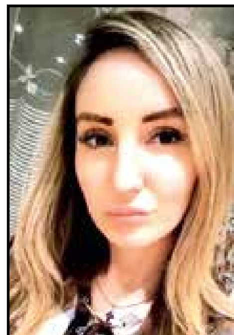
ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-6-15

World of Transport and Transportation, 2023,
Vol. 21, Iss. 6 (109), pp. 295–300

Rationale for Transport Costs when Transporting Bulk Cargo in Containers with the Integral Method



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ABSTRACT

Currently, a large volume of exports of coal and other bulk cargo to China is carried out by container method, the main advantage of which is the possibility of multimodal transportation. This issue is also relevant for other countries, linked by transport corridors with sea transportation. However, one of the main problems of container transportation of coal is reduced net weight of the cargo transported in two containers as compared to one standard gondola wagon used previously.

The study describes an integral calculation of five possible options for loading coal into a container with formation of a «cap» in the form of spherical or elliptical segments. As a result of the calculations, volumetric and mass underload of containers was identified, which significantly affects transportation costs. A polynomial approximation of the considered options for placing coal in containers on railway flat wagons within a train showed an increase in operating costs due to underloading associated with the downtime of the flat wagon and container under cargo operations (loading/unloading) and transportation tariffs. Proposals have been made to reduce transport costs for container transportation of coal and other bulk cargo by rail.

Keywords: railways, container transportation of bulk cargo, integral calculation of cargo placement in a container, costs due to uneven placement.

Acknowledgments. The authors express their gratitude to I. S. Zaikin, student of Russian University of Transport for the assistance in collecting data during the study.

For citation: Kurzina, E. G., Kornienko, N. A., Kurzina, A. M. Rationale for Transport Costs when Transporting Bulk Cargo in Containers with the Integral Method. World of Transport and Transportation, World of Transport and Transportation, 2023, Vol 21, Iss. 6 (109), pp. 295–300. DOI: https://doi.org/10.30932/1992-3252-2023-21-6-15.

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

At the end of 2020, Russian export supplies of coal, as well as other bulk cargo, began to be carried out in open top containers [1]. Currently, regular transportation of hard coal is carried out from Transbaikalia to the PRC through the border crossing point Zabaikalsk–Manchuria (Pic. 1), and the share of such container transportation to China is generally 95 %. According to Russian Railways, this method allows to simplify and speed up the process of sending coal for export. The container is simply moved from the Russian flat wagon to the Chinese one[1].

Similarly, it is possible to tranship the container on road vehicles and sea vessels, which is especially important in the context of development of international transport corridors, including North–South Transport Corridor [2; 3].

The total volume of domestic container transportation is growing steadily from year to year [4–6]. This type of transportation has also been actively developing recently in the countries, with which we are connected by common transport corridors [7–9].

The advantages of container transportation of bulk cargo include:

– reduced time of border and customs control operations from 4 hours to 1,5 hours;

– acceleration of turnround of cargo wagons involved in transportation;

– reduced time of transshipment to another mode of transport (sea, road), i.e. possibility of inter- and multimodal transportation;

– solution to the problem of frozen coal piles at border stations during transshipment from Russian rolling stock to Chinese, etc.;

– reduced load on the railway infrastructure;

– increased speed of cargo flow;

– minimisation of environmental damage.

However, despite the increase in the volume of shipments of coal in containers through the network, several issues still remain relevant [1; 10; 11]. One of the main problems is reduced net weight of cargo transported in two containers compared to one standard gondola wagon.

The *objective* of the research is to perform integral calculation of possible options of loading coal into containers and to develop suggestions to reduce transport costs of container railway transportation of coal and other types of bulk cargo.

RESULTS

Previously, coal and other bulk cargo were transported mainly in gondola wagons (Pic. 2 *a*). The internal volume of the gondola wagon body is 88 m^3.

Currently, coal is transported in two 20-foot containers with an internal volume of 32 m^3 each, installed on a flat wagon (Pic. 2 *b*).

Consequently, the nominal volume of transported bulk cargo in a gondola wagon is 1,375 times greater than on a flat wagon with two containers.

Statistics show that on average about 34 tons of coal are transported in one 20-foot container with a maximum capacity of 39,4 tons. Thus, the underweight is 5,4 tons. Losses in the volume of

[1] Information from the website of JSC Russian Railways. 20.01.2021. [Electronic resource]: https://company.rzd.ru/ru/9397/ page/104069?id=258901.

Pic. 1. Container transportation of coal to China.
Photo of Xinhua News Agency. [Electronic resource]: https://russian.news.cn/2021–04/13/c_139878444.htm. Last accessed 30.08.2023.

a) b)

Pic. 2. Coal transportation: a) in gondola wagons; b) in containers.
Photos of the website of JSC Russian Railways. [Electronic resource]: https://company.rzd.ru/ru/9407/page/68650?id=2148; https://company.rzd.ru/ru/9407/page/68650?id=21273.

transported cargo can be associated with uneven loading and even underloading of wagons.

In this connection, it is relevant to analyse the reasons for underloading of containers with coal and the associated transportation costs.

Loading of coal on the access roads of mines and quarries into gondola wagons and containers is carried out by a rotary excavator. In most cases, loading results in formation of a «cap» on the loaded pile without subsequent levelling and compaction. The shape of the «cap» depends on the flowability of coal. In this regard, five options for loading coal into a container were considered (Pic. 4):

1. 2/3 of the height of the container is completely filled with coal, and there is a spherical segment on top with radius R = 1,161 m and height c = 0,762 m.

2. 2/3 of the height of the container is completely filled with coal, and there is an elliptical segment on top with semi-axes a = 1,161 m and b = 1,6235 m, height c = 0,762 m.

3. 2/3 of the height of the container is completely filled with coal, and there is an elliptical segment on top with semi-axes a = 1,161 m and b = 2,086 m, height c = 0,762 m.

4. 2/3 of the height of the container is completely filled with coal, and there is an elliptical segment on top with semi-axes a = 1,161 m and b = 2,3485 m, height c = 0,762 m.

5. The container is completely filled with coal.

Container's volume is V = A • B • C = 5,902 • 2,330 • 2,352 = 32,34 m^3.

Depending on the loading options, the container's volume will be:

1. $V_1 = V_{2/3} + V_{sph}$
2. $V_2 = V_{2/3} + V_{ell1}$
3. $V_3 = V_{2/3} + V_{ell2}$
4. $V_4 = V_{2/3} + V_{ell3}$
5. $V_5 = V$,

where $V_{2/3}$–2/3 of the container's volume, equal to $V_{2/3}$ = 32,34 • 2/3 = 21,56 m^3;

V_{sph} – volume of a spherical segment of a sphere, which is found by integrating a body of revolution, given by the canonical equation of a ball with a radius of 1,161 m, within the limits of integration from 0 to 0,762 m;

V_{ell1} – volume of an elliptical segment of a sphere, which is found by integrating the body of revolution, given by the canonical equation of the ellipse with semi-axes a = 1,161 m and b = 1,6235 m, within the range of integration from 0 to 0,762 m;

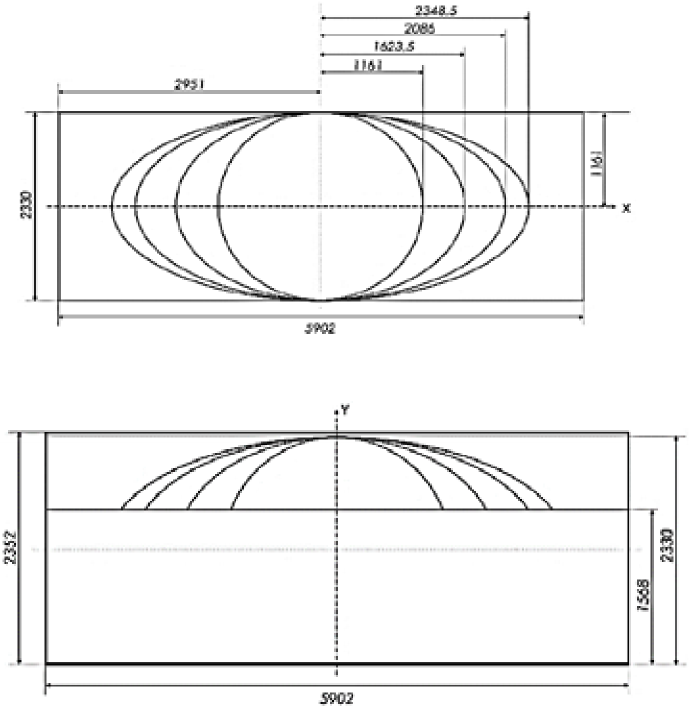
V_{ell2} – volume of an elliptical segment of a sphere, which is found by integrating the body of revolution, given by the canonical equation of the ellipse with semi-axes a = 1,161 m and b = 2,086 m, within the range of integration from 0 to 0,762 m;

V_{ell3} – volume of an elliptical segment of a sphere, which is found by integrating a body of rotation specified by the canonical equation of an ellipse with semi-axes a = 1,161 m and b = 2,3485 m, within the limits of integration from 0 to 0,762 m.

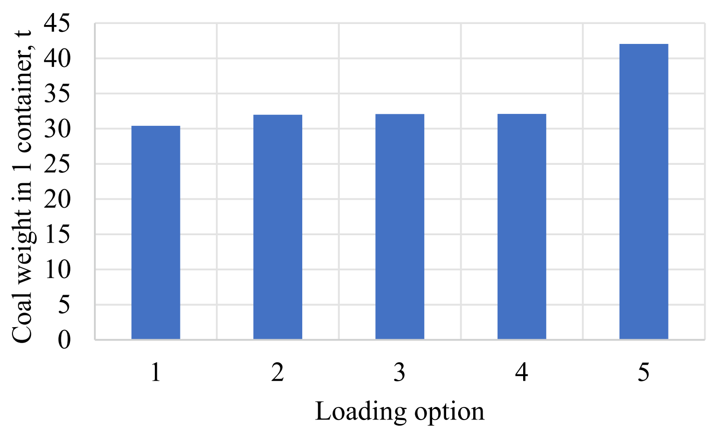
In the general case, the volume of a body of rotation relative to the *OY* axis is determined by the formula:

$$V_{Oy} = \pi\int_c^d x^2 dy \, .$$

For a spherical segment, the integrand will be $R^2 = x^2 + y^2$, and for an elliptical one it will



Pic. 3. Graphic presentation of the considered options for loading coal into a container [performed by the authors].



Pic. 5. Graphic presentation of the results of calculations of the possible loading of containers with coal with approximation by a polynomial dependence [performed by the authors].

be $\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$.

$$V_{sps}=\pi\int_{0}^{0,762}(R^2-y^2)dy=\pi(R^2y-\frac{y^3}{3})\Big|_0^{0.762}$$

$$V_{es1}=\pi\int_{0}^{0,762}a^2(1-\frac{y^2}{b^2})dy=\pi(a^2y-\frac{y^3}{3b^2})\Big|_0^{0.762}.$$

V_{ell2} and V_{ell3}, which differ in the sizes of the semi-axes b, are calculated similarly.

The results of calculations of the volume of transported cargo are presented in table 1.

The calculation results showed that the volumetric underload of containers can range from 7,64 m^3 to 8,94 m^3.

If we take the average density of coal $\rho_c = 1{,}3$ t/m^3, then the weight of coal in 1 container will be $m_c = \rho_c \cdot V_c$, and the underload of the container

Table 1

Results of calculating container loading volume for five possible options [performed by the authors]

№ of the option of loading	$V_{2/3}$, m^3	$V_{»cap»}$: V_{sph} and V_{ell}, m^3	V, m^3	Volumetric underload of a container, m^3
1	21,56	0,585π	23,40	8,94
2	21,56	0,971π	24,61	7,73
3	21,56	0,993π	24,68	7,66
4	21,56	π	24,70	7,64
5	-	-	32,34	-

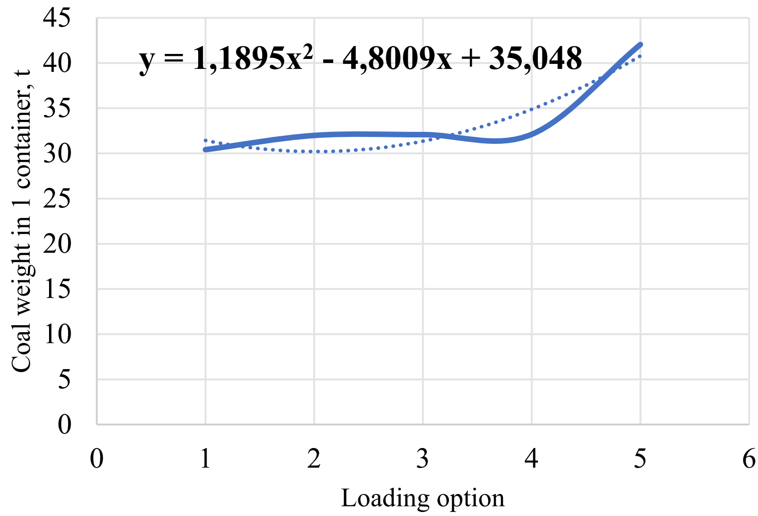


Рис. 6. Графическое представление результатов расчетов возможной загрузки контейнеров углем с аппроксимацией полиноминальной зависимостью [выполнено авторами].

by weight will be $\Delta \mathbf{m}_c = m_c - m_{c1}$. The results of calculating the underload of containers by weight are shown in Table 2 and Pic. 4.

Consequently, the weight underload of coal in one container according to the considered options can range from 9,932 tons to 11,622 tons.

If the weight of coal according to possible loading options is described by a polynomial relationship (Pic. 5), then the weight of coal in five containers can be found as the area of a curvilinear trapezoid. In this case, the weight of coal in five containers will be:

$$M_5 = \int_0^5 (1{,}1895x^2 - 4{,}8009x + 35{,}048)dx =$$

$$= (1{,}1895\frac{x^3}{3} - 4{,}8009\frac{x^2}{2} + 35{,}048x)\Big|_0^5 = 164{,}79$$

It should be noted that with a full load of five containers (option 5), the transported weight of coal will be 210,21 tons.

If, for example, it is necessary to transport 1050 tons of coal, then at maximum load 25 containers will be used, and at underload – 32

Table 2

Results of calculating container loading in tons for five possible options [performed by the authors]

Number of loading option	Coal weight in 1 container m_c, t	Container underload $\Delta \mathbf{m}_c$, t
1	30,420	11,622
2	31,993	10,049
3	32,084	9,958
4	32,110	9,932
5	42,042	-

containers, which will significantly increase the costs associated with idle time of the flat wagon and container under cargo operations (loading/unloading) and tariffs for transportation, by up to 25 %.

Thus, to reduce the costs associated with the cost of increased number of open top containers to transport a given mass of coal with its uneven placement, it is necessary to introduce the operation of levelling and compacting the cargo in the container. There are special rollers intended for levelling bulk cargo in gondola wagons but it is necessary to create such devices for containers as well.

It should also be noted that in order to increase the carrying capacity and speed of movement of flat wagons transporting containers, developments are currently underway to create high-speed six-axle platforms that will allow transportation of a larger number (three pieces) of open top containers, thereby bringing the comparable volume of transported cargo to the volume transported by gondola wagons (quite naturally assuming that containers will be uniformly and fully loaded).

Increasing the speed of movement of flat wagons, as well as the possibility of thermal insulation of containers, helps solve problems of coal freezing, thus making the implementation of such developments a very urgent task.

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Article received 15.05.2023, approved 13.09.2023, accepted 17.09.2023.