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Estimated Transportation Cost of Low-Tonnage LNG

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ABSTRACT

Demand for low-tonnage transportation of LNG requires improved logistics. Assessing the value of all parts of the supply chain is an important component of solving the problem of optimizing transportation costs for both consumers and LNG suppliers. In connection with tightening of environmental requirements regarding bunker fuel, the task of optimizing the supply of LNG for water transport by the cost of transportation becomes particularly relevant.

The objective of the study is to develop a universal approach to estimating the cost of transporting low-tonnage LNG for bunkering vessels in the Russian Federation.

The research methodology is focused on the analytical method based on a system-structural approach.

As part of the departmental project of the Russian Ministry of Industry and Trade «Development of gas-powered fleet for navigation in coastal waters and inland waterways», the authors developed technical and economic models for calculating the unit cost of LNG transportation by road and water. To calculate the unit cost of LNG transportation by rail, the data of TMkarta information and reference system were used.

Based on model calculations and data of TMkarta system, regression relations were obtained that allow one to determine the cost of transportation for various options of transport and technological schemes based on a limited set of parameters. An approach has also been proposed for estimating the cost of LNG transshipment. The regression ratios were tested for selected routes. As a result, conclusions were drawn about the most effective LNG transportation options.

Keywords: LNG, logistics, transport, unit cost of transportation, cost items, tank container, tank, regression ratios, road transport, inland water transportation.

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Background. In recent years, demand for low-tonnage transportation of liquefied natural gas (LNG) has been steadily growing in Russia. This is due to both an increase in the number of consumers and the need to limit emissions of harmful substances into the atmosphere. Prospects for the use of LNG are associated with its use as fuel for various vessels and public urban traffic, as well as for heat and electricity supply of communities and industrial facilities. So, according to the authors of the article, the increase in production of low-tonnage LNG for the period from 2014 to 2018 has amounted to 88,9 thousand tons. According to estimates [1, p. 163], over the next 15 years, the installed capacity of LNG small-scale plants in Russia will exceed 5 million tons, that is, it will increase by 35 times compared to 2017. In addition to environmental reasons, the increase in LNG consumption is due to factors such as low cost of gas compared to other energy carriers, economically efficient consumption, and availability of well-developed domestic technologies for its production. All this contributes to a favorable forecast for development of the domestic low-tonnage LNG market [2; 3].

Currently, in many regions of Russia, the infrastructure necessary for transportation and storage of low-tonnage LNG is underdeveloped; its creation should be carried out practically from scratch. It is known that LNG can be transported by various modes of transport: road, rail, and water ones. Moreover, for each mode of transport, two alternative delivery methods are possible: in bulk or in tank containers [4–6]. The lack of ready-made infrastructure solutions and the wide range of potentially possible logistic schemes for LNG transportation leads to the relevance of statement and solution of the problems of determining the optimal layout of the transportation system and justification of the location of LNG production facilities. Such tasks belong to the field of strategic logistics planning and are solved within the framework of a formal mathematical formulation, which allows finding the optimal logistic scheme for each scenario of changes in cargo flows and the location of LNG production and consumption sites. The logistics scheme may include several modes of transport and provide for intermediate transshipment of liquefied gas if it proves to be economically feasible. Therefore, estimating the cost of transporting LNG by road, rail and water transport in bulk and in tank containers is one of the key aspects of practical implementation of strategic planning algorithms.

Obtaining such estimates is hampered by the fact that the domestic market for low-tonnage LNG transportation is still being formed and full-scale data on transportation costs are practically unavailable.

Objective. The objective of the study is to develop technical and economic models for determining the integrated efficiency of a vessel LNG bunkering system, considering the costs of its delivery to ports of destination by alternative modes of inland transport.

Methods. To calculate the estimated cost of LNG transportation, technical and economic methods and models were used that consider various technical, organizational and economic features, the regulatory framework currently applied in Russia, and the multiplicity of technical and operational parameters.

Results.

1. General approach to estimating the cost of LNG transportation by various modes of transport

To obtain estimates of the cost of transportation of low-tonnage LNG by road and inland water transport, technical and economic models of the specialized motor transport enterprise (SME) and of the specialized shipping company (SSC) operating on inland waterways were created. It is assumed that those companies transport LNG in bulk and in tank containers on an ongoing basis on the selected line. The input parameters of each model comprise cargo flow, transportation distance (mileage with cargo), as well as a set of technical and operational and cost parameters that allow calculating the total cost of transportation, taking into account all cost items. The implementation features of these models are described below. To obtain estimates of the cost of LNG transportation by rail, we used the data of TMkarta[1] information and reference system, which allows us to calculate the freightage charged by JSC Russian Railways for transportation in Russia, taking into account current information on the railway transport and tariff network, and plans for

[1] [Electronic resource]: http://www.tmkarta.com/ru/about/long.php.

formation of cargo trains, a unified tariff-statistical and harmonized nomenclature of goods.

However, the direct use of technical and economic models in the problems of logistics planning is rather inconvenient since it requires input and control of many local parameters and cost indicators [7–11].

In case of railway transportation, mass requests addressed to TMkarta system will significantly slow down operation of calculation algorithms. Therefore, in the present work, based on model calculations and data from TMkarta system, regression relations were obtained that allow one to determine the cost of transportation based on a limited set of parameters.

To ensure the relevance of the created regression dependencies, which include cost indicators at the date of the calculation, the structure of these dependencies was formed in such a way as to provide the opportunity to adjust the results with regard to the current date taking into account inflation, changes in fuel and vehicles costs, and adjustments in railway transportation tariffs.

Costs *C* for LNG transportation for all modes of transport are determined by the ratio:

$$C = (c + c_t) \cdot t \cdot Q \cdot L_{cargo}, \quad (1)$$

where c is the unit cost of transportation, rub./t • km [further on *rub*. means RUB, Russian ruble – *ed. note*];

c_t is the unit cost of using tare, rub./t • km;

Q is the transportation intensity, t/days;

L_{cargo} is the distance run with cargo (one-way), km;

t is duration of transportation period, days.

The unit cost of transportation c is determined based on regression formulas, to obtain them the following ranges of changes in cargo flow and distance were taken:

$20 < Q < 5000$, t/days;

$20 < L_{cargo} < 2000$, km.

The number of vehicles N_{tr} necessary for ensuring the intensity Q, as well as the required number of tare units (tank containers or tanks) N_{tare} are determined by the ratios:

$$N_{tr} = (Q \cdot T_{round})/(M_{LNG} \cdot k_{use});$$
$$N_{tare} = n_{un} \cdot (N_{tr} + 2), \quad (2)$$

where T_{round} means duration of a round trip, days;

M_{LNG} is the carrying capacity (for transporting of LNG) of a vehicle (vessel, gas carrier or container vessel, train), t;

n_{un} is the number of tare units per vehicle, pcs.;

k_{use} is the coefficient of the use of vehicles during the transportation period, determined by the working time regime and rest time of drivers, the need to service vehicles, etc. (k_{use} = 0,49 is accepted for road transport, k_{use} = 1,0 for others).

The number of N_{tare} in the formula (2) is determined on the basis of the assumption that at the destination and at the point of departure there are additional sets of containers with which cargo operations are performed while vehicles are moving.

When calculating unit cost of transportation, the following assumptions were made:

1. For convenience of accounting for taxes, insurance contributions, duties, and various standards in the models of SME and SSC, one year is taken as the period for determining the unit cost. The calculation of the value of *c* is carried out by dividing the annual costs by the total amount of transported cargo and laden running mileage. A change in duration of the transportation period, which is modelled by the parameter *t* in formula (1), does not lead to a significant change in the specific indicator *c*.

2. The calculations of all costs were made using October 2018 prices.

3. Since the organizations involved in the LNG supply chain are generally large, they are required to apply a common taxation system and are VAT payers. It is known that these organizations can reimburse the paid (incoming) VAT from their suppliers. Therefore, when calculating the cost of works/services, the costs of the relevant cost items are considered with VAT. Attraction of credit funds is not assumed.

4. When transporting LNG in bulk by road and water transport, the cost of containers in which gas is transported is considered in the unit cost of transportation, since such tanks are an integral part of vehicles. In case of container transportation, the cost of containers is not included in transport costs but is considered as part of c_t.

5. When transporting LNG by rail, the cost of tank cars and tank containers is not taken into account in the unit cost of transportation c but should be calculated separately as the unit cost of tare c_t since JSC Russian Railways currently has virtually no own capacity for LNG transportation [1, p. 94].

6. When determining the unit cost of transportation, the characteristics of vehicles do not vary, that is, specific types of tank cars, tank containers and railway tanks are accepted, which are the most common and affordable in modern conditions. Inland water LNG carriers are accepted as LNG carrying vessels with maximum dimensions permissible under the limitations of the Russian Single deep-water system (SWS).

To determine the most influential factors in SME and SSC models, we analyzed the sensitivity of each model, in which the variables varied within their characteristic range. The variables that have the greatest impact have been included in the number of parameters of the regression formulas for determining the parameter *c*. In addition to transportation costs, information on duration of all links in the gas supply chain, including duration of cargo operations, is also given below.

To compare all the possible options for delivery of low-tonnage LNG, it is necessary to evaluate the unit cost of using tare c_t. There are many organizational patterns of ownership of cargo tanks (purchase of new and used equipment, rental, leasing), in which the costs vary significantly and are calculated differently. In this paper, a simplified approach is used, in which the calculation of c_t considers only the costs of depreciation and maintenance of tare:

$$c_t = (k_{main} \cdot C_{tare} \cdot N_{tare}) / (T_{ser} \cdot T_{oper} \cdot Q \cdot L_{cargo}), \quad (3)$$

where C_{tare} is the cost of a unit of tare, rub.;

T_{ser} is service life of tare, years;

k_{main} is the coefficient that determines the level of annual costs of maintenance and repair of cargo tanks (for tank car, $k_{main} = 1,05$ is taken, for tank containers $k_{main} = 1,07$);

T_{oper} – number of days of vehicle operation during the year, which account for depreciation of tare, days.

Further, when making the calculations, the following assumptions are made:

- cost of the tank container of type KCM 40/0,7 according to the manufacturer[2] is 9952000 rub.;
- cost of the tank car of type 15–5106 is taken by adjusting the data [1, p. 94] on the calculation date and amounts to 17700000 rub.;
- $T_{ser} = 20$ years; $T_{oper} = 365$ days for railway transport, $T_{oper} = 240$ days for road transport and is equal to the navigation period (T_n) in case of water transport;
- N_{tare} is determined by formula (2).

2. Road transport

When modelling LNG transportation by road, the requirements of ADR (The European Agreement concerning the International Carriage of Dangerous Goods by Road [12]), the Rules on the Carriage of Goods by Road and a number of other regulatory documents and regulations obliging the carrier to fulfill special requirements for transportation of dangerous goods and bear the associated costs are considered. The estimated cost is adjusted by the factor of profitability of road cargo transport, equal to 4 % [13].

The round-trip time of a road train is determined as a function of distance of transportation using the regression dependence obtained through processing 95 routes using Yandex.Maps service, considering the maximum travel time along the shortest route without using toll high-speed sections of routes and taking into account the absence of traffic jams on the route and at the places of loading/unloading. The duration of a round trip also includes the duration of cargo operations, however, it is small (up to 2,5 hours) and does not significantly affect the results. When calculating the number of trips made by drivers per shift, compliance with the requirements established by the Order of the Ministry of Transport of Russia dated August 20, 2004 No. 15 is checked, since considering the total of drivers' working hours, driving time per driver per week cannot exceed 56 hours. Transportation is carried out year-round.

Since in Russia, in bulk transportation of LNG by road, tank trucks with a volume of about 50 m^3 are used, containing up to 20 tons of LNG [14], gas carrying truck of type GT7 LNG PPCT-52[3] with a carrying capacity of 18,14 tons was chosen as a sample tank truck. A tank container of type KCM-40/0,7[4] with a carrying capacity of 14,28 tons, which corresponds to the dimensions of a standard 40-foot container was chosen as a sample LNG

[2] [Electronic resource]: http://www.cryont.ru/company/bas/store.

[3] [Electronic resource]: http://gt7.ru/catalog-tr/transportirovshchiki-spg/spg-pptst-52/.

[4] [Electronic resource]: http://www.cryont.ru/production/.

Table 1

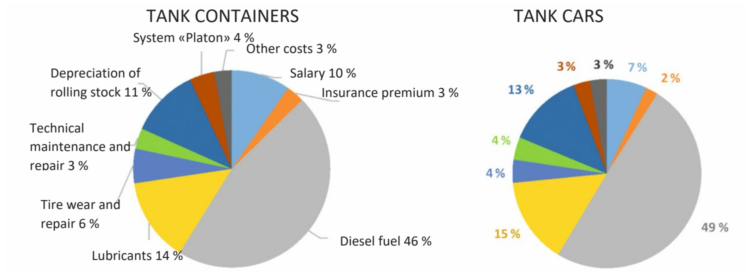
The procedure for calculating costs by cost items for LNG road transportation

Cost item	Calculation procedure
Salary:	
– drivers	average for the region for driver license of category C, CE for vacancies published on the site www.avito.ru.
– administrative and supervising/ managerial staff	average for the region for the required list of job positions for vacancies published on the site www.avito.ru (the number is taken in the range of 10–15 % of the number of drivers, but not less than four).
Insurance premium:	
– pension, social and medical insurance	in accordance with established tariffs and base for calculation of insurance premium as in 2018 (Articles 425, 426 of the Tax Code of the Russian Federation).
– injuries insurance	depending on the class of professional risk of the insurer, established in accordance with OKVED [Russian National Classification of Economic Activities] 249.41.1.
Fuel and lubricants:	
– consumption	in accordance with the Fuel and Lubricant Consumption Standards for Road Transport (Decree of the Ministry of Transport of the Russian Federation No. AM-23-r dated March 14, 2008 as amended on July 14, 2015).
– price of diesel fuel	average price in the region according to the site http://www.benzin-price.ru.
– price of lubricants	selection of brands of lubricants is performed using the website http://oil2.ru based on technical characteristics of the articulated lorry and on the prices of lubricants published on the Website www.auto.ru.
Technical maintenance and repair:	
	by types of technical maintenance according to GOST [State standard] 21624-81, costs assumed to be at a rate of 3 % of the cost of vehicles.
Tire wear and repair:	
– tire mileage standard	in accordance with the methodology RD3112199-1085-02, approved by the Ministry of Transport.
– tire price	depending on the brand of tires for tractors of articulated lorries and semi-trailers for all-season models published on the site www.auto.ru.
– cost of tire mounting	the sum of costs of removal/installation, balancing and tire recycling according to the prices published on specialized sites.
Depreciation of rolling stock:	
	in accordance with the Decree of the Government of the Russian Federation dated 01.01.2002, No. 1 (as amended on April 28, 2018) «On classification of fixed assets included in depreciation groups» and Art. 259.1 part 2 of the Tax Code of the Russian Federation.
«Platon» [Platon Electronic Toll Collection] system:	
	in accordance with the Decree of the Government of the Russian Federation dated 03.11.2015, No. 1191 as amended on June 28, 2018, paragraph 4, Article 31.1 of the Federal Law of 08.11.2007, No. 257-FZ.
Other costs:	
	include cleaning, parking, equipment, pre-trip and post-trip technical inspections for obtaining a diagnostic card for vehicles, compulsory motor third-party liability insurance policies, fees for registering vehicles, medical examinations and outfit of drivers, office rental, staff training, banking services; are calculated in the amount of 3 % of the amount of costs of the main cost items.

tank container. Models of an articulated lorry with a container semi-trailer were selected in accordance with the technical characteristics of the cargo tanks.

The main data sources, the used regulatory documents and the calculation procedure for the main cost items are shown in Table 1.

Pic. 1 shows the ratio of items of transportation costs for conditions that are further referred to as «basic» and are determined by the following parameters: transportation intensity – 500 t/day, distance – 500 km, fuel cost – 48 rub./l, tractor/tank/semi-trailer cost – 7,5/8,66/ 2,35 mln rub. accordingly, the same mileage with cargo and when empty, salary of drivers/supervisors – 64/52 thous. rub. per month. It can be seen that the differences in the structure of transportation costs in tank trucks and tank containers are insignificant and are determined mainly by differences in capacity of tanks, number of drivers and cost of vehicles.



Pic. 1. The cost structure of a motor transport enterprise under basic conditions.

Unit cost of transportation under the base scenario for tank trucks and tank containers is 7,6 and 6,9 rub./t • km excluding VAT. With the accepted load capacity of road trains, this is equivalent to 138 and 99 rub./km respectively. Accounting for the cost of tank containers based on formulas (2) and (3) does not lead to a large increase in the cost of transportation, since the required number of tank containers is small. So, under basic conditions, 47 tank containers are needed. This leads to an increase in the unit cost of transportation from 6,9 to 7,3 rub./t • km (c_t = 0,4 rub./t • km) or to 104 rub./km.

Estimated data can be compared with available data on cost of transportation by road. It should be noted that in dependence (1) only laden mileage is taken into account, while traditionally tariff rates for road transportation also include empty miles. Taking into account that in the considered example, empty miles are equal to laden mileage, we divide the obtained values by 2 and get the following estimates of the previously mentioned costs: 69, 50 and 52 rub./km.

These values can be compared with the price list of the company TransAvtoTsisterna (TransAuto Tank] LLC [15], which carries out transportation in tank trucks at a price of 50 rub./km, and with the data of AvtoPravo-zashchita.Ru website [16], where the cost of trucking is estimated at 55–155 rub./km, and the cost of transporting ordinary goods by road trains with a carrying capacity of 20 tons over long distances varies from 30 to 57 rub./km. Comparison of the data obtained allows us to conclude that LNG transportation is in the upper price category, but does not go beyond the range of values characteristic of road transport.

Further, the analysis of sensitivity of SME model was performed, which showed that the greatest influence on the value *c* is exerted by distance of transportation (0,93), fuel price

Table 2

Regression coefficients

Coefficient	Tank containers	Tank cars
a_1	0,024	0,032
a_2	2,501	2,055
a_3	0,018	0,011
a_4	36,20	38,02
a_5	-0,486	-0,548
a_6	0,119	0,096
a_7	0,738	0,702
a_8	2,598	2,771

(0,48) and fraction of empty miles (0,33). The values of the conditional coefficient characterizing the degree of influence of each factor are indicated in parentheses. Based on these data, after performing a series of mass numerical experiments with SME model, the following regression dependence was obtained to determine the unit cost of road transportation:

$$c_{road} = k_{pr} \cdot (c_{fl} + c_{oth} \cdot k_{cpi}), \quad (4)$$

where c_{fl} are unit costs for diesel fuel and lubricants;

c_{oth} are other unit costs;

k_{cpi} is the coefficient of consumer price index for goods and services, taken according to the data of the Federal Statistics Service [17], based on the fact that these estimated indicators were obtained in October 2018;

k_{pr} = 1,04 – coefficient, considering profitability of transportation.

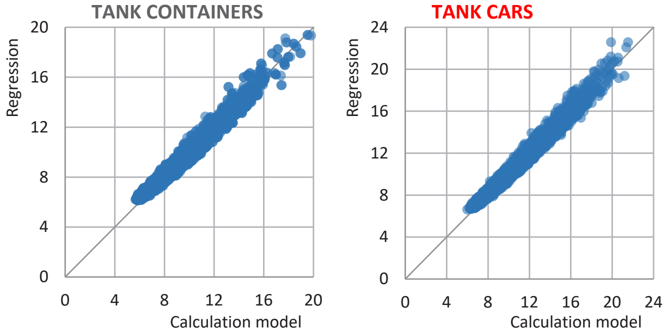
Unit costs in formula (4) are determined according to the following ratio:

$$c_{fl} = a_1 \cdot (L_{empty}/L_{cargo} + a_2) \cdot c_{fuel}; \quad (5)$$

$$c_{oth} = \left[(a_3 \cdot Q + a_4)\left(L_{cargo}\right)^{a_5 \cdot Q^{a_6}} + a_7\right] \cdot \left(L_{empty} / L_{cargo} + a_8\right), \quad (6)$$

where L_{empty} means empty miles, km (taken as $L_{cargo} \le L_{empty} \le 2 \cdot L_{cargo}$);

c_{fuel} is cost of fuel, rub./l (arbitrary range of values);



Pic. 2. Correspondence of the regression values and the results of the design model of SME.

a_1–a_8 are regression coefficients, taken according to Table 2.

Let us note that when constructing dependencies (5) and (6), the following range of possible fuel prices was accepted: $40 < c_{fuel} < 90$. Since formula (5) is approximated with zero errors, which is explained by linearity of the model for determining fuel costs, in practical calculations fuel price can take values from 0 to 1000 rub./l, without leading to an increase in errors of dependence (5). Let us also note that the cost of transportation, determined by the formula (6), does not include the cost of container fleet.

Duration of a round trip T_{road} considering duration of cargo operations is:

$$T_{road} = 0{,}0127 \cdot (L_{cargo} + L_{empty}) + 2{,}5, \text{ hour.} \quad (7)$$

The standard deviation (S) of the dependence is 0,8 hours; the coefficient of determination (R^2) is 0,989, which indicates a high degree of adequacy of the linear model. The average relative approximation error (A) is 8 %, decreasing from 25–40 % for short trips (less than 100 km) to 1–3 % for long distances (more than 1000 km).

To analyze the errors of the regression formula (4) in comparison with the calculations according to the technical and economic model of SME, the following approach was applied. A mass numerical experiment was performed (30 000 runs), during which a set of all its parameters was supplied to the model input each time, and each parameter was randomly selected from an acceptable range of values. The boundaries of the ranges were determined on the basis of the range of different cost indicators that are characteristic of the current time, for example, the cost of the tractor of an articulated lorry varied from 6,0 to 9,0 mln rub., tire price from 18 to 27 thous. rub., and salary of the driver from 50 to 80 thous. rub. per month. The parameters of the regression model were set randomly along with other parameters of the model. This approach provides a comprehensive check of adequacy of the regression model and the degree to which it considers the influence of various factors. The resulting picture of the correspondence of regression and model values is shown in Pic. 2.

The obtained accuracy parameters of the regression model (4) indicate its suitability for practical calculations:

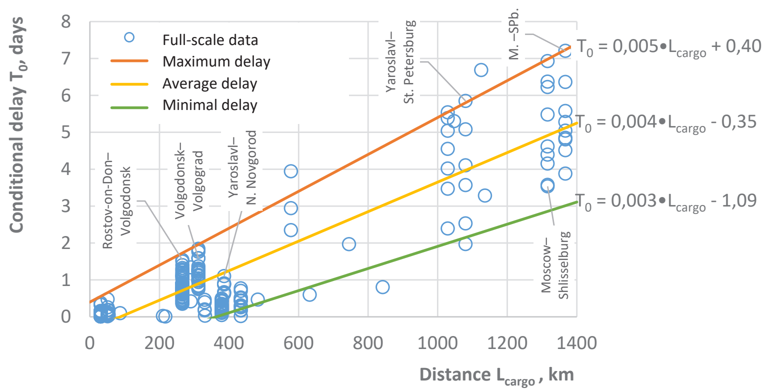
• tank containers S = 0,271 rub./t • km, A = 2,3 %, R^2 = 0,977;

• tank trucks S = 0,275 rub./t • km, A = 2,1 %, R^2 = 0,983.

3. Water transport

The calculation model of SSC is based on the methodology of JSC CNIIMF [Central Marine Research and Design Institute][18], but it takes into account the specifics of the transported cargo and the increased requirements for safety, crew qualifications, technical equipment of the vessel, etc. The logic of calculating the costs when the vessel is operating on the line is similar to the logic used in SME model: first, the total annual costs are determined (during navigation and inter-navigation periods), then they are adjusted for profitability and the specific indicator *c* is calculated.

The vessels with the maximum dimensions according to the restrictions stipulated for SWS were chosen as design vessels for transportation of LNG since such vessels will have the greatest economic efficiency. Since currently there are no built LNG gas carriers for operation on inland waterways (IWW), a design of a draft gas carrier with a capacity of 7100 m³ (100 %) capable of transporting 2500 tons of LNG was taken for bulk transportation. The main



Pic. 3. Conditional delay of a vessel on voyage when moving along SWS routes.

characteristics of the vessel were obtained using data on the gas carrier of project 23070 for transportation of liquefied petroleum gas [19]. The cost of such an LNG gas carrier is estimated at $32 million. A universal vessel with characteristics close to RSD19 project was chosen as a design vessel for container transportation [20]. Its cost is estimated at $18 million. Since transportation of LNG containers is possible only on the open deck [21], the vessel is loaded with only 35 containers of KCM-40/0,7 type, containing 500 tons of LNG, which significantly worsens the economic performance of such a transportation scheme. For certainty, when calculating the cost of shipping containers by water, the possibility of transporting associated cargo in the holds of a vessel was not considered.

An important feature of the operational model of a gas carrier vessel is that the trip time is calculated not according to a predetermined formula, but as a parameter that can vary. This is due to the fact that the vessel's delay on IWW caused by locking, various navigational restrictions and weather conditions, strongly depends on the region of transportation and has a significant impact on the economic efficiency of the entire system, therefore it should be taken into account separately. To do this, the model assumes that the vessel is moving on IWW at the highest operational speed that is characteristic of real voyages, while it is in standby (idle) mode during other periods. To obtain estimates of the duration of real vessel trips within SWS, the analysis of the AIS monitoring data of movement of 14 mixed navigation vessels that made trips between 22 ports located on waterways from Azov to St. Petersburg in 2018 (a total of 260 trips) was performed in 2018. Data was acquired from Marinetraffic[5]. During the analysis, time was determined between the signals about departure from a port and arrival at another port. Then, the conditional running time, determined under the assumption that the vessel is moving at a maximum average cruise speed, which, according to available data, is 18 km/h, was subtracted from the obtained time. The received conditional delay of the vessel in the voyage is shown in Pic. 3 as a function of the distance between the ports (some routes are signed). The picture also shows the parameters of a linear function that characterizes the maximum calculated delay (orange/higher line), the average trip delay (yellow/middle line), and the smallest full-scale delay values (green/lower line).

The average duration of the round trip of the vessel T_{water} under the accepted condition of equality of distances with the load and in the ballast ($L_{cargo} = L_{empty}$) can be determined from the expression

$T_{water} = 2 \cdot (L_{cargo}/18 + T_{port} + 24 \cdot T_0)$, hour, (8)

where T_0 is average duration of conditional delay of a vessel (one-way trip), days;

T_{port} is average duration of operations in a port, taking in account loading-unloading works and auxiliary operations, hour.

As average values in the model it is taken that T_{port} = 5,8 h – for tank containers, T_{port} = 9,3 h – for vessel tanks.

It should be noted that the presented calculation scheme of T_{water} is rather arbitrary. In particular, average speed of the vessel along the river differs significantly from speed of 18 km/h, which is achieved only in sections of rivers without locks or in reservoirs. According to the results of processing about 10 thousand values

[5] [Electronic resource]: https://www.marinetraffic.com.

Table 3

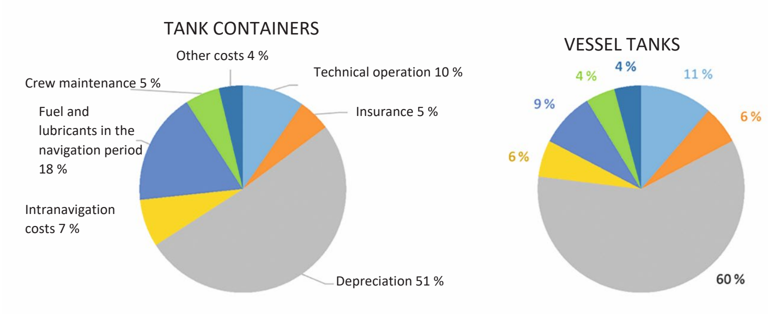
The procedure for calculating costs by cost items for LNG transportation by inland water transport

Cost item	Calculation procedure
Crew costs:	
– payroll	is formed in accordance with the recommendations of the International Transport Workers' Federation based on the currently valid Total Crew Cost agreement.
– food ration	is estimated based on the Decree of the Government of the Russian Federation dated December 7, 2001 No. 861 «On food rations for crews of sea, river vessels and aircraft» and Order of the Ministry of Transport of Russia dated September 30, 2002 No. 122 «On the procedure for providing meals to crews of sea, river vessels and aircraft».
Insurance contributions	0 % until 2027 according to sub-paragraph 4, paragraph 1–2, Art. 427 of the Tax Code of the Russian Federation.
Fuel and lubricants:	
– fuel consumption	is calculated depending on ship power plant and operating modes of the vessel (in operation, during dockage, with cargo loading/unloading operations or without them).
– fuel price	is determined on the basis of information and analytical publications with regard to the base port.
– price of lubricants	4 % of the corresponding fuel costs.
Technical operation:	
– materials and supply	0,1 % of the vessel cost.
– maintenance	0,25 % of the vessel cost.
– average ship repair	3 % of the vessel cost (repair is performed once per 5 years).
Insurance:	
	The standard rate of insurance costs is determined as a percentage of the vessel cost per year by the statistical method based on a database of insurance companies.
Depreciation:	
	is calculated in accordance with the Decree of the Government of the Russian Federation dated 01.01.2002 No. 1 (as amended on April 28, 2018) «On classification of fixed assets included in depreciation groups» and Art. 259.1 of part 2 of the Tax Code of the Russian Federation.
Other costs:	
	include costs for radio communications and navigation, banking services, labor protection and safety measures, training of staff (crew) and are estimated as the amount of 5 % of the total amount of fixed costs.
Internavigational costs:	
	are determined by crew cost and fuel costs during dockage without cargo operations.
Registration and annual confirmation of registration in RMRS [Russian Maritime Register of Shipping]:	
	are calculated as regulated by paragraph 1, sub-paragraphs 108–109 of the Tax Code of the Russian Federation.

of instantaneous speed of vessels, moving at arbitrary points of SWS, it was found that average instantaneous speed is 11,5 km/h, standard deviation S = 3,2 km/h. However, in order to simulate the «fast» LNG delivery, the model takes a speed of 18 km/h. In addition, according to full-scale data, average trip speeds upstream and against the current differ by 0,8–1,2 km/h. However, since the vessel, working on the line, moves in both forward and reverse directions, it was decided to neglect this difference.

The main data sources, regulatory documents used and the procedure for calculating costs by cost items are presented in Table 3.

Pic. 4 shows the ratio of cost items under basic conditions: distance – 500 km, delay on the line (one way) – 1,65 days, fuel price – 25 thous. rub./t, duration of the navigation period – 215 days, gas carrier/container vessel price is 2050/1100 mln rub., the average salary of command/rank staff is 80/38 thous. rub. per month, crew number on gas carrier/ container vessel is of 16/12 people. As it can be seen, the main differences in the cost structure are due to the number of vessels and the difference in



Pic. 4. Cost structure for maintaining vessels during LNG transportation.

their cost, which determines the amount of fuel costs and depreciation of vessels.

Unit cost of transportation under basic conditions is 12,7 rub./t • km for tank containers (excluding their cost) and 4,2 rub./t • km for a bulk method of transportation. If in case of road transportation, the cost of container fleet practically does not affect the cost of transportation, since the number of containers is small due to high speed of delivery, then in case of water transport, taking this factor into account leads to a significant rise in price. So, under basic conditions, 283 containers are needed, which leads to an increase in unit cost of transportation by 2,8 rub./t • km (from 12,7 to 15,5 rub./t • km).

The sensitivity analysis of SSC model was performed similarly to SME model. It was found that the dominant influence on the unit cost *c* is exerted by transportation distance (6,58). Other highly influential factors are vessel delay on the line (0,68), navigation duration (0,39), vessel cost (0,30), and fuel cost (0,17). The transportation intensity has no effect, that is, the absolute costs are directly proportional to the volume of transportation. This is because all costs except fuel costs in SSC model are accepted in fractions of the vessel cost. The significant influence of duration of the navigation period is due to the fact that useful work of the vessel occurs only during navigation, accordingly, all annual costs must be compensated for in this period. Based on this analysis, the structure of the regression dependence was chosen in such a way as to take into account two main pricing factors, which are vessel cost and fuel price, and not to introduce any other parameters that take into account inflation. Unit cost of LNG transportation by water transport is determined by the ratio:

$$c_{water} = k_{pr} \cdot (c_{fl} + c_{oth}), \quad (9)$$

where c_{fl} means unit costs for fuel and lubricants;

c_{oth} means other unit costs;

k_{pr} = 1,035 is the coefficient, considering profitability of transportation.

The cost components in formula (9) are determined by the following relationships:

$$c_{fl} = [(T_0 + b_1)/L_{cargo} + b_2] \cdot c_{fuel}; \quad (10)$$

$$c_{oth} = b_3 \cdot [(b_4 - T_n^{b_5}) \cdot (c_v + b_6) \cdot (T_0 + b_7) / L_{cargo} + (T_0 + 1)^{b_8} + b_9 \cdot c_v], \quad (11)$$

where T_n means duration of navigation, taken in the range from 180 to 365 days;

T_0 varies in the range from 0 to $T_{0\,max} = 0{,}005 \cdot L_{cargo} + 0{,}4$;

L_{cargo} is the distance of transportation (vessel trip with cargo), km;

c_{fuel} is the fuel price, thous. rub./t (arbitrary range of values);

c_v is the vessel cost, mln rub. (arbitrary range of values);

b_1–b_9 are regression coefficients taken according to Table 4.

The model assumed that the distance run by the vessel in ballast is equal to the distance run by a laden vessel. The error analysis of the regression formula (9) was performed in the same way as for SME model. The ranges of variation of various indicators are as follows: the cost of a gas carrier vessel is 1630–2400 mln rub. the cost of a container vessel is 890–1200 mln rub. payroll of command personnel is $1200–1800 per month, that of the rank personnel is $450–900 per month, dollar rate is 50–100 rub./dollar; duration of navigation is 180–365 days.

Correspondence of regression and model values is shown in Pic. 5, which demonstrates a fairly high accuracy of the regression model having the following indicators:

- tank containers S = 0,538 rub./t • km, A = 4,2 %, R^2 = 0,985;
- vessel tanks S = 0,256 rub./t • km, A = 5,0 %, R^2 = 0,980.

Table 4

Regression coefficients

Coefficient	Tank containers	Vessel tanks
b_1	2,0638	0,7639
b_2	0,0773	0,0091
b_3	1,3957	0,4726
b_4	5,5701	3,8432
b_5	0,2808	0,2180
b_6	157,35	130,01
b_7	0,2206	0,3704
b_8	-0,0861	-0,1063
b_9	0,0014	0,0008

4. Railway transport

To obtain the values of the unit cost of LNG delivery by rail, the data of TMkarta system were used. Based on the ranges of distance and transportation intensity specified in formula (1), a calculation matrix was formed that includes 44 routes and 21 values of daily transportation intensity. Routes were chosen in such a way as to ensure a change in distance by increments of 50 km, and so that the geography of transportation would cover the entire European part of Russia. The transportation intensity also varied with a constant step of 250 t/day. Further, for each combination of route and cargo flow, the values of the tariff rate and travel time for bulk and container transportation at low (cargo speed, speed of laden train) and high speeds were determined.

The fee for transportation of goods by rail is calculated for the distance determined in accordance with Tariff Guide No. 4, therefore L_{cargo} is taken equal to the tariff distance. Tariffs for transportation by rail include fee for mileage of loaded and empty wagons with a locomotive and cost of services for using the infrastructure of JSC Russian Railways, while fees for cargo (loading/unloading) operations must be calculated separately. As rolling stock in the calculations, we used a tank car for transportation of LNG and ethylene of model 15–5106 with a carrying capacity of 23,56 tons (bulk transportation), as well as a four-axle fitting platform for transportation of heavy containers and a tank container model KCM-40/0,7 (container transportation). The dimensions and landing dimensions of KCM-40/0,7 allow transporting two loaded tank containers on a single platform [22; 23]. The number of cars in the train was assumed to be 75, that is, a single train carries either 75 tank cars or 150 LNG tank containers. The platform's ownership was indicated in TMcard system as «common fleet», and tank cars and tank containers as its own fleet, that is, neither tanks nor containers are included in the cost of transportation.

The analysis of the obtained data showed that the factors determining the cost of transportation comprise three parameters: cargo flow, distance and urgency of delivery. This made it possible to form the following relationships for determining the unit cost of LNG transportation:

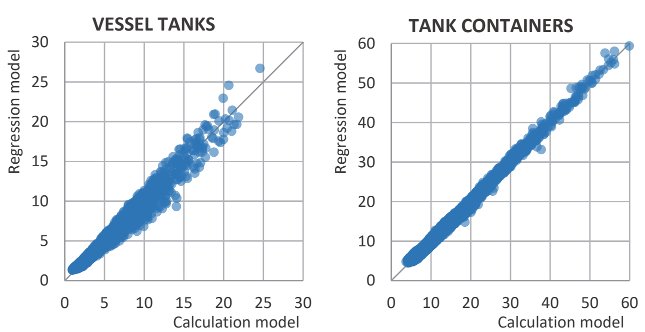
$$c_{railway} = k_{ds} \cdot \left[\frac{e_1 \cdot Q^{e_2 \cdot L_{cargo}^{e_3}}}{\left(L_{cargo}^{e_4} + e_5\right) + e_6 \cdot L_{cargo}^{e_7}} \right], \quad (12)$$

where k_{bs} is the coefficient of delivery speed, determined according to the ratio:

$$k_{ds} = \begin{cases} 1, & \text{low speed;} \\ e_8 \cdot \ln(Q) + e_9 \cdot \ln(L_{cargo})^{e_{10}} + e_{11} & \text{high speed;} \end{cases}$$

a_1–a_9 are regression coefficients, taken according to Table 6.

Despite the random nature of choice of estimated routes in Russia, unit cost of transportation is approximated with fairly high accuracy, which indicates stability of the



Pic. 5. Correspondence of the regression values and the results of the calculation model of SSC.

specific indicator as a whole. The accuracy indicators of the regression model (12) are as follows:

- tank containers S = 0,089 rub./t • km, A = 1,4 %, R^2 = 0,999;
- tank cars S = 0,170 rub./t • km, A = 3,4 %, R^2 = 0,997.

The resulting formula for determining $c_{railway}$ does not take into account influence of inflationary processes, therefore, actualization of the obtained values for a specific date of transportation should be carried out by selective updating of information on design trips and by adjusting tariffs with regard to corresponding value. For example, from May to October 2018, the railway tariff for transportation of liquefied hydrocarbon gases (ETSNG [Single tariff and statistics nomenclature of cargo] 226074) had decreased by 3,4 %.

An important aspect of railway transportation is its duration $T_{railway}$. When normalizing data for railway transportation, delivery time is taken as a multiple of one day (see Pic. 6), however, it is more convenient to use smooth approximations to solve the calculation problems. In particular, in this work, a linear model was used, and it was assumed that duration of return of empty containers is equal to duration of laden transportation:

$$T_{railway} = 2 \cdot (f_1 \cdot L_{cargo} + f_2), \text{ hour,} \quad (13)$$

where f_1, f_2 are regression coefficients, taken according to Table 7.

Table 7 also shows indicators characterizing accuracy of dependence (13) and indicating its applicability for solving research problems. It should be noted that duration of delivery of tank containers is twice the duration of delivery of tank cars, which may be due to the peculiarities of formation of trains of various types. Dependence (13) does not consider duration of cargo operations, which, however, turns out to be significantly less than duration of transportation, and therefore may not be taken into account.

From Table 6 it can be seen that the railway tariff for container transportation does not depend on cargo flow, whereas when transported in tanks, such a dependence exists. With a distance of 500 km, a cargo flow of 500 t/day and low speed of delivery, the unit cost is 2,8 and 3,6 rub./t • km for transportation in tank cars and tank containers, respectively. However, cost of using tare very significantly adjusts the final

Table 6

Regression coefficients

Coefficient	Tank containers	Tank cars
e_1	0,1222	0,0454
e_2	0	-64,302
e_3	0	-1,0307
e_4	-7,0141	0,0071
e_5	0,0495	-1,0231
e_6	244,02	106,70
e_7	-0,8709	-0,6673
e_8	0	0,0016
e_9	-16,303	-20,309
e_{10}	0,0347	0,0093
e_{11}	18,811	21,981

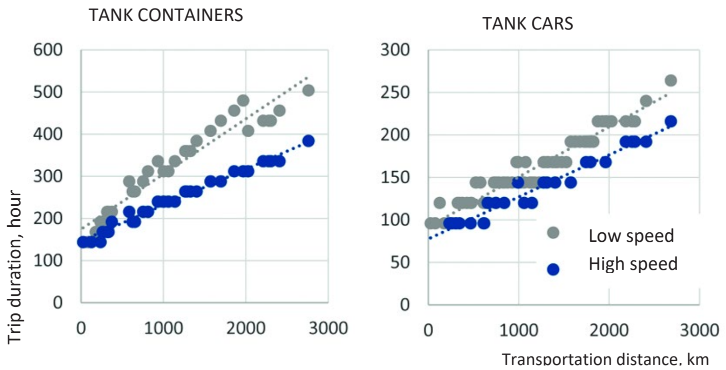
cost of delivery, increasing it by more than double. So, under these conditions, 365 tank cars or 998 tank containers are needed, while c_t is 3,7 and 5,8 rub./t • km, respectively. The coefficient of urgency of delivery for transportation in tank cars varies in the range from 1,293 to 1,463, and for container transportation from 1,337 to 1,839. The use of expedited delivery in all cases is impractical from the point of view of the total cost of transportation since a decrease in tare costs with an increase in delivery speed does not compensate for increase in tariff for transportation. For example, unit cost of delivery, taking into account tare costs (distance – 500 km, cargo flow – 500 t/day) at a low/high speed of delivery is 6,5/7,0 rub./t • km for tank cars and 9,4/10,1 rub./t • km for tank containers, respectively.

5. Cost of cargo operations

To obtain all the cost components of the intermodal logistic scheme for LNG transportation, the cost of cargo operations with containers and railway tank cars was estimated.

To determine the cost of transshipment of tank cars, the provisions of the Agreement on the International Railway Transit Tariff (MTT) [24][6] signed by Russia, were used. In accordance with section III «Additional fees and charges», fee for transshipment of liquid cargo carried in tank cars as of January 1, 2018 amounted to 1,2

[6] OSJD Website http://osjd.org/doco/public/ru?STRUCTURE_ID=5034&layer_id=6073&refererLayerId=6076&id=1105 – *ed. note.*



Pic. 6. Duration of transportation on considered railway routes.

Table 7

Dependence parameters to determine duration of transportation by railway

Parameter	Tank containers		Tank cars	
	Low speed	High speed	Low speed	High speed
f_1	0,131	0,085	0,059	0,049
f_2	174	147	92	78
S, hours	28,6	9,5	10,1	7,8
A, %	8,5 %	3,6 %	5,7 %	5,0 %
R^2	0,927	0,979	0,938	0,958

CHF (Swiss francs) per 100 kg or 19827 rub. for transshipment of a design tank car, i.e. 842 rub./t. The authors of [1] determined the price of LNG transshipment into tank cars and from tank cars in Baikal region at the beginning of 2017 as 919 rub. per ton, which allows us to assess the estimated values for transshipment of railway tank cars as adequate.

Cargo operations during the container mode of transporting LNG can be divided into:

a) operations performed by special equipment when loading containers at LNG plants;

b) operations performed by forces and equipment of railway;

c) operations performed in ports.

Cargo operations performed on railway are calculated at the rates of fees of table No. 4 of Tariff Guide No. 3. For containers with gross weight of more than 30 tons, fee is 160 rub. per container operations, fee for operations with empty containers is charged with a coefficient of 0,75. In case of transshipment of LNG containers between rail and motor transport, two container operations fall on one container, and in case that an empty container is changed to loaded one there are four container operations.

Analysis of container transshipment tariffs in river ports and container transshipment tariffs in cabotage in Russian seaports[7] showed a significant variation in the cost of those services. For example, cost of transshipment according to the «vehicle–warehouse–vehicle» scheme for loaded 40-foot containers is 8 350–12 480 rub./cont., and for empty ones the cost is of 4280–9110 rub./cont. In addition, exact values of cargo transshipment tariffs are subject to commercial secrets of port operator and cargo owner. Depending on the volume of cargo transshipment and the terms of the contract, various discounts on provision of services up to 50 % may be applied. In case of transshipment of dangerous goods, an increase in base tariffs is envisaged. Storage of goods beyond the normal time is paid separately. Therefore, to assess cost of cargo operations C_{co} in the ports with N_{un} containers, the following simplified approach was used:

[7] [Electronic resources]:
http://www.seaport.spb.ru/article/22;
http://terminalspb.ru/o_kompanii/raskritie_informacii;
http://www.fct.ru/disclosure;
http://ulct.ru/disclosure;
http://bscbalt.ru/index.php?id=10#.W450r8J9iUk;
http://www.nle.ru/for_clients/cargo_tarifs;
http://rostovport.ru/klientam/uslugi;
http://www.arpnet.ru;
http://yarport.com/uslugi/pogruzochno-razgruzochnye-raboty.php.

$C_{co} = c_{load} \cdot N_{un/}P_{load}$, (14)

where P_{load} is productivity of a container loader of corresponding loading capacity, cont./day;

c_{load} is the cost of renting a container loader, rub./day.

According to the Websites of construction equipment rental companies, the cost of renting a container loader is from 1400 to 3000 rub. per hour. When renting a loader with a driver, rental price increases. Formula (14) can also be used to estimate the cost of cargo operations performed by special equipment when loading containers at LNG plants.

6. Comparison of cost of transportation by various modes of transport

Visualization of the obtained regression formulas for determining unit cost of transportation by all modes of transport is performed in Pic. 7, where the cost is given as a function of distance and cargo flow, while considering both the cost of transportation and the cost of acquiring and maintaining the container. For road transport, the following values of the parameters of the regression formulas are accepted:

$L_{empty} = L_{cargo}$, $k_{pr} = 1$, $c_{fuel} = 48$ rub./l.

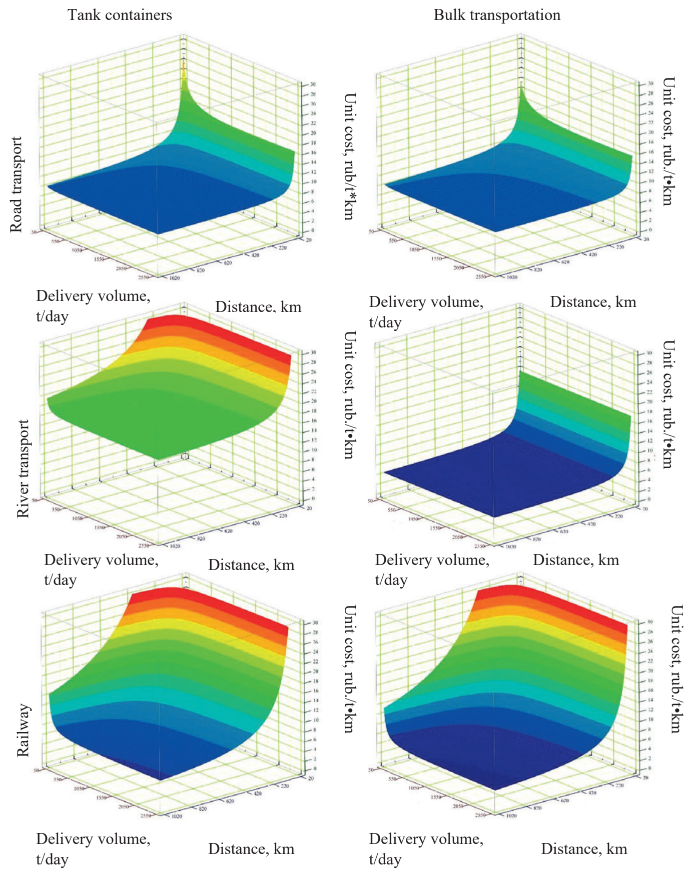
For water transport it is accepted that $T_n =$ 215 days, $T_0 = 0{,}004 \cdot L_{cargo}$, $c_{fuel} = 25$ thous. rub./t, cost of a gas carrier/container vessel c_v is 2050/1100 mln rub. respectively. For rail transportation it is accepted that delivery is carried out at a low speed, since this reduces the total cost. The cost of cargo operations is not considered, since it depends on the logistic scheme, the characteristics of transshipment complexes, and in some cases can be included either in the cost of infrastructure or in transportation costs. Pic. 8 shows the areas on «distance–cargo flow» plane, illustrating where the use of various modes of transport is the most efficient regarding the following pairs: «road–railway» when transported in containers; «motor transport–railway» for bulk transportation; «water transport–railway» for bulk transportation.

The presented graphs allow us to draw several conclusions.

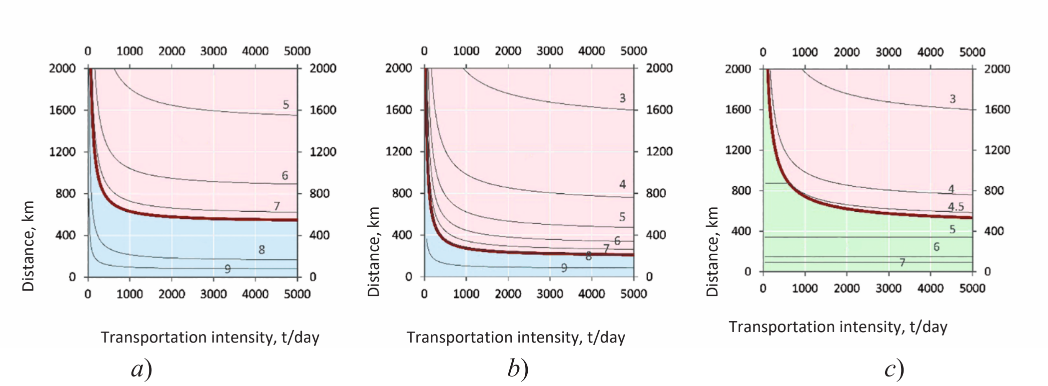
Railway transportation in tanks provides the lowest cost in case of high cargo flow and long-distance delivery, but they have a longer duration: average delivery speed even at high speeds does not exceed 10–12 km/h. The cost of delivering containers by railway is significantly higher, and delivery time is even longer (average speed does not exceed 7 km/h). If the comparisons consider not only the costs of transportation and use of tare, but also the costs associated with the loss of LNG from evaporation, then low speed of delivery will significantly worsen performance of railway transport. However, it seems that in this case too, in case of a distance of over 800 km and a cargo flow of more than 1000 t/day railway transport will provide the best economic performance.

LNG transportation by gas carrier ships is cheaper than transportation in tank trucks (with the exception of very short distances, with a length of less than 20–30 km), but they are inferior in terms of efficiency to railway transport at long distances and greater cargo flows. Let us note that water transport is traditionally cheaper than railway, but in this case, its performance is significantly deteriorated by the limited navigation period and long duration of the voyage along SWS. In case of LNG transportation in bulk at short distances, when trip delays are minimal, water transport is more efficient than railway, and if there are no trip delays, it surpasses the railway for all combinations of distance and cargo flow, even in conditions of limited navigation. LNG container transportation by water is characterized by higher cost and can be excluded from further consideration. This is mainly due to low carrying capacity of vessels due to inability to transport LNG containers in the holds, as well as to the fact that long delivery period forces to have a very large fleet of containers, increasing the cost of maintaining tare. One of the advantages of LNG transportation with gas carriers is the absence of gas losses due to evaporation, which eliminates the additional costs due to this factor. However, transportation along SWS is seasonal, so the scope of river transport for transportation of low-tonnage LNG is rather limited.

Road transportation at long distances is inferior in effectiveness to other modes of transport, however, at short distances (even with high cargo flow), it is comparable to river transportation, and also surpasses railway transportation by a wider range of distances and cargo flows. This is explained mainly thanks to high delivery speed. If, when comparing road and railway transport, the costs associated with



Pic. 7. A characteristic shape of dependence of unit cost of transportation (including tare) on distance and delivery volume.



Pic. 8. Areas on «distance–transportation intensity» plane where the use of various modes of transport is most efficient: a – transportation in tank containers for «vehicle–railway» pair; b – transportation in bulk for a pair of «motor transport–railway»; c – bulk transportation for «water transport–railway» pair. The numbers on the graphs show lines of equal unit cost of transportation, considering the costs of using tare.

LNG losses from evaporation are considered, the ranges of distances and cargo flows at which motor transport is preferred will be further extended. In addition, road transport shows a minimal difference between cost of delivery in bulk and in tank containers, while for all other modes of transport this difference is much larger. The reasons for small difference in case of road transport are obvious and comprise the minimum difference in capacity of the tank container and tank truck, as well as the same delivery time.

General conclusion. The regression formulas presented in this paper for determining the cost of LNG transportation by road, railway and water transport are among core elements in solving the problem of designing infrastructure for transportation of liquefied natural gas in Russia.

The structure of the formulas ensures their versatility and the possibility of practical application for estimating the cost of LNG transportation, considering the features of intermodal logistics.

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