}/\rho g$, km	Specific stiffness, $E/\rho g \cdot 10$, km
Aluminium alloy 1581	2.7	350	200	12.96	7.4	2.59
High-tensile steel 345	7.8	480	345	6.11	4.39	2.54

Table 6

Calculations of energy required to perform transport works $3,6 \cdot 10^6$ tkm net

Model	$(1 + k_r)$	Specific resistance $w, \text{ n/t}$	Transport works $A, \text{ tkm net}$	Energy consumption $\Pi, \text{ GJ}$	Saved energy $\Delta, \text{ GJ}$
19-1299	1,265	12,39	$3,6 \cdot 10^6$	56,42	–
19-9549	1,315	12,39	$3,6 \cdot 10^6$	58,65	2,23
19-9814	1,343	12,8	$3,6 \cdot 10^6$	59,9	3,48

Table 7

Results of calculation of savings from the use of aluminium alloy hopper car in loaded mode

Comparison vs cars with axle load, tf	Energy saving for empty car traction, GJ	Electricity savings, kWh	Cost of saved electricity at the price of 4 rubles/kWh	Diesel fuel savings, kg	Cost of saved diesel fuel at the price of 45 rubles/kg	Total traction savings
25	2.23	1756	7,024	66.09	2,974	9,998
23.5	3.43	2701	10,804	103.14	4,641	15,445

Table 8

Results of calculation of savings from the use of aluminium alloy hopper car in empty mode

Comparison vs cars with axle load, tonnes	Energy saving for empty car traction, GJ	Electricity savings, kWh	Cost of saved electricity at the price of 4 rubles/kWh	Diesel fuel savings, kg	Cost of saved diesel fuel at the price of 45 rubles/kg	Total traction savings
25	2.25	1772	7,088	66.69	3,001	10,089
23.5	5.79	4560	18,240	171.61	7,722	25,962

Energy costs for overcoming the main resistance to movement were determined in accordance with the following papers [12, 13]:

$$\Pi_{\text{э,тп}} = (1 + k_r)w(v, q_0)A, \quad (1)$$

where $k_r = m_r/m_t$ — car tare coefficient; v — velocity; $w(v, q_0)$ — basic specific resistance of the car, depending on the average speed v and axle load q_0 ; $A = 3,6 \cdot 10^6 \text{ tkm net}$ — conditional volume of transport works per year (Table 6).

The results of calculation of energy resources saving in loaded mode for the volume of performed trans-

port work of $3.6 \cdot 10^6$ net tonnes are given in Table 7. Here it is assumed that 85 % of the work is performed on electric traction, 15 % — on diesel traction.

The results of energy calculation for empty cars transportation when carrying out transport works of $3.6 \cdot 10^6$ net tonne kilometres are given in Table 8.

Total savings from the use of aluminium alloy hopper car are presented in Table 9.

This calculation explains the popularity of aluminium cars in North America. Trains there are driven by diesel locomotives and the cost of diesel fuel is 4 times higher. For American railways, the value of saved fuel would be 1831 kg and the cost in rubles would be 329,690 rubles, i.e. the effect is almost 8 times greater. But for Russian railways, the effect is also tangible.

Table 9

Results of calculation of traction savings from the use of aluminium alloy hopper car in loaded and empty modes

Comparison vs cars with axle load, tf	Savings, rubles
25	20,087
23.5	41,407

Effect for the carrier from change in railway track maintenance costs as a result of operation of cars with aluminium body with smaller tare

The change in railway maintenance costs as a result of the operation of cars with aluminium body is carried

¹ Methodology for assessing the economic efficiency of the operation of innovative freight cars on the railway infrastructure of Russian Railways (approved by the Order of the Ministry of Transport of the Russian Federation No.457 dated 23.10.2017).

Table 10

Characteristics of the cars compared

Model, specific features	Axle load, tf		Carrying capacity, t	Tare, t	Relative change in track load k_{τ}	
	loaded	empty			loaded	empty
19-1299 aluminium body	25	5.25	79	21	–	–
19-9549 steel body	25	6	76	24	1	1.143
19-9814 steel body	23.5	6	70	24	0.94	1.143

Table 11

Calculation of change in railway maintenance costs in loaded mileage

Model	Cargo weight, t	Tare weight, t	Loaded mileage, km	Tkm gross	Damage rate of railway track $k_{\tau \text{ tp}}$	$(m_r^a + m_r^a)L_{\text{tp}}^a$, tkm	$k_{\tau}(m_r^c + m_r^c)L_{\text{tp}}^c$, tkm gross	Change in track impact, tkm	Change in expenses (at an expense rate of 0.02213 rubles/tonne), rubles
19-1299	79	21	45 570	4 557 000	1	4 557 000	–	–	–
19-9549	76	24	47 368	4 736 800	1	–	4 736 800	–179 800	–3,978
19-9814	70	24	51 428	4 834 200	0.78	–	3 770 676	+786 324	+17,401

out for empty and loaded cars and is determined by formulas in accordance with the paper¹:

- when loaded

$$\Delta E_{\text{tp}} = e_{\text{TKM}}((m_r^a + m_r^a)L_{\text{tp}}^a - k_{\tau \text{ tp}}(m_r^c + m_r^c)L_{\text{tp}}^c); \quad (2)$$

- when empty

$$\Delta E_{\text{nop}} = e_{\text{TKM}}(m_r^a L_{\text{nop}}^a - k_{\tau \text{ nop}} m_r^c L_{\text{nop}}^c), \quad (3)$$

where e_{TKM} – consumption rate per gross metered tonne kilometre in freight traffic, rubles/tkm; m_r^a and m_r^c – weight of cargo in steel and aluminium car, respectively; m_r^a and m_r^c – tare weight of steel and aluminium car; $k_{\tau \text{ nop}}$ and $k_{\tau \text{ tp}}$ – coefficients reflecting the change in the impact of vertical and horizontal forces of an aluminium car on the track compared to a steel car in empty and loaded runs.

Coefficient k_{τ} is defined from the expression

$$k_{\tau} = \gamma_B \cdot \left(\frac{Q_1}{Q_2}\right)^{\chi} + \gamma_{\text{VB}} \cdot \left(\frac{\sqrt{Q_1^2 + Y_1^2}}{\sqrt{Q_2^2 + Y_2^2}}\right)^{\chi}, \quad (4)$$

where γ_B – share of railway track damage associated with the impact of vertical forces – railway alignment, wear of rail pads, filler pieces, filler piece pads, sleepers (ranges from 0.60 to 0.65); Q_1/Q_2 – ratio of the maximum probable vertical dynamic force exerted by the wheels of the innovative car Q_1 to the same strength of the analogue car Q_2 , which shows how much the impact on the path has changed in the vertical direction;

the force relations are raised to a degree of χ ($\chi = 4$), which takes into account the accepted relationship between the force impact on the railway track F and the damage to its components: $D \sim F^{\chi}$; γ_{BB} – share of railway track damage associated with the total impact of vertical and lateral forces – straightening, track gauge adjustment, rail, bolt and screw replacements, wear of lining pads in steep curves, insulating elements of

fastenings (makes 0.35–0.40); $\frac{\sqrt{Q_1^2 + Y_1^2}}{\sqrt{Q_2^2 + Y_2^2}}$ – ratio, which

shows how much the impact on the track has changed in the vertical and horizontal directions in total; Y_1 , Y_2 – maximum probable lateral dynamic force of the car and its analogue, respectively.

Due to the lack of experimental data, the changes in vertical and horizontal forces were determined theoretically, taking into account that their changes are directly proportional to the axial load.

This representation is an estimate from above, because the results of experiments with bogies with a load of 25 tonnes showed a smaller increase in the coefficient of k_{τ} .

Expenditure rate RS-51 for measuring gross tonnes per 1000 gross tonnes of track structure was assumed to be average for the network and amounted to 22.13 rubles per 1000 gross tonnes².

The initial data for the calculation are shown in Table 10–13.

² Expenditure rates determined on the basis of the volume-dependent expenses of “Russian Railways”, JSC for transportation activities // “Russian Railways”, JSC. 2023.

Table 12

Calculation of change in railway maintenance costs in empty mileage

Model	Tare weight, t	Loaded mileage, km	Tkm gross	Damage rate of railway track $k_{\text{тп}}$	$(m_r^a + m_r^b)L_{\text{тп}}^a$, tkm	$k_{\text{тп}}(m_r^c + m_r^d)L_{\text{тп}}^c$, tkm gross	Change in track impact, tkm	Change in expenses (at an expense rate of 0.02213 rubles/tonne), rubles
19-1299	21	45 570	956 970	1	956 970	–	–	–
19-9549	24	47 368	1 136 832	1,7	–	1 932 600	–975 630	–21,590
19-9814	24	51 428	1 234 272	1,7	–	2 098 262	–1 141 290	–25,256

Table 13

Results of calculation of savings from application of aluminium alloy hopper car in loaded and empty modes from reduction of track maintenance costs

Comparison vs cars with axle load, tf	Savings, rubles
25	25,568
23.5	7,855

The reduction in the cost of maintaining the railway track structure for an aluminium alloy hopper car with an axle load of 25 tf and a tare coefficient of 0.265 will be:

- compared to a steel hopper car with an axle load of 25 tonnes and tare coefficient of 0.315–0.0025 rubles/km (11 % of the cost rate);
- compared to a steel hopper car with 23.5 tonnes axle load and tare coefficient 0.343–0.0007 rubles/tkm (3 % of the cost rate).

So, the use of cars with aluminium alloy body brings effect to the carrier both in terms of reduction of train traction costs and track maintenance costs.

Effect for the consignor from reduction of tariff costs when cargo is transported in a car with a higher carrying capacity

The peculiarity of the current Price List is the independence of the tariff from the amount of cargo in

the car, the tariff mainly depends on the distance of carriage. Therefore, at the considered transport work of $3,6 \cdot 10^6$ tkm net the consignor, sending the cargo in a car with a higher carrying capacity, reduces the number of consignments and due to this saves expenses for tariff payment in loaded mode. The results of calculations are given in Table 14.

Thus, the consignor receives the main savings from the use of cars with increased load capacity.

RESULTS OF THE STUDY

The use of cars with aluminium body brings benefits to the freight carrier and consignor, as well as to the national economy in general. Cost savings for the annual volume of transport work $3.6 \cdot 10^6$ tkm net when operating an aluminium hopper car of 12-1299 model will amount to:

- for the carrier due to saving of fuel costs for traction of trains in comparison with steel cars with axial load of 25 tf – 20,087 rubles, in comparison with cars with axial load of 23.5 tf – 41,407 rubles;
- for the carrier due to reduction of track maintenance costs in comparison with steel cars with axial load of 25 tf – 25,568 rubles, in comparison with cars with axial load of 23.5 tf – 7,855 rubles;
- for the consignor due to reduction of expenses for tariff payment in comparison with steel cars with axial load of 25 tf – 188,980 rubles, in comparison with cars with axial load of 23.5 tf – 416,940 rubles.

Table 14

Results of calculation of savings from the use of hopper car due to reduction of tariff costs (range ~1700 km)

Car model	Carrying capacity, t	Loaded mileage, km	Increase in length of loaded mileage, km	Savings on tariff payment for loaded mileage*, rubles	Savings on payment of empty mileage tariff*, rubles	Total
19-1299	79	45 570	–	–	–	–
19-9549	76	47 368	1798	87,720	51,260	138,980
19-9814	70	51 428	5858	263,160	153,780	416,940

Note: * – calculation according to ETRAN program.

CONCLUSION

It is more expensive for the car owner to purchase cars with aluminium bodies. In order to compensate for the increased costs, it is advisable for the car owner to increase the lease rate or to take measures for state support for the purchase of cars with smaller containers.

The widespread use of aluminium alloy cars in North America is due to energy savings for traction by diesel locomotives, which have lower efficiency compared to electric locomotives, and the high cost of diesel fuel compared to fuel prices in the Russian Federation.

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