# THE OPERATING PROCEDURE OF THE DEVICE ENHANCING THE WHEEL-RAIL ADHESION

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***Resume***
The results of the analysis of sand application efficiency for improving wheel-rail adhesion are presented. An algorithm for the sandbox operation is substantiated, based on supplying sand under the wheels when their slip reaches a critical level, delivering sand in proportion to the vehicle speed, and automatically purging the sand supply pipes. The principle of sandbox operation is based on the mechanical interaction between the moving elements and sand. It has been established that the maximum adhesion coefficient is achieved when the sand is evenly distributed in a single layer within the wheel-rail contact area. The important role of the contact area in the wheel-rail adhesion is emphasized. A sandbox implementing the developed sand supply algorithm is proposed. The introduction of this sandbox on Ukrainian-manufactured trams is described.

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## 1 Introduction

The main idea of creating the rail transport is to reduce the rolling resistance of wheels on the base. This is primarily achieved by increasing stiffness of wheels and the base, as well as giving them rational geometric shapes. As a base, it was proposed to use rails laid on sleepers that would simultaneously serve as guiding elements for the train.

The first studies with a steam locomotive built in 1809 by engineer R. Trevithick revealed the imperfection of this idea. It was noticed that the application of traction force to the wheel was accompanied by an increase in the skidding of wheels on rails, which complicated movement or made it impossible in some cases. This phenomenon was called slipping later [1-2].

A well-known method of combating skidding by placing quartz sand between bodies in relative motion allowed increasing the traction force and preventing slipping [3-5]. Sand expectedly enhanced the wheel-rail adhesion in all weather conditions and, moreover, was an available material. The effectiveness of using sand to enhance the wheel-rail adhesion provided this method with absolute priority and spread in rail and urban rail transport. This is explained by the relative cheapness of sand and its unique property to instantly and effectively enhance the wheel-rail adhesion [6-8]. For example, the braking distance of a train when using sand is approximately 30% smaller than without sand in the same conditions [3, 9].

Sand is still the main means of short-term levelling of wheel skidding on the rail. Increased volumes of sand purchases for enhancing the wheel-rail adhesion, as well as large expenses for cleaning sand from the rail bed and city streets, have determined the need to use sand even more effectively and economically while achieving the maximum possible wheel-rail adhesion coefficient with minimal amounts of sand [9-10].

## 2 Presentation of basic materials

The imprinting film method was used to assess the contact area of the vehicle wheels with different wear indicators. The fractional composition of sand was carried out taking into account a sieve analysis. The algorithm of supplying sand to the wheel-rail contact area was created and justified by comparative analysis using experimental and theoretical results.

Sanding systems in the technical literature are evaluated by two indicators, namely, efficiency ($\eta$) and sand supply performance [11]. Efficiency is an important characteristic of a sandbox. It can be used to assess the completeness of sand supply to the wheel-rail contact area, but efficiency cannot be considered an exhaustive characteristic, since it does not define the most important purpose of the sandbox, which is to enhance the wheel-rail adhesion.

Since the sand supply to the wheel-rail contact area without losses is not identical to the concept of increasing the wheel-rail adhesion coefficient, the efficiency of the sanding system can be considered only as a characteristic of sand losses while supplied to the contact area. The efficiency of the sanding system is defined as the ratio of the amount of sand that has come into the wheel-rail contact area to the total mass of sand supplied under the locomotive wheel [11]:

$$\eta = \frac{m_1}{m_2}, \tag{1}$$

where:
$\eta$ - the efficiency of the sanding system;
$m_1$ - the amount of sand that has come into contact, kg;
$m_2$ - the total amount of sand supplied to the contact, kg.

Analysis of Equation (1) shows that efficiency is in no way related to the amount of sand required to achieve the maximum wheel-rail adhesion coefficient. This suggests that efficiency is an incomplete characteristics of the system and does not answer the question of whether this system is efficient and what part of sand is excessively supplied to the contact area.

Some specifications provide the efficiency of the sandbox, but it is not indicated under which conditions these values are valid. The conditions for obtaining efficiency are very important since it is obvious that with fixed constant values of the sand supply performance at different movement speeds, the values of the efficiency of the sandbox will be different.

To answer this question, information is needed about the amount of sand leading to the maximum adhesion coefficient. Studies show that this amount of sand is a variable value and depends on many factors, namely [11]:

- the wheel-rail contact area size;
- conditions of wheels and rails (level of wear);
- physicochemical and physicomechanical properties of the contacting surfaces;
- natural losses of sand on the way to the wheel-rail contact area;
- relative skidding of wheels;
- level of load on the wheel-rail contact area by normal and tangential forces;
- ambient temperature and temperature in the wheel-rail contact area.

Each of these factors of the wheel-rail interaction has a strictly defined amount of sand at which the maximum possible adhesion coefficient is achieved. Experimental determination of the sandbox efficiency involves conducting a series of measurements at different vehicle speeds and in different weather conditions. This requires equipment that allows for collecting sand that did not come into the wheel-rail contact area. Although the experimental equipment needed is simple, conducting experiments is quite problematic.

In addition to efficiency, an informative characteristic of the sandbox is its performance, which is expressed as the ratio of the amount of sand supplied by the sandbox per unit of time [1]:

$$P = \frac{M_k}{t} \tag{2}$$

where:
$P$ - sandbox performance, kg/s;
$M_k$ - the amount of sand supplied to the wheel-rail contact area, kg;
$t$ - time, s.

However, just like efficiency, the sand supply performance does not define the purpose of the sanding system, which contributes to achieving the maximum adhesion coefficient and does not give recommendations for the rational use of sand to enhance the wheel-rail adhesion. This problem has a technical, economic, environmental, and social nature and affects such characteristics of sand use as the adhesion coefficient, the costs of purchasing and preparing sand, as well as human health, since after putting the sanding systems into operation small particles of sand remain in the atmosphere for a long time and lead to serious diseases while getting into the human lungs.

Despite the apparent chaos, the mechanical and physicochemical processes occurring during the interaction of sand with the wheel-rail contact area are interconnected, mutually dependent and are subject to the basic laws of the molecular-mechanical theory of friction [12].

When the sand particles are supplied to the contact area, their multiple crushing is observed, which begins in the micro-gap between the wheel and the rail and continues in the contact area itself. Small particles that do not come into the wheel-rail contact, and those that were in contact, play an unfavourable role. They can remain in the atmosphere for a long time and cause diseases when inhaled into human lungs [13].

It has been experimentally established that before the sand crushing, almost 80% of sand particles have a size of 0.1 to 0.3 mm. After the sand crushing, its main part (70%) has a particle diameter of 0.05 mm and less [14-15].

The size of sand particles was determined by sieving it through cells of different diameters. Sand crushing was caused by a single pair of locomotive wheels running into it, the axle load of which was 115 kN (this experiment was performed with sand used to enhance the wheel-rail adhesion on Donetsk Railway of Ukraine) [16].

The maximum adhesion coefficient is achieved under conditions when a sand particle penetrates into the wheel-rail surfaces simultaneously, i.e., the sand is distributed in the contact in one layer [5-6]. The strength of the metal-particle-metal bond determines the wheel-rail friction coefficient and force. The penetration of a sand particle occurs to a depth that depends on the Brinell hardness of the material, the particle radius and shape. We assume that the sand particles are spherical for simplification, although in reality, their shapes may vary.

The criterion that evaluates the particle crushing is the following dependence [17]:

$$(h/r) = 1/2\,(\sigma/HB), \tag{3}$$

where: $h$ - the depth of penetration, m;
$r$ - the particle radius, m;
$\sigma$ - the particle crushing stress, Pa;
$HB$ - Brinell hardness of the material, Pa.

As a result of the sand crushing, the total surface area increases by many times. The new sand surface formed has high molecular activity due to a large number of uncompensated molecular bonds. This process has a beneficial effect on the implementation of the molecular component of the adhesion coefficient [18].

When coming into contact, sand can be distributed both in one layer and several layers. It has been experimentally proven that the first option is effective in terms of the adhesion coefficient for dry wheel-rail surfaces. In the second option, the adhesion coefficient tends to decrease with an increase in the amount of sand.

In the first option, each particle of sand has favourable conditions for simultaneous penetration into the wheel-rail surfaces and fixing in them. Thus, the best conditions are created to achieve the maximum possible values of the mechanical component [10]. For a single sand particle, the mechanical component of the adhesion coefficient is equal to the ratio of the particle application value to its radius [18]:

$$f_{mech} = \frac{h}{r}, \tag{4}$$

where:
$f_{mech}$ - the mechanical component of the adhesion coefficient;
$h$ - the amount of micro-roughness penetrated into the surface, m;
$r$ - the radius of curvature of the micro-roughness apex, m.

As follows from Equation (4), the mechanical component of the adhesion coefficient will be the higher, the smaller is the sand particle formed after crushing. The mechanical component as a whole, for the wheel-rail adhesion coefficient, is respectively equal to the sum of the effects of all individual particles.

In this case, the magnitude of forces transmitted from the wheel to the rail depends on the following factors:

- the strength of sand particles;
- the depth of penetration of sand particles into the wheel-rail surfaces;
- the strength of the mechanical bond between sand particles and the material of the wheel and the rail;
- the strength of the molecular bond between the sand particles and the material of the wheel and the rail.

In addition, no less favourable conditions are created for implementing the molecular component. Each sand particle has the largest contact area with the wheel-rail surfaces. In the considered option of sand distribution in the contact area, both the mechanical and molecular components can reach their maximum possible values.

In the second option, there is no possibility of simultaneous penetration of each sand particle into the wheel-rail surfaces. In this regard, the efficiency of force transmission due to the mechanical component will be correspondingly lower.

In addition, despite the fact that the contact area of sand particles and the wheel-rail surfaces will be quite large, there is no reason to assume that the molecular component of the adhesion coefficient will also be quite large since the transmission of traction forces will be localized in sand thickness, the shear strength of which is low [9].

Additionally, the more sand particles are in the contact area, the less intensively they will be crushed and, therefore, lower values of the molecular component of the adhesion coefficient will be achieved.

Compared to the first option, this option is inferior in terms of the level of both mechanical and molecular interaction. Therefore, the first option of the distribution of sand particles in the contact is better from the point of view of achieving maximum values of the wheel-rail adhesion coefficient.

The wheel-rail adhesion takes place on small contact areas. The size of these contact areas is only a few square centimetres (for new wheels 1 - 2 cm$^2$) [19]. Nevertheless, with the help of such small areas, traction forces of several tens of tons can be transmitted from the wheel to the rail.

The contact area plays an important role in the wheel-rail interaction, both with and without sand. The larger the contact area is, the more sand particles can be placed there, so the more sand will affect the wheel-rail adhesion.

The wheel-rail adhesion coefficient with quartz sand in the contact area is shown by the equation [20]:

$$f_{ad} = f_{mol} + 1.4\left(\frac{p_w}{2r^2 HBn}\right), \tag{5}$$

where:
$f_{ad}$ - the adhesion coefficient;

$f_{mol}$ - the molecular component of the adhesion coefficient;
$r$ - the radius of a quartz sand particle, m;
$HB$ - Brinell hardness of the wheel surface, Pa;
$n$ - the number of quartz sand particles;
$P_w$ - the normal wheel load, N.

This equation is approximate, as it is derived from the assumption that sand particles are distributed in a single layer. The equation takes into account the contact area through the parameter of the amount of sand in the contact (the molecular component of the adhesion coefficient is determined experimentally).

The parameter n in Equation (5) attracts attention, as it means the number of quartz sand particles in the contact. Since the contact area of worn wheels is larger, the number of sand particles will be bigger, and therefore the wheel-rail adhesion will be larger.

The wheel-rail contact area mainly depends on the load level, the diameter of the wheel, and the degree of wear of the wheel-rail working surfaces. Since the contact area has its limits, the number of particles placed in the contact is also limited. Other things being equal, the contact area differs depending on the wear of wheels and rails.

Figure 1 shows the average statistical imprints of the spots of the wheel-rail contact. The imprints were obtained by the imprinting film method. The diameter of the wheels studied was within 1000 - 1050 mm [20].

As follows from Figure 1, the contact area of worn wheels is several times bigger than of the unworn ones. Therefore, the number of sand particles placed in the contact area of worn wheels will also be several times bigger, and the adhesion is correspondingly larger.

## 3 Findings and discussion

The developed sand dispensing system has been implemented on T3L441 trams manufactured by Electrontrans (Lviv, Ukraine). The system's performance characteristics are presented in Figure 2. For comparison, the performance characteristics of a system, based on a pneumatic dosing method, are also shown. As follows from the presented characteristics, the developed system demonstrates higher efficiency in economic parameters [10-11].

The shaded area indicates the sand savings achieved through the use of the mechanical dosing method.

With increasing speed, the drawback of the stepwise sand dispensing performance, shown in Figure 2, became apparent. For example, with stepwise sandbox performance when beginning motion and at a speed of 100 km/h, the amount of sand that comes into the wheel-rail contact area differs several times. This is due to the fact that in the first and second cases, the train passes a different path per unit of time, therefore, with the same sandbox performance, the density of sand distribution along the rail will be different.

It can be assumed that the wheel-rail adhesion

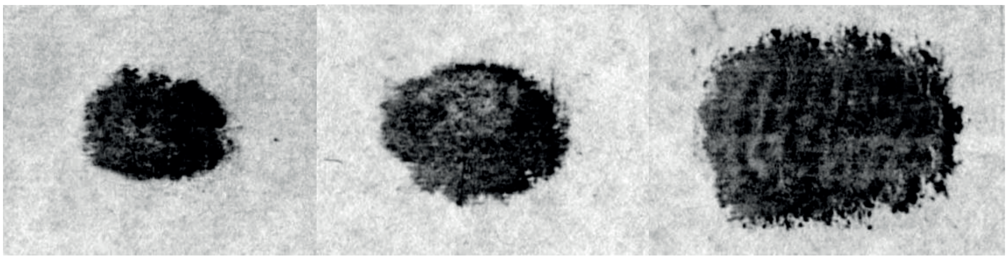

***Figure 1*** *Imprints of contact spots of a new and worn wheel with the rail: 1 - a new wheel; 2 - rolled 2.0 mm; 3 - rolled 5.0 mm*

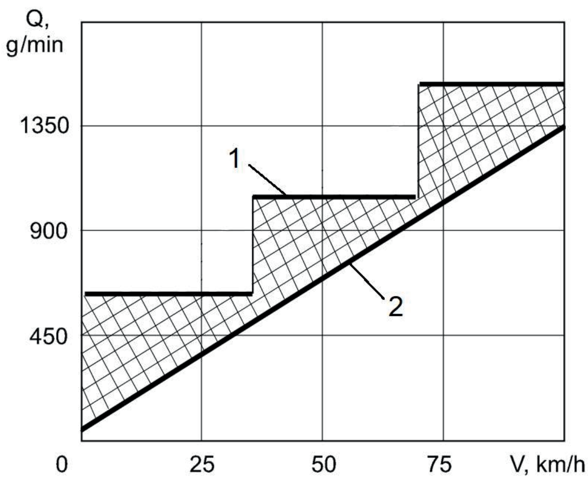


***Figure 2*** *Dependence of the sand supply productivity on tram speed, 1 - pneumatic sand dosing method, 2 - mechanical sand dosing method*

*Table 1 Percentage of sand supply to the wheel-rail contact area depending on the fractional composition of sand*

| Fractional composition | % |
|---|---|
| Fraction >1.6 mm | 100 |
| Fraction 1.6 to 1.0 mm | 90 |
| Fraction 1.0 to 0.63 mm | 70 |
| Fraction 0.63 < mm | 25 |

coefficient would change in accordance with the density of sand distribution. That is, stepwise sand supply performance by a sandbox does not provide stable values of the wheel-rail adhesion coefficient.

In this regard, a sandbox is created that allows sand to be supplied depending on the vehicle speed [6, 11, 16]. There are three methods that can be used. The first method is characterized by a stepwise dependence of the change in the sand supply performance on the movement speed, and the second is a linear dependence (Figure 2), and the third method is constant sand dispensing performance. The third method is apparently less effective. Its main advantage is in the relative simplicity of implementation.

The advantages of the second method, characterized by the linear sand supply performance, are obvious both in comparison to the constant sandbox performance and in comparison to the stepwise sand supply performance. The linear characteristics allows for providing the same density of sand distribution on the rail head at any speed, which ensures stability of the wheel-rail adhesion coefficient. However, its implementation requires creating new sandbox designs.

Attempts to create such sandboxes based on the already well-tested method of capturing and supplying sand with compressed air, which was implemented in almost all designs of existing sandboxes, were unsuccessful. The maximum that was possible to do on that basis was to provide a stepwise change in the sand supply performance (Figure 2). The stepwise change in the sand supply performance was ensured by controlling the compressed air parameters.

Creating sandboxes capable of changing the sand supply performance depending on the vehicle speed became possible based on the mechanical principle of sand dosing, which involves the mechanical impact on sand.

Experiments on the effectiveness of sand use were performed on a full-scale stand developed at the Department of Locomotive Engineering of Volodymyr Dahl East Ukrainian National University under the mentorship of Professor O. L. Holubenko. The stand reproduced the interaction of a wheel with a diameter of 1050 mm and a section of the P65 rail 12 meters long in the dynamic mode [2].

When the train starts moving and at a speed of 100 km/h, the amount of sand reaching the wheel-rail contact varies significantly (by several times) depending on the dispensing mode. This is explained by the fact that the train passes different distances per unit of time, which affects the sand distribution density.

With the stepwise sand dispensing performance, uneven sand distribution is observed, leading to a change in the adhesion coefficient. According to the data in Figure 2, the sand dispensing performance characteristics of the mechanical method differs significantly from the pneumatic method in terms of sand savings.

To save sand when supplying it under wheels, it is possible to achieve a high percentage of sand supply to the wheel-rail contact area by screening out small sand particles during its preparation. Screening out sand particles with a diameter of less than 0.63 mm will ensure a loss of sand particles of only about 15% [18]. When screening out sand particles smaller than 1.6 mm, 100% sand supply to the wheel-rail contact is ensured, Table 1.

The wheel-rail adhesion coefficient in real operating conditions varies over a wide range. The minimum and maximum values of the adhesion coefficient differ by 6-7 times. When the weather conditions deteriorate, the adhesion coefficient can reach record low values, at which the rolling stock movement becomes impossible at all [15].

As studies have shown, such significant changes in the adhesion coefficient are largely due to the physicochemical state of the wheel-rail surfaces, which is formed under the influence of many factors. The most important of them are the weather and climatic conditions of the rolling stock operation, which are mainly due to the influence of temperature, humidity, and the accidental presence of various components on the rails [15].

Currently, the operation of trains is carried out without strict consideration of the influence of weather and climatic factors. This explains the fact that currently existing recommendations on the sand supply performance differ quantitatively several times.

The lack of influence of weather and climatic conditions leads to overconsumption of sand, a decrease in its frictional capabilities, an increase in wear of the wheel-rail working surfaces, as well as a loss of technical and economic efficiency of the locomotive as a traction vehicle.

The developed algorithm was implemented in the tram sandbox, which was introduced on T3L441 trams manufactured by LLC SP "Electrontrans" (Lviv, Ukraine). The sandbox was developed by the research

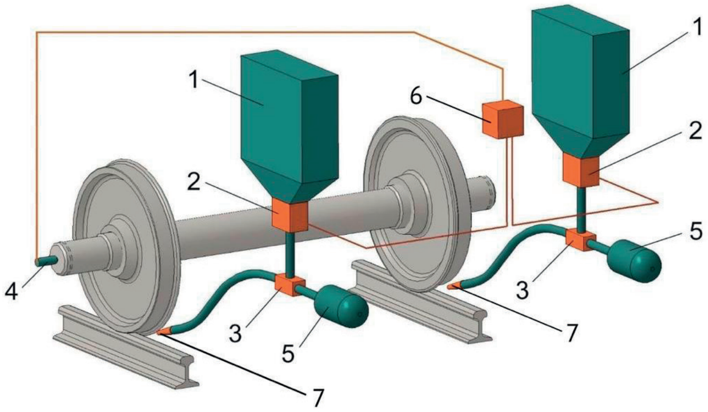


***Figure 3*** *Block diagram of placing sandboxes on the running gear of the tram: 1 - sand hopper; 2 - dispenser; 3 - nozzle; 4 - relative wheel slip sensor; 5 - small-sized compressor; 6 - control unit; 7 - tip*

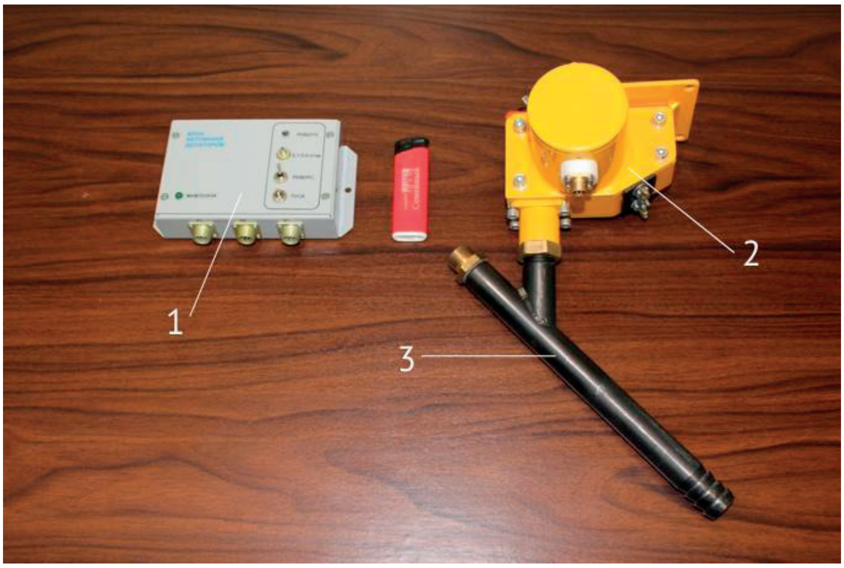


***Figure 4*** *Sandbox design: 1 - control unit; 2 - sand supply dispenser; 3 - nozzle*

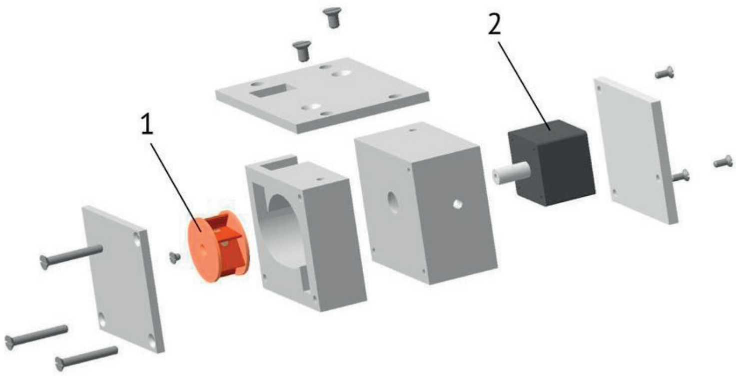


***Figure 5*** *Sand supply dispenser: 1 - impeller; 2 - stepper motor*

and production association “Poshuk” (Severodonetsk, Ukraine) [9]. The block diagram of placing sandboxes on the running gear of the tram and their design are presented in Figures 3 and 4, respectively.

Figure 4 does not show the elements used by the sandbox but developed and supplied by other developers and manufacturers (compressor, relative wheel slip sensor).

The sandbox is designed based on the mechanical principle of sand dosing and provides the sand supply to the contact proportional to the locomotive speed, which is provided by the impeller 1 (Figure 5). The installation of the sandbox on the tram is shown in Figure 6.

The sandbox operation algorithm involves blowing out the sand supply hoses after each sand supply cycle, as well as blowing out the sand supply hoses without

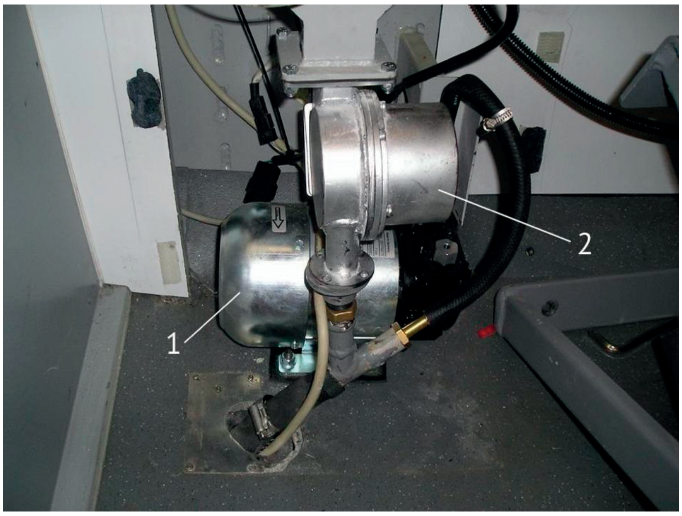


***Figure 6*** *Installation of the sandbox on the tram: 1 - compressor; 2 - sand supply dispenser*

sand supply, which is carried out with a given duration and frequency depending on the season (winter/summer).

Due to the use of the developed sand dispensing algorithm, the sandbox achieves the following characteristics (compared to analogues):

- high efficiency in terms of the wheel-rail adhesion coefficient;
- sand savings due to sand dispensing under the wheels, depending on the tram's speed;
- high operational performance due to the reliability of the dispenser and the purging of the sand dispensing pipes.

The author's supervision, conducted over 18 months, confirmed the high reliability of the sandbox.

## 4 Conclusions

1. The optimal procedure of supplying the sand to the locomotive wheels in accordance with the criteria of the adhesion coefficient and sand saving should have the following functions:
- supplying sand to wheels when reaching the critical level of the wheel skidding relative to rails;
- pulsed supply of sand carried out proportional to the movement speed;
- automatic blowing out of sand supply hoses after each sand-supply cycle;
- automatic periodic blowing out of sand supply hoses without sand supply in summer and winter.
2. Sand supply by modern sanding systems should be based on the predominant principle of the mechanical impact on sand during its dosing. The developed sand dispenser corresponds to this principle.
3. A high percentage of sand supply to the wheel-rail contact area can be achieved by screening out small sand particles during its preparation. Screening out sand particles with a diameter of less than 0.63 mm will ensure an approximately 15% loss of sand particles. When screening out sand particles smaller than 1.6 mm, 100% sand supply to the wheel-rail contact area is ensured.
4. The maximum adhesion coefficient is achieved in conditions when the sand is distributed in the wheel-rail contact area in a single layer and a sand particle simultaneously gets into the wheel-rail surfaces. The strength of the metal-particle-metal bond determines the wheel-rail adhesion coefficient and force.
5. The contact area plays an important role in the wheel-rail interaction, both with and without sand. The larger the contact area is, the more sand particles can be placed there and, thus, the more sand will affect the wheel-rail adhesion. All other things being equal, the adhesion of worn wheels (with sand particles) is greater as compared to the new wheels.
6. A locomotive sandbox is proposed, which is designed on the mechanical principle of sand dosing. The sandbox provides dosed sand supply to the contact area proportional to the locomotive speed and has the functions of blowing out the sand supply hoses after each sand-supply cycle, as well as blowing out the sand supply hoses without sand supply, which is carried out with a given duration and frequency depending on the season (winter/summer).

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**Conflicts of interest**

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

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