**Optimization of open-top wagon unloading processes and reduction of worker injuries at railway transport enterprises**

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**Abstract:** This article examines critical aspects of occupational safety and the reduction of industrial injuries during loading and unloading operations within the railway sector. Particular attention is given to operations involving open-top wagons, which impose considerable physical strain on workers and are associated with a high risk of injury during manual opening and closing of lower hatches. Based on the analysis of multi-year safety statistics, the study identifies key factors contributing to workplace accidents, including reliance on manual labor, insufficient adherence to safety regulations, and limited use of mechanized equipment. A comparative review of international practices in the United States, Germany, and China demonstrates that the adoption of automated and robotic systems significantly reduces injury rates in high-risk operational environments. The research proposes a technical solution in the form of an improved device for mechanized hatch closing, designed to substantially reduce physical effort and shorten process cycle times. Calculations confirm that the use of such mechanization can decrease worker load by a factor of 7.5–10.8 and significantly improve operational efficiency. The findings indicate that the implementation of small-scale mechanization enhances workplace safety, lowers injury probability, and contributes to increased productivity and economic performance in freight handling processes. The practical relevance of the study lies in the applicability of the proposed solution across a wide range of industrial railway facilities, supporting the advancement of safety culture and the sustainable development of railway logistics systems.

**INTRODUCTION**

Technological processes related to loading and unloading operations are carried out in the most accident-prone areas of the transport complex [1]. Therefore, when intensifying technological processes, it is necessary to take into account the occupational safety requirements of railway workers. In many developed countries, the level of injuries on railway tracks and during the unloading of open wagons is gradually decreasing thanks to the use of advanced technologies, strict safety standards and the mechanisation of work processes. However, risks remain, especially at less automated or overloaded stations [2].

In the United States, strict occupational safety rules apply to railways, including industrial access roads. The Federal Railroad Administration (FRA) and the Occupational Safety and Health Administration (OSHA) monitor compliance with safety standards and regulations. The causes of injuries include improper handling of unloading mechanisms, workers falling from platforms or while working at height, and collisions with rolling stock due to insufficient coordination between workers and equipment operators. Measures taken in the United States to reduce injuries include automation of unloading processes: robotic and automatic loading and unloading systems significantly reduce the need for workers to be present in hazardous areas; use of remote control: remote control systems for working with wagons and unloading mechanisms allow operators to remain at a safe distance, training and certification: workers undergo mandatory safety training, which reduces the risk of injury [3].

In Germany, strict safety rules for working on the railway are regulated by federal and industry standards. Mechanised unloading systems are actively used here, which significantly reduces the risk of injury. The main causes of injuries are: human error: mistakes in operating machinery and incorrect use of equipment, falls and injuries when working with machinery, especially at old or poorly equipped stations[4].

**EXPERIMENTAL RESEARCH**

China has one of the largest railway networks in the world, where accidents often occur on industrial access roads due to high freight volumes and intensive labour. Main risk factors: high workloads for employees, insufficient training and preparation of employees, especially at secondary stations and terminals. Measures taken by the country to improve safety: introduction of robotic systems to minimise human involvement in the unloading process, emphasis on training workers in new technologies and safety techniques, and tighter control over compliance with regulations [5].

Uzbekistan Railways JSC is implementing projects to modernise the railway infrastructure [6], [8], [9]. There are plans to introduce automated hatch closure systems at large railway stations, which will improve the efficiency of transporting goods such as coal and mineral fertilisers. However, at small stations, the manual method of closing the lower hatches of open wagons is still widespread, which slows down the unloading process, increases labour costs and causes injuries among workers [10].

The use of loading and unloading mechanisms is one of the key factors affecting the efficiency of railway logistics, in particular the turnover of wagons and delivery times. Foreign research in this area focuses on the role of technological modernisation, process automation and the introduction of modern management systems in optimising rolling stock turnover times [11].

In his works, Robert C. Lieb [12] examines in detail the impact of automated loading and unloading systems on improving logistics processes. He emphasises that automating operations significantly reduces the time required to process railcars, which leads to faster turnover and lower operating costs. His research shows that automation of loading and unloading reduces the downtime of railcars at terminals and improves wagon turnover by 10-15% in systems where robotic loading and unloading mechanisms are implemented. Reducing the number of manual operations also lowers the likelihood of errors and delays, which directly affects delivery times.

Jean-Paul Rodrigue analyses the impact of innovative loading and unloading technologies on transport processes in his works [13]. In particular, he highlights intermodal systems and robotic cranes as key factors contributing to the acceleration of transport operations, including wagon handling. He concludes that innovative technologies such as automatic cranes and container management systems can reduce loading and unloading times at large logistics hubs by up to 30%, and that speeding up the handling of railcars at intermodal terminals helps to reduce delivery times on international routes. In other words, the use of intelligent cargo management systems optimises processes, reducing overall cargo delivery times by 5-10%.

Michael B. Stroh's research [14] focuses on the use of intermodal loading and unloading mechanisms that reduce cargo handling time when transferring from one vehicle to another. He emphasises that the use of standardised containers and automated container handling systems significantly increases rolling stock turnover. The author's main conclusions are that intermodal terminals equipped with automated systems can reduce rolling stock turnover by 20-25%, while the use of containerisation and cargo standardisation technologies helps to speed up loading and unloading processes, reducing the overall time required for delivery. In addition, automated systems at terminals reduce the time required to handle railcars, which is particularly important in ports and large logistics hubs.

John J. Coyle [15] examines issues related to logistics optimisation and the impact of modern loading and unloading technologies on accelerating operations. In his research, he emphasises the importance of coordinated actions between different participants in the supply chain and the importance of implementing automated solutions to improve wagon turnover. The author concludes that optimising logistics processes using automated mechanisms reduces the average time spent processing railcars by 15-20%, and that integrating modern technologies for managing freight flows and loading/unloading operations directly improves accuracy and reduces delivery delays. reducing the downtime of railcars at stations and terminals improves the overall turnover of rolling stock, which leads to faster delivery of cargo.

Dimitri B. Papageorgiou's research [16] (Optimisation of Material Handling Systems in Freight Transportation) focuses on modelling and optimising cargo loading and unloading processes using modern mechanised systems. He emphasises the importance of mathematical modelling for developing effective solutions to minimise wagon handling time. The main conclusions of his work are as follows models based on the analysis of loading and unloading operations show a 15-25% reduction in wagon handling time when automated systems are used; optimisation of unloading and loading processes contributes to an increase in terminal throughput, which reduces downtime and speeds up cargo delivery; the development of integrated freight flow management systems improves not only wagon turnover but also the overall efficiency of transport operations.

**RESEARCH RESULTS**

Since issues related to optimising the transport process are closely linked to ensuring safe working conditions for employees, social factors must be given priority over economic factors when making a final decision.

The transport industry is one of the industries with a high degree of risk in terms of injury. Industrial injuries in the organisation of cargo operations on access roads and in the process of unloading semi-wagons are a pressing problem associated with insufficient mechanisation and compliance with safety regulations. Risk factors include the use of manual labour on access roads, outdated equipment and low levels of mechanisation at many industrial enterprises, insufficient training and a weak system for monitoring compliance with safety standards. The main causes of injuries are: workers falling while unloading railcars, manual handling of loads and equipment, which increases the likelihood of injury, and insufficient coordination between railway rolling stock operators and workers involved in unloading.

An analysis of compliance with occupational health and safety requirements at UTJ JSC enterprises was conducted (see Fig. 1 and Table 1).

**FIGURE 1.** Recorded types of injuries sustained by employees of UTJ JSC at work

As shown in Table 1.1, the total number of accidents was 188, with an annual decrease in the number of incidents: from 34 cases in 2017 to 27 cases in 2023. The number of fatalities remains stable, ranging from 5 to 6 cases annually.

The number of cases with serious injuries decreased from 19 cases in 2017 to 11 cases in 2023, which may indicate a decrease in the severity of injuries. The number of cases involving serious injuries decreased from 19 cases in 2017 to 11 cases in 2023, which may indicate positive changes in occupational safety. The number of cases involving minor injuries also shows a decrease, from 9 to 5 cases over the period. The largest share of accidents is associated with serious injuries (55.3%), followed by fatalities (19.7%) and minor injuries (25.0%). A positive trend is observed in the reduction of the proportion of serious and minor injuries by 2023, but the proportion of fatalities remains stable.

**TABLE 1.** Types of accidents recorded at UTJ JSC enterprises in the period from 2017 to 2023

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| №  п/п | Accidents (year) | Total number of accidents | Of these: | | | |
| Fatal accidents | Accidents involving serious injuries | Accidents with minor injuries |
| 1 | 2017 | 34 | 6 | 19 | 9 |
| 2 | 2018 | 21 | 5 | 10 | 6 |
| 3 | 2019 | 30 | 5 | 18 | 7 |
| 4 | 2020 | 23 | 5 | 13 | 5 |
| 5 | 2021 | 23 | 6 | 14 | 3 |
| 6 | 2022 | 30 | 7 | 17 | 6 |
| 7 | 2023 | 27 | 9 | 11 | 7 |
| Total: | | 188 | | | | |

The occupational safety conditions for workers involved in station operations involving the interaction of mainline and industrial transport were also analysed. In particular, the medical records of workers at the railway workshop of Uzmetkombinat JSC were studied (see Fig. 2).

**FIGURE 2.** Types of injuries sustained by employees of Uzmetkombinat JSC

The results of the analysis of medical records showed that 63% of cases of illness were related to injuries to the hands, feet and spine, of which 81% were employees of enterprises involved in opening and closing the lower hatches of open wagons. Moreover, the working conditions of these workers do not meet the requirements of paragraph 36 of Order No. 1582 of the Head of the State Inspectorate of the Republic of Uzbekistan for the Supervision of Safe Work in Industry, Mining and the Utility Sector of 13 June 2006. The main cause of most accidents during loading and unloading operations is the absence or insufficiency of mechanisation equipment for performing heavy and dangerous operations, for closing the hatches of open wagons, and for loading without spacers or pallets.

As practice shows, it is practically impossible to avoid injuries at work, but comprehensive mechanisation of loading and unloading operations makes it possible to eliminate or minimise manual, dangerous and heavy labour for many loaders and unskilled workers.

Existing mechanisms for closing the lower hatches of open wagons have both advantages and disadvantages. The main problems are long processing times, the heavy weight of some devices, the need to work with high-pressure hydraulic systems, and high cost. At the same time, hydraulic systems require a source of electricity, as they cannot operate without electric pumps that supply pressurised fluid. This means that the operation of such mechanisms requires appropriate infrastructure – power supply to the work site, powerful pumping stations and additional equipment. In mobile or remote locations, this can be a serious problem, requiring additional costs for generators or power lines. Thus, in addition to their high cost, significant weight and long processing time per car, the use of hydraulic mechanisms is limited by their dependence on electricity. This highlights the need to develop alternative solutions, such as mechanical or combined devices that could operate autonomously or with lower energy consumption. This points to the need to find more effective solutions that combine speed, convenience and cost-effectiveness.

As a result of a comprehensive analysis of existing devices, with an emphasis on the prospects for their modernisation and integration of innovative solutions, as well as taking into account the strategic objectives of import substitution and localisation of production, it is necessary to develop an improved device that will be adapted to the specific operating conditions of Uzmetkombinat JSC Uzmettkombinat JSC and can be effectively used at railway enterprises in the Republic of Uzbekistan, contributing to increased productivity, reliability and technological independence.

However, in real-life conditions, the process of lifting a hatch cannot always be standardised based solely on technical characteristics. The human factor plays a significant role, as people with different physical abilities may apply different amounts of force to the device handle. These include: the physical capabilities of workers, workers with different physical strength and endurance will exert different amounts of force when lifting, levels of fatigue and concentration, experience and skills, and weather conditions. This affects the speed and efficiency of the operation. The level of fatigue and attention of workers may vary depending on the time of day, workload, and conditions in which the operation takes place (e.g., low temperatures in winter).

Workers with extensive experience and technical knowledge can perform the operation faster and more efficiently than less experienced workers. Working conditions may be more difficult in winter, for example due to icing of hatches and mechanisms, which also increases the effort required to open or close the hatch.

If the weight of the load is known (200 kg), the mathematical expression is the torque transmission, which can be found as:

 (1)

where: r2 - radius of the large gear shaft;

*Q -* cargo weight.

Since the forces between the two blocks are equal, we can express this *M2* as:

 (2)

where: r2 - radius of the large gear wheel.

By equating formulas (1) and (2), we can find the force *P2*:

 (3)

The forces between the two shafts are equal. *P2= P3*, from here we find the torque *M3*:

 (4)

Using a lever *l* and forces *P0* torque is produced *M3*:

 (5)

where: *l* – lever length.

Then strength *P0* will be equal to:

 (6)

Based on expression (6), the force values were calculated, and the necessary force for uniform lifting of semi-wagon hatches at different values of their mass was calculated. The final values are shown in Figure 3.

**FIGURE 3.** Graph showing the relationship between the force required to close the hatches of open wagons and their weight

As shown in Figure 3, when using the proposed device, the force required to close the hatches of open wagons during loading and unloading operations varies from 46 N to 66 N when the hatch weight changes from 1300 N to 2100 N. This indicates a 7.5-10.8-fold reduction in the load on each worker when closing the hatches of open wagons.

The annual costs of wagon downtime for each delivery, saved through the use of a special device by workers on Track 1 of Uzmetkombinat JSC, which specialises in cleaning semi-wagons, are calculated using the following formula [10]:

 (7)

where: - time saved from waiting for wagons on cleaning tracks, wagon-hour;

- rate of expenditure for idle wagons, sum;

*n*- number of serves per day.

As a result of the practical implementation of a device for closing the hatches of open wagons on the 1st track of Uzmetkombinat JSC, which specialises in cleaning, the duration of technological operations performed with wagons in a single transfer has been reduced by 70 minutes. Four deliveries are made to this track per day. The daily time saving is 350 minutes. Thanks to the reduction in car downtime according to expression (7), the savings amounted to 351.3 million sum.

The capital costs for special devices for closing the hatches of open cars, required to equip the team of workers on the 1st track of Uzmetkombinat JSC, are calculated based on the cost of one device as follows:

 (8)

where: - number of devices required by the carriage cleaning team, pcs;

- price of one device, sum;

Ten specialised small-scale mechanisation devices are required to perform operations to close the hatches of open wagons in a single pass. The production costs for one specialised device are shown in Table 2. Taking into account staff training in the use of the device, the total capital investment for the introduction of the device for the mechanised closure of the lower hatches of open wagons will amount to 31 million sum.

**TABLE 2.** Costs of manufacturing one special device

|  |  |  |
| --- | --- | --- |
| **№** | **Cost structure** | **Sum** |
| 1. | Raw materials and consumables | 378 699 |
| 2. | Total cost of materials | 378 699 |
| 3. | Labour costs | 200 000 |
| 4. | Total direct costs | 578 699 |
| 5. | Production cost | 578 699 |
| 6. | Period costs | 2 050 000 |
| 7. | Profitability (20%) | 115 740 |
|  | **Price excluding VAT** | **2 744 439** |

The results of calculating the net discounted income from the introduction of a special device for closing manholes, used by a team of workers on the first track for cleaning semi-wagons at Uzmetkombinat JSC, are presented in Table 3.

**TABLE 3.** Net present value calculation table

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Period, year | Capital investments, *Сt* million sum | Total annual economic profit, *Rt* million sum |  | Annual income  million sum | Net Present Value (NPV), million sum |
| 1 | 31 | 351,3 | 0,862 | 271 845 | 271 845 |
| 2 | - | 351,3 | 0,743 | 261 073 | 532 918 |

The data in Table 3 shows that in the first year of the project, the income from its implementation amounted to *NPV=271.845* million sum.

The exact value of the payback period is calculated using the following formula.

 months, (9)

where: *t1-* the year in which the *NPV* balance was negative (*NPV t1*);

*t2-* гa case in which the *NPV* balance is positive (*INPV*).

Calculations showed that the payback period for capital investments is two months, and the total annual economic effect is 351.3 million soums per year.

**CONCLUSIONS**

Analysis of accidents at UTJ JSC production facilities for the period 2017-2023 showed that the number of accidents with serious consequences remains high. At the same time, accidents involving injuries to the arms, legs and spine accounted for 51.6% of all injuries. The main cause of serious injuries to workers in production is the lack of small mechanisation equipment for cargo operations. An analysis of the medical records of employees of the railway workshop of Uzmettkombinat JSC showed that 63% of cases of illness are due to injuries to the hands, feet and spine, of which 81% are employees of enterprises involved in opening and closing the lower hatches of open wagons. The best practices of scientific and theoretical developments by scientists and the achievements of modern science in the field of interaction between industrial enterprises and railway transport have shown that despite detailed and careful study of works devoted to this issue, no theoretical clarity has been achieved in methods for optimal interaction between both sides, taking into account the specifics of automation and mechanisation of station and freight operations, which determines the relevance of the research topic.

The use of small mechanisation equipment when closing the lower hatches of open wagons allows for the optimisation of production processes and increases the efficiency of labour resources. Mechanisation reduces the physical strain on workers, minimises the risk of occupational injuries associated with manual labour, and contributes to the creation of safer and more comfortable working conditions for personnel.

The introduction of a special device for closing the hatches of open wagons has reduced the time required for technological operations to clean wagons by 70 minutes and increased the number of wagon deliveries by 50%, as well as contributing to improved working conditions, reduced labour costs and a 35% increase in the productivity of workers involved in cleaning wagons. The economic effect of using a special device to close hatches amounted to 351.3 million soums per year. The payback period for capital investments in the development and implementation of the device was only 2 months.

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