Method for calculating the supply of transport and logistics services depending on the demand for freight transportation

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Abstract. The article examines the problems that arise in railway freight transportation when determining the optimal size of rolling stock fleet under seasonal fluctuations in the volume of transportation and ensuring a certain reserve of vehicles. In order to optimize the number of vehicles in the fleet, it is necessary to find a balance between undesirable expenses for maintaining wagons in periods of falling demand for them (surplus supply of transport and logistics services) and unearned income from their lack (deficit) in periods of maximum growth of transportation volumes. The methodology and example of calculating the fleet of freight wagons, the efficiency of their use and determining the optimal number of rolling stock and the need for a certain reserve of vehicles are presented. It is noted that the railway transport of Ukraine was and continues to be one of the main types of transport in the transportation of goods and passengers. However, considering the long operating time of the rolling stock, more than 70% of semi-wagons and more than 80% of grain wagons require replacement or extension of their service life due to capital repairs. The role of railways is especially critical in the current period of russia's war against Ukraine, due to the lack of air transport, river and sea transport and the insufficient capacity of highways and border railway stations. Determining the required number and optimizing the number of vehicles in the fleet can be carried out according to the calculation methodology, which is based on the analytical determination of the minimum of the objective function of the total operating costs associated with both the deficit and the surplus of vehicles compared to the demand for transport and logistics services. It has been established that the application of this calculation method allows to optimize the inventory and working fleet of wagons taking into account the different cost per day of shortage and surplus of the fleet of wagons (supply of transport services compared to their demand). Compared to traditional methods of calculation, the proposed method saves operational costs for maintaining the fleet of wagons in the amount of 2-5%.

1. Problem statement

Freight transportation is an important segment of the competitive transport market [1]. Railway transport of Ukraine is one of the main types of transport in ensuring transportation of passengers and cargo. Before the start of the large-scale russian aggression Ukraine's railways accounted for more than 80% of all cargo transportation in t-km. According to the latest publications, the share of rail transport in the total volume of cargo transportation (in tons) in Ukraine is 20%, and the share of cargo transportation by rail transport on average in European countries is 18% [2]. The cargo turnover of transport enterprises in recent years amounted to 280 billion t-km and was distributed as follows: railway transport – 60.4%, road transport – 14.5%, pipeline transport – 24%, water transport – 1% and aviation transport – 0.1% % [3].

The role of rail transport is especially noticeable in the difficult years 2022-2023 for Ukraine, during the period of military aggression by russia. Due to the lack of aviation and the almost complete cessation of transportation by water transport, a significant part of the volumes was shifted to railway transport. The main problems of railway transportation are the lack of railway wagons, their obsolescence, lack of the required number of locomotives. The issue of renewing the inventory of wagons is solved in different ways: extending the service life of wagons due to repairs, attracting investors to the construction of wagons, who later become their owners, and attracting investors to renew the fleet of railway properties.

One of the problems is determining the required number of wagons by type, taking into account seasonality. The authors of the article offer their approach to determining the required number of wagons as an alternative, considering the economic component. At the same time, the question of determining the optimal number of wagons on average, regarding the peak periods of the year, is considered.

The analysis of the freight wagon fleet of JSC "Ukrzaliznytsia" (Ukrainian railway) shows that a significant part of it is operated with an exceeded service life, namely 72% for semi-wagons and 86% for grain trucks [2].

Unfortunately, due to the lack of investment, JSC "Ukrzaliznytsia" has almost stopped purchasing wagons in recent years. In such a situation, the shortage of freight wagons by 2025 will amount to about 48-50 thousand wagons [2].

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The situation with a shortage of wagon fleet is somewhat alleviated due to the activity of private carriers, operator and forwarding companies, and this factor is key in shaping transportation forecasts in the future.

The problem of balancing the fleet of vehicles in accordance with the demand for transportation is of a particularly critical level and mass scale for cargoes whose transportation has a significant seasonal unevenness throughout the year, for example, grain cargoes (cereals), a significant part of which is transported by railways. The war only worsened this situation, due to the blockade of Ukrainian seaports, when the load on railway transport increased sharply due to the use of alternative logistical solutions for the export of grain.

2. Analysis of the state of research

Research on the supply of transport and logistics services depending on the demand for freight transportation, improving the quality of transport services, determining the factors affecting the formation of freight flows in scientific works are increasingly common. Among the publications, it is appropriate to note the work [4], based on which the hierarchical component in the organization of operational work was analysed, its connection with shippers, and a model of optimal distribution of empty rolling stock was developed, taking into account the existing principle of management decision-making. In [5], a model was developed to determine the optimal structure and size of a fleet of railway cars at a chemical plant under conditions of uncertainty of demand and travel time, as well as substitution between types of cars. It should be noted that the proposed model minimizes the total direct costs of wagons under the given restrictions on the availability of wagons and the determined maximum number of their types. The size of the fleet is calculated using an approximation from the theory of reserves, which takes into account existing uncertainties. In the article [6], the problems of the size of the vehicle fleet of freight road transportation and technical support are considered. A mathematical model of the decision-making problem was developed, taking into account technical and economic criteria and the interests of various interested parties, which was formulated on the basis of the queuing theory. Using a fleet of wagons with limited carrying capacity to transport goods on railway networks is a complex management problem. An approximation model of queue organization for the dynamic task of determining the size of the wagon fleet in order to maximize public welfare, which improves the use of freight wagons, is considered in [7]. The Markov decision-making process (MDP) proposes to determine the optimal trade-off between the number of wagons and the costs of placing empty wagons. Management of a fleet of freight wagons by the decomposition method for optimization of a heterogeneous fleet of platforms is proposed in [8]. Reducing empty mileage, waiting at the station of departure or destination is an important point in the rational organization of freight transportation and determining the required number of wagons by type. The authors of the paper [9] propose an improved approach to approximate dynamic programming for planning the dimensions of vehicle traffic. They consider not only the problem of determining the composition of the vehicle for the transportation of certain types of cargo, but also the planning of a predetermined frequency of cargo delivery.

Modern innovations in the field of freight transportation and logistics play an important role in providing more integrated, efficient and sustainable services on the global market. While much attention is paid to how modern innovations, including technological and managerial innovations, change the supply of services, little is done to describe their changing relationship with freight demand. In work [10], the authors present the results of a comprehensive study of companies from the Global Fortune 500 list, aimed at understanding what causes the demand for modern transport services. They examine the importance of three key service attributes that are growing in importance, i.e. operational control by mode of transport, service flexibility and additional value-added services. Determine the impact of factors on service selection, including supply chain strategy, demand, internal flexibility, and industry type. This leads to recommendations for shippers on how they can adjust their supply chains in the future to take advantage of new freight services. The authors also emphasize the need to introduce modern approaches to the selection of services in the logistics industry. The problems of planning vehicles in intermodal transportation are one of the most important problems of logistics. In the paper [11], the authors propose a holistic approach to vehicle planning that combines various solutions such as freight planning (mode of transport, service type and route selection), vehicle composition and allocation, empty movement, expansion/contraction of vehicles and outsourcing. A complex integer linear programming model is developed for an international logistics company that operates a large intermodal network in Europe. The calculated results showed that the application of the redistribution strategy can provide a cost reduction of up to 10% of the logistics company. Considering the current situation of the company, outsourcing can be reduced up to 30% and vehicle loading can be increased by 5% due to the application of the proposed model. A large case study also shows that the proposed model can be used to create efficient and effective vehicle plans.

In their work [12], the authors consider the problem of a heterogeneous fleet of rolling stock by combining two or more routes into a longer route. The paper [13] proposes an intermodal fleet planning framework with a classification scheme that takes into account different characteristics of the rolling stock, levels of decision-making, and multiple players or decision-makers. Most of the articles in this field, as a rule, are devoted to the problems of planning vehicles of one mode of transport. However, there is a limited amount of research on intermodal fleet vehicle movement dimensions using multiple modes and resources. On the other hand, there is a close interaction between vehicle planning components such as vehicle size/composition, its placement, vehicle inventory control, empty vehicle movement issues, etc. are decided separately.

The problem of the vehicles fleet size and the combined route of vehicles with time windows during which companies hire a third-party logistics company is considered in the article [14]. The delivery charges considered in this paper are calculated using stepwise cost functions in which values are determined according to vehicle type and total distance travelled, with fixed values for predefined distance ranges. A mixed integer linear programming model is presented and two sequential insertion heuristics are proposed. The introduced methods are investigated using computational comparative analysis with a known optimal solution.

At the same time, despite the diversity of views, the issue of further research and the provision of transport and logistics services depending on the demand for cargo transportation remains relevant and open.

3. The main results of the study

The aim and task of the study is to develop a method of analytically determining the necessary optimal number of railway freight wagons (or other means of transport) during a certain period of time, within which there are significant fluctuations in demand for them (there is a shortage or surplus), based on the efficiency of the use of transport means This will make it possible to dynamically forecast both the needs of the working fleet of wagons and the volumes of orders for the production of wagons for wagon-building plants.

High-quality satisfaction of the demand for the transportation of goods in conditions of its fluctuations requires the presence of a certain reserve of a fleet of vehicles (wagons, containers, etc.). At the same time, the additional fleet causes additional non-productive operational costs in periods of reduced demand for transportation. Therefore, when optimizing the fleet of vehicles, it is necessary to find a balance between these unwanted costs in periods of falling demand and unearned revenue from transportation in periods when a shortage of rolling stock is created when demand increases.

In a general form, a similar optimization problem was formulated (to determine a fleet of containers) back in 1982. In [15], the approach proposed at that time was used and the problem was brought to an engineering solution.

To formalize the problem, we introduce the following terms:

D_o is the "estimated" demand for transportation, based on which the need for a working fleet of vehicles, units per day, is determined;

D_{max} is the maximum possible demand for transportation, units per day;

$p(D)$ is the differential function of the probability density distribution of the random value of demand D.

The distribution function $p(D)$ is determined using the model shown in Figure 1 (the differential distribution function is shown on it by a solid line, the integral function by a dashed curve).

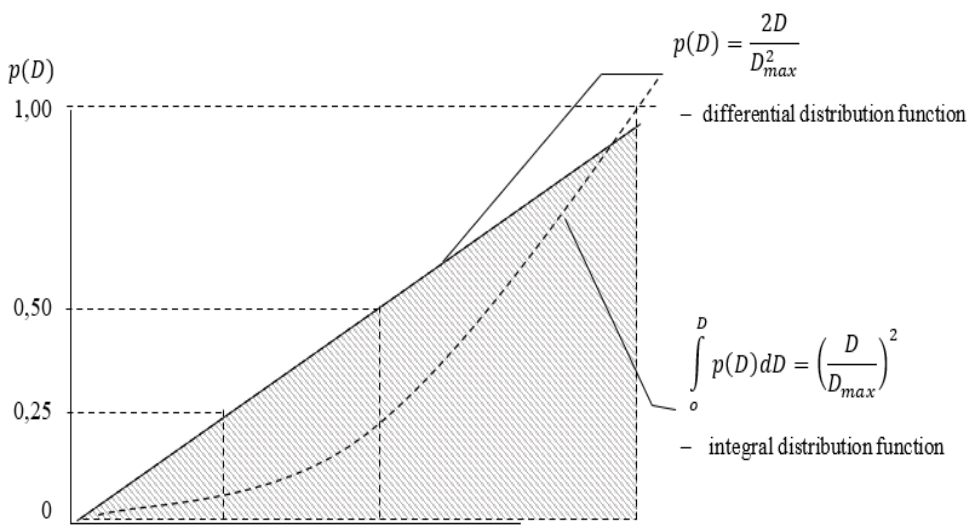

Fig. 1. Graphical model of estimated demand for transportation (in relative values to the maximum possible)

The differential and integral distribution functions are easily established using geometric arguments from the shaded triangle in Figure 1. The model is based on the fact that the stock of the fleet is needed when more than average demand values are likely, for example $(0{,}75 \leq p(D > D_o) \leq 1)$. However, excessive fleet (surplus) leads to additional operating costs. These costs can be defined as

$$E_p = C_p \int_{D_o}^{y} (y - D)p(D)dD, \qquad (1)$$

where

y is the increased demand ($y > D$), which is expected for the fleet of vehicles;

C_p is the "price" of a day of excess of a park unit.

After integration, we get:

$$E_p = \frac{C_p}{3D_{max}}(y^3 + 2D^3 - 3yD^2), \qquad (2)$$

Fleet deficit (when $D > y$) also has consequences – "costs" (unearned revenues from transportation)

$$E_d = C_d \int_y^{D_{max}} (D - y)p(D)dD = C_d\left(\frac{y^3}{3D_{max}^2} - y + \frac{2}{3}D_{max}\right), \quad (3)$$

where C_d is the "price" of the day of shortage of a fleet unit.

From a practical point of view, it is obvious that neither one (E_p) nor other (E_d) costs can be avoided at the same time. However, it is necessary to minimize them in the sum, that is, to find the objective function $E_p + E_d \rightarrow min$. The method of finding this minimum by differentiation is known - solving the equation with respect to the argument y

$$\frac{dE_p}{dy} + \frac{dE_d}{dy} = 0 \quad (4)$$

under conditions

$$\frac{d^2E_p}{dy^2} > 0 \text{ та } \frac{d^2E_d}{dy^2} > 0.$$

Omitting intermediate transformations, we present the solution of equation (4), which gives the value of the demand for transportation y_o. It is this value that should be used to calculate the optimal number of vehicles, i.e. the one at which the possible total costs associated with both an excess and a shortage of a working fleet of wagons or other vehicles will be minimal:

$$y_o = D_{max}\sqrt{\frac{\left(\frac{D_o}{D_{max}}\right)^2 C_p + C_d}{C_p + C_d}} \quad (5)$$

For the practical use of formula (5), the values of the quantities included in it should be specified. The values of the "estimated" D_o and the maximum possible D_{max} demand for transportation are established through market research and forecasts (this applies to D_o), which requires separate studies that are not the subject of this article, while the estimate of D_{max} can be the maximum throughput (carrying) capacity of transport for of this cargo in this period of time on the specified local transport network.

Values of the "price" of a day of surplus C_p or deficit C_d per unit of the fleet of vehicles can be determined as

$$C_p = 24C_{OR} \quad (6)$$

where C_{OR} – собівартість вагоно-години, контейнеро-години простою транспортного засобу;

$$C_d = \frac{24(A+BL)}{K_{lw}t_{fo} + (1+\alpha_e)\left(\frac{1}{V_{at}} + \frac{t_{tech}}{l_{tech}}\right)L} \quad (7)$$

where A, B are the tariff rates, respectively, per container, start-end operation (we use rates in UAH per wagon) and transportation operation (UAH per wagon-km, container-km);

L is the transportation distance, km;

K_{lw} is the coefficient of local work (it is known from operational reporting of railways and takes into account the ratio of the number of wagons with which cargo operations are performed within the local transport network to the total number of them involved in transport work, including transit for the local network);

t_{fo} is the average wagon idle time under cargo operation at the station of departure or destination, hours;

α_e is the coefficient of empty mileage in relation to loaded mileage;

V_{at} is the average train speed on the section between technical stations, km/h;

t_{tech} is the average idle time of wagons (containers) at the technical station (stations where technical operations with trains and wagons are carried out, provided by the technology of cargo transportation);

l_{tech} is the average distance between technical stations, km.

Regarding the coefficient of local work, we note that its value ranges from 0 (with transit wagons, no cargo operation is performed on the local network) to 2 (with "local" wagons, two operations are performed on the network - loading and unloading).

An example of the application of the proposed calculation method for the wagon fleet and conditional "average" operating conditions of railways, which are characterized by the following data:

$C_{OR} = 0.6$ UAH/wagon-hour;

$A = 310$ UAH/wagon;

$B = 1.14$ UAH/wagon-km (for the most common tariff scheme No. 1 and an average wagon load of 62 tons);

$L = 420$ km;

$K_{lw} = 1{,}8$; $t_{fo} = 35{,}38$ h; $\alpha_e = 0{,}67$; $V_{at} = 33{,}9$ km/h; $t_{tech} = 7{,}49$ h; $l_{tech} = 105$ km.

Under such conditions, the average transportation fee (without value added tax) is $A + BL = 789$ UAH, at the same time, the duration of the wagon turnover time θ_w equals

$$\theta_w = \frac{1}{24}\left[K_{lw}t_{fo} + (1+\alpha_e)\left(\frac{1}{V_Д} + \frac{t_{tech}}{l_{tech}}\right)L\right] = 5{,}6 \text{ days} \quad (8)$$

In this way, the daily "price" of a surplus of the wagon fleet unit is $C_p = 14{,}4$ UAH, and the "price" of the day of shortage is $C_d = 140{,}9$ UAH.

Let's assume that the average daily demand for transportation on the railway network of Ukraine is D_o=14,000 wagons and calculate what working fleet of wagons n_{wf} is necessary to satisfy the changing demand for transportation, which can reach D_{max}=20,000 wagons, with minimal total costs. Using formula (5), we have

$$n_{wf} = \theta_w y_o = \theta_w D_{max}\sqrt{\frac{\left(\frac{D_o}{D_{max}}\right)^2 C_p + C_d}{C_p + C_d}} = 5{,}6 \cdot 20000\sqrt{\frac{\left(\frac{14000}{20000}\right)^2 \cdot 14{,}4 + 140{,}9}{14{,}4 + 140{,}9}} = 109{,}320 \text{ wagons},$$

which is 12% more than the actual working fleet of freight wagons. It should be noted that the traditional method of calculation would have given a different result - with a demand of 20,000 cars per day, the working fleet should be increased by 43%.

For analysis purposes, let's transform formula (7) and put D_{max}=1 in it, then

$$y_o = \sqrt{\frac{D_o^2\frac{C_p}{C_d}+1}{\frac{C_p}{C_d}+1}} \quad (9)$$

The results of calculations of the amount of demand for transportation y_o, for which the optimal number of vehicles should be calculated according to formula (9), are shown in Table 1 and also presented in Figure 2.

Table 1 shows that from an economic point of view, in conditions of fluctuating demand for transportation, the working fleet of vehicles should be kept 2÷5% smaller compared to the one calculated by the traditional method. This is explained by the fact that the "price" of a day of surplus of a unit of the c_p fleet is much lower than the "price" of a day of its deficit c_d.

Table 1 – The demand for transportation, on which the optimal size of the fleet of vehicles should be calculated (in relation to the maximum possible)

The ratio of the surplus price to the shortage price (per day) of the fleet of vehicles, $\frac{C_p}{C_d}$	The ratio of estimated demand to the maximum possible demand, $\frac{D_o}{D_{max}}$					
	0.5	0.6	0.7	0.8	0.9	1.0
0.05	0.982	0.985	0.988	0.991	0.995	1
0.10	0.965	0.97	0.976	0.983	0.991	1
0.15	0.95	0.957	0.966	0.976	0.988	1

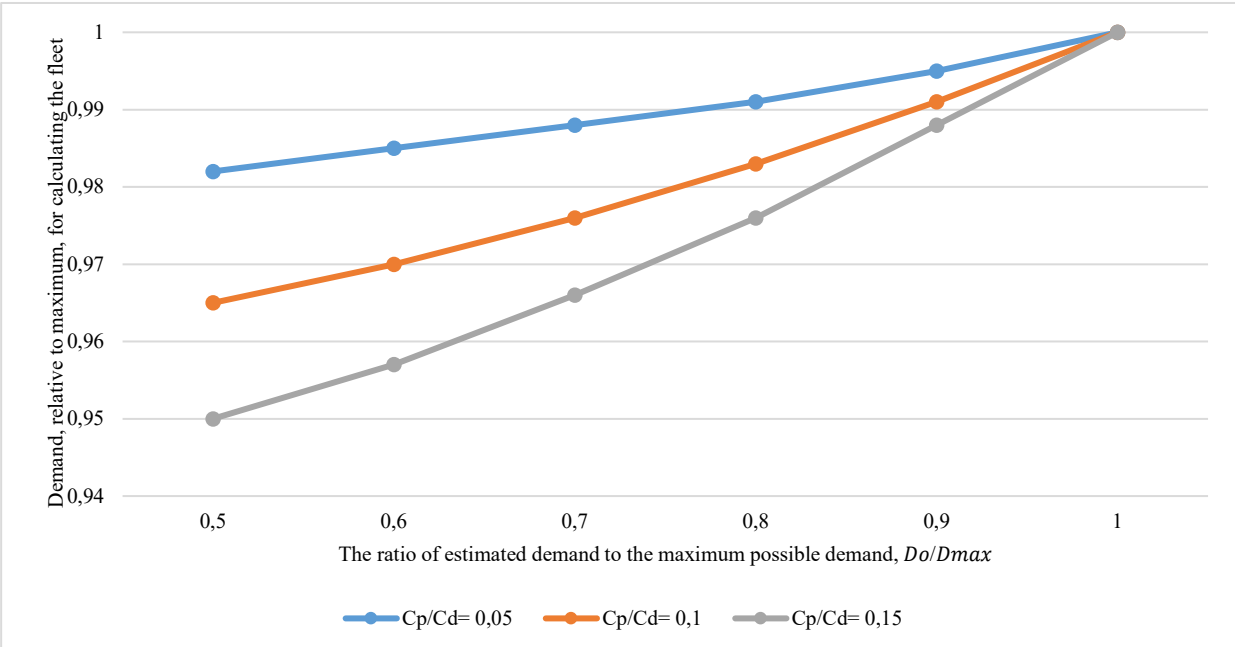

Fig. 2. Demand for transportation, on which the optimal size of the fleet of vehicles should be calculated (in relation to the maximum possible)

This technique for optimizing the number of vehicles in the fleet can also be used without fundamental changes to optimize the fleet of train locomotives.

4. Conclusions

The supply of transport and logistics services, that is, the number of vehicles available in a given place and time period for transportation, must correspond to the demand for transportation (the amount of cargo that requires certain types of vehicles), which requires a certain reserve (stock) of vehicles in the event of an increase demand.

The presence of a reserve of vehicles during the period of reduced demand for transportation leads to an excess (surplus) of vehicles and additional non-productive costs for their maintenance.

The proposed method of calculating the fleet of vehicles allows you to determine it taking into account fluctuations in the demand for transportation of goods based on the minimization of the total costs of maintaining the fleet in periods of its excess and possible loss of income from transportation in periods of shortage of the fleet (offers of transport and logistics services).

Using the example of calculations performed for the conditions of railways of Ukraine during the transportation of grain cargoes, it is proved that in conditions of fluctuating demand for transportation, the reserve of the working fleet of wagons should be maintained, while the calculations showed that it can be

2÷5% less compared to the one calculated by the traditional method.

The methodology can be used to calculate the required fleet of vehicles of various types of transport, taking into account the achievement of an economically justified balance of demand and supply of transport and logistics services.

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