Efficiency of implementation of interval traffic regulation by the "virtual coupling" system on the section of the railway line in the framework of the "digital railway" project

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Abstract. In order to remain competitive in the world market, to maximize the needs for transportation with increasing volumes of work, to ensure the availability and quality of services provided on railway transport in the field of organizing the transportation process, it is necessary to use modern digital approaches. The article provides an assessment of the existing technology for organizing the driving of connected trains using the example of the operation of the Mariinsk - Krasnoyarsk-Vostochny section of the Krasnoyarsk railway. With the development of technology for driving connected trains, it has become possible to connect trains by means of a virtual coupling, which does not imply physical coupling of trains using an automatic coupling device, while the trains are in a constant, equidistant, position from each other. To analyze the efficiency of organizing the driving of double trains in the "Virtual Coupling" mode, the authors of the article built train schedules with an interval for double trains of four minutes, and in the future with an interval of two minutes. The calculation of the main indicators of the train schedule and the line capacity has been made. The calculation revealed that with the introduction of the technology of interval regulation according to the "Virtual Coupling" system, the required throughput of the railway line increases by 19.05% relative to the existing traffic schedule with the use of double trains. The use of trains with "Virtual Coupling" on the Mariinsk - Krasnoyarsk-Vostochny section is preferable, since their use reduces losses in the traction network, power consumption and other parameters of the traction network, and the voltage at the locomotive current collectors is significantly higher than when using connected trains. The economic effect from the use of this technology for organizing the work of the Mariinsk-Krasnoyarsk Vostochny section will amount to 894.14 thousand rubles per year.

1. Introduction
Today, the main factor in ensuring competitiveness in the railway transport system (RWTS), which determines its position in the transport services market, is to provide a service of a qualitatively new modern level of services, entirely dependent on the opinion of consumers of this list of works and services, in connection with which the task of creating an electronic platforms for the management of all transportation activities in the field of freight and passenger transportation, infrastructure, rolling stock. For the development of digital technologies of the holding of Russian Railways, the concept of a comprehensive scientific and technical project “Digital Railway” was approved, the purpose of
which is to ensure the sustainable competitiveness of railway transport systems in the world market of transport and logistics services through the use of modern digital technologies and communications. The basis of this project is the complete integration of intelligent communication technologies between the cargo owner, the vehicle, the traffic control system and the infrastructure - the formation of new end-to-end digital technologies for organizing transportation activities in the railway transport system as a whole and components of its activities [1, 2].

The main directions of the project are:

- reducing the influence of the human factor on the state of the railway transport system;
- improvement of transport logistics;
- expansion and creation of new international transport corridors;
- reduction of the volume of paper workflow;
- reduction in the number of employees in the area of heavy traffic;
- minimization of the life cycle cost of railway infrastructure and rolling stock;
- increasing the reliability and safety of train traffic and the production of shunting work in the industry and on non-public tracks.

The railway transport system is especially in dire need of modern digital technologies in order to remain competitive in the world market, to meet the needs for transportation with increasing volumes of work, to ensure the availability and quality of services provided [1, 3, 4]. The lack of capacity of particularly loaded sections of the railway transport system requires the search for new ways to increase the technical capabilities of these sections, which will not only increase freight traffic, but also ensure the safety of train driving in difficult geographic and climatic conditions [5, 6, 7].

For the railways of Russia, the driving of trains of increased weight and length is of vital importance, in order to solve the problem of safe driving of trains of these categories, a large number of different driving technologies have been used in all years [3, 8, 9]. In 2001, an intelligent system for automated train driving (ISATD-RT) was created, which is installed on locomotives and allows information to be exchanged among themselves via a radio channel. ISATD-RT is designed to control the locomotives of connected trains weighing up to 12 thousand tons in the automatic driving mode. A distinctive advantage of this system is the possibility of automated asynchronous and synchronous control of power plants of electric locomotives of various types in traction and electric braking modes, coordinated operation of brake systems with combined brake lines, as well as the implementation of the function of automated synchronous or time-delayed control of locomotives from the head of the train [10, 11].

Passage of connected (double and triple) trains is effective not only during breaks in traffic due to the provision of technological "windows", but also in everyday train work, especially when there are difficulties in the movement of existing carriage flows [5, 12].

2. Assessment of the existing technology for organizing the driving of connected trains on the example of a section of the railway line Mariinsk - Krasnoyarsk-Vostochny of the Krasnoyarsk railway

According to the existing technology of driving connected trains on the Mariinsk - Krasnoyarsk-Vostochny section, these trains are formed at railway stations from two freight trains, each of which must be formed in terms of mass and length in accordance with the train schedule, as well as taking into account the restrictions on traction and power of the locomotive and power supply devices. Combining and disconnecting trains is allowed at stations and tracks on descents up to 0.004 ‰ and ascents up to 0.006 ‰ in compliance with safety conditions [13-16]. On the basis of the data, the graphs of train movements on the section of the railway line were constructed. The calculated values of performance indicators and the value of the throughput of a section of the railway line with the existing options for organizing train traffic are presented in Table 1.
Table 1. Performance indicators of the Mariinsk-Krasnoyarsk-Vostochny section according to the considered options for organizing the train passage technology.

| Railway section performance indicator | Units measurements | when organizing the work of a section without twin trains with the existing volume of work, train schedule (TS-1) | Indicator value when organizing the work of a section without double trains with an increase in the volume of work, train schedule (TS-2) | when organizing the work of the section in the mode of double trains, train schedule (TS-3) |
|--------------------------------------|-------------------|-------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------|
| Train-hours                          | t-h               | 711.76                                          | 843.52                                                          | 843.59                                                          |
| Number of trains of even direction   |                   |                                                 |                                                                 |                                                                 |
| - freight                            | train             | 54                                              | 64                                                              | 64                                                              |
| - passenger                          |                   | 14                                              | 14                                                              | 14                                                              |
| - suburban                           |                   | 5                                               | 5                                                               | 5                                                               |
| - prefabricated                      |                   | 2                                               | 2                                                               | 2                                                               |
| Number of trains of odd direction    |                   |                                                 |                                                                 |                                                                 |
| - freight                            | train             | 54                                              | 64                                                              | 64                                                              |
| - passenger                          |                   | 19                                              | 19                                                              | 19                                                              |
| - suburban                           |                   | 5                                               | 5                                                               | 5                                                               |
| - prefabricated                      |                   | 2                                               | 2                                                               | 2                                                               |
| Sectional speed                      | km / h            | 38.9                                            | 43.64                                                           | 42.18                                                           |
| Technical speed                      | km / h            | 59.21                                           | 62.52                                                           | 61.3                                                            |
| Sectional speed coefficient          |                   | 0.66                                            | 0.68                                                            | 0.68                                                            |
| Train weight                         | tons              | 6300                                            | 6300                                                            | 6300(12600)                                                     |
| Average train composition            | railway carriage  | 71                                              | 71                                                              | 71                                                              |
| Locomotive turnover                  | hour              | 22.11                                           | 22.38                                                           | 22.88                                                           |
| Required number of train locomotives | locomotive        | 55                                              | 62                                                              | 64                                                              |
| Average daily mileage of a locomotive| km                | 824.7                                           | 893.26                                                          | 865.35                                                          |
| Locomotive performance               | mln t-km-gross    | 4.41                                            | 5.63                                                            | 5.45                                                            |
| Available throughput of a railway line| steam trains      | 157                                             | 157                                                             | 157                                                             |
| The required capacity of the railway line |          |                                                 |                                                                 |                                                                 |
| - even direction                     | train             | 75                                              | 85                                                              | 85                                                              |
| - odd direction                      |                   | 80                                              | 90                                                              | 90                                                              |

With the improvement of the existing train schedule to the maximum volume of freight traffic and with the commissioning of double trains, the required throughput of the railway line increases by 11.7%. In TS-2, sectional and technical speeds increased by 8.77% and 5.3%, respectively, but in TS-3, with the commissioning of double trains, the value of indicators decreased by 3.3% and 1.95%,
respectively, relative to the TS-2. This dynamics is due to the fact that the organization of the section when driving double trains allows increasing the train weight to 12,600 tons and reducing the speed limit on the stretch. The locomotive turnover in TS-2 increases by 1.21%, and in TS-3 by an additional 2.2%. At the same time, the average daily mileage of a locomotive in TS-2 increases by 7.67%, and in TS-3 it decreases by 3.12% relative to TS-2. The productivity of the locomotive also increases by 21.7% in the TS-2, and decreases by 3.4% in the TS-3.

In order to remain competitive in the world market, to maximally satisfy the needs for transportation with the increasing volumes of the railway transport system, to ensure the availability and quality of services provided in the field of organizing the transportation process, it is necessary to use modern digital approaches [13, 17, 18].

3. Organization of driving connected trains in the "Virtual Coupling" mode

With the development of the technology of driving connected trains, it became possible to connect trains by means of "Virtual Coupling", which does not imply physical coupling of trains using an automatic coupling device, while the trains are at a constant, equidistant, position from each other. The distance is chosen by calculations and depends on the maximum stopping distance, based on the maximum realizable speeds on the section, the plan and profile of the track, the weight of the trains and a number of other factors. At the time of the trial operation of the virtual coupling technology, for reasons of traffic safety, this distance was determined at 1500 meters, Figure 1.

![Figure 1](image1.png)

**Figure 1.** Differentiation between auto-blocking and "Virtual chaining".

The approbation of the interval control technology was carried out with the synchronous movement of two trains with a minimum permissible distance from each other, while the locomotives are equipped with radio modems, with the help of which the modes of train driving from the leading locomotive to the slaves are transmitted via a secure digital channel. The slave locomotive transmits to the leader complete information about its condition. To carry out tests on the locomotives, specially developed M-Link radio modems were installed on the locomotives, and the software of the ISATD-RT control program was updated [19]. After the introduction of this system, trains can move with an interval of four minutes instead of the available 5-8 minutes, and in the future, they will run with an interval of two minutes [13, 15, 20], Figure 2.

On the basis of the traction calculations (Figure 3) of the section operation when driving double trains in the virtual coupling mode, a train schedule was built according to this pass technology. The performance indicators and throughput of the section under consideration when organizing train traffic in the "Virtual Coupling" mode are summarized in Table 2.
Figure 2. Technology of interval regulation of train traffic according to the "Virtual Coupling" system.

Figure 3. Current consumption of a freight train weighing 12,600 tons with a 2x3ES5K locomotive on the Mariinsk - Achinsk section.
Table 2. Performance indicators and throughput of the Mariinsk – Krasnoyarsk-Vostochny section with the introduction of the technology of interval regulation according to the "Virtual Coupling" system (TS-4).

| Railway section performance indicator | Units measurements | Indicator value |
|---------------------------------------|--------------------|-----------------|
| Train-hours                           | t-h                | 1107.12         |
| Number of trains of even direction    |                    |                 |
| - freight                             |                    | 84              |
| - passenger                           | train              | 14              |
| - suburban                            |                    | 5               |
| - prefabricated                       |                    | 2               |
| Number of trains of odd direction     |                    |                 |
| - freight                             |                    | 84              |
| - passenger                           | train              | 19              |
| - suburban                            |                    | 5               |
| - prefabricated                       |                    | 2               |
| Sectional speed                       | km / h             | 45.66           |
| Technical speed                       | km / h             | 62.7            |
| Sectional speed coefficient           | -                  | 0.68            |
| Train weight                          | tons               | 6300            |
| Average train composition             | railway carriage   | 71              |
| Locomotive turnover                   | hour.              | 23.85           |
| Required number of train locomotives  | lok.               | 83              |
| Average daily mileage of a locomotive | km                 | 911.87          |
| Locomotive performance                | mln t-km-gross     | 5.75            |
| Available throughput of a railway line| steam trains       | 157             |
| The required capacity of the railway line |            |                 |
| - even direction                      | train              | 105             |
| - odd direction                      |                    | 110             |

4. Analysis of efficiency in organizing the driving of double trains in the "Virtual Coupling" mode at the Mariinsk - Krasnoyarsk-Vostochny training ground, under various conditions for organizing the passage of trains

The introduction of the technology of interval regulation according to the "Virtual Coupling" system allows increasing the required throughput of the railway line by 19.05% relative to the TS-3. Sectional and technical speeds in TS-2 increased by 8.77% and 5.3%, respectively, but in TS-3, with the commissioning of double trains, they decreased by 3.3% and 1.95%. In TS-4, these speeds increased by 7.62% and 2.23%, respectively, relative to TS-3. The locomotive turnover in TS-2 increases by 1.21%, and in TS-3 by another 2.2%. In TS-4, with the introduction of the technology of interval control according to the "Virtual Coupling" system, the turnover of the locomotive increases by 4.07%. The average daily mileage of a locomotive in TS-2 increases by 7.67%, and in TS-3, when double trains are commissioned, it decreases by 3.12%. In TS-4, the average daily mileage of a locomotive increases by 5.10% relative to TS-3 [13, 15, 16].

The effectiveness of the implementation of interval regulation of train traffic using the "Virtual Coupling" system on the Mariinsk - Krasnoyarsk-Vostochny section of the Krasnoyarsk railway:

- the possibility of end-to-end organization of the operation of double trains within the framework of traction arms and, as a result of increasing the productivity of the direction of t / km per day by 10-12%
• an increase in the capacity of the direction by 10-12% (depending on the supply of energy and saturation of the traffic schedule);
• the elimination of the occupation of station tracks associated with operations on physical coupling from 2-4 hours per twin train;
• the possibility of operational "virtual formation of double trains in large quantities on sections and sections where work is carried out" in the windows "increasing the passage of trains per unit of time.

An analysis of the indicators of train schedules by options for organizing the movement of trains on the site shows a reduction in locomotive-hours of work, so in TS-2 there is a decrease by 8.17%, in TS-3 by 4.57%. With the introduction of the technology of interval control of trains according to the "Virtual Coupling" system by 10.46% relative to the TS-1. Reducing the cost of locomotive hours leads to a reduction in crew hours of locomotive crews, for example, with TS-2, brigade hours are reduced by 25%, with TS-3 by 17%, and with TS-4 by 23.46% relative to TS-1.

According to the economic calculations carried out by the authors, it has been determined that the most economical option for organizing train traffic is the option with the introduction of the technology of interval regulation according to the "Virtual Coupling" system, since the cost of freight transportation in comparison with other options for organizing train traffic is 1.85 rubles / 10 t. km.

The best option for organizing train traffic is GDS-4, as the economic effect of the Mariinsk – Krasnoyarsk-Vostochny section, obtained through the introduction of the "Virtual Coupling", increases by 41% relative to the existing schedule of trains with double trains. After analyzing the data obtained, we can conclude that the introduction of this technology will not only increase the throughput of the landfill, but also reduce the time for the formation and disbandment of double trains.

5. Conclusion
The advantages of organizing the driving of double trains in the virtual coupling mode identified during research on the example of the operation of the Mariinsk-Krasnoyarsk-Vostochny railway section can be distinguished:
• increasing the throughput of railway lines and sections without the need to build new railway lines, which will significantly reduce the financial costs of the industry while increasing the volume of work;
• minimization of the inter-train interval, which will lead to an increase in the throughput and carrying capacity of railway lines;
• optimal use of the existing station tracks, which will increase the efficiency of using the infrastructure of the structural divisions of the industry;
• the possibility of introducing modern solutions for managing the movement of trains of all categories, in order to reduce the delivery time of goods and thereby increase the level of customer focus;
• no need to form long-train trains, while the possibility of forming short trains, which will significantly reduce the time for the production of associated technological operations.

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