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STOCHASTIC MODELING OF DELAY PROPAGATION IN TRANSPORTATION SYSTEMS FOR CAPACITY OPTIMIZATION

The minimal headway for virtually coupled (VC) freight trains operating under stochastic timetable disturbances on the Trans-Siberian Railway is investigated. By analyzing empirical data from the Oy-Mos section, we identify distinct delay distribution patterns for regular freight (Erlang), heavy-haul (chi-square) and extra-long trains (Weibull). Using a hybrid discrete-event simulation (DES) and Petri net model, the impact of reduced headways (up to 3 min) on the capacity and timetable reliability is evaluated. The results reveal that headways below 6 min trigger secondary delay propagation, while 6-minute intervals are optimal for the capacity without compromising robustness. The adjustment of the interval from 13 min in the current automated blocking system to 7 min allows for a 54.2% increase of capacity for regular freight trains, 53.3% for heavy-haul trains, and 58.6% for extra-long ones. The proposed framework integrates real-world disturbances into the VC planning, offering a novel approach to the freight railway optimization.
Key words: virtual coupling, freight trains, minimal headway, stochastic disturbances, timetable reliability, discrete-event simulation.

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Көлік жүйелеріндегі кідірістердің таралуын стохастикалық модельдеу арқылы өткізу қабілетін оңтайландыру

Зерттеу Транссібір магистралындағы қозғалыс кестесінің стохастикалық ауытқулары жағдайында виртуалды тіркелген жүк пойыздары үшін қозғалыстың ең аз аралық интервалын анықтауға арналған. О–М учаскесінің эмпирикалық деректері негізінде кідірістердің тән үлестірім заңдылықтары белгіленді: нормативтік салмақ пен ұзындықтағы жүк пойыздары үшін — Эрланг үлестірімі, ауыр салмақты пойыздар үшін — хи-квадрат үлестірімі, ал ұзын құрамды пойыздар үшін — Вейбулл үлестірімі. Дискретті-оқиғалық модельдеу мен Петри желілерінің гибридті моделін қолдану арқылы қозғалыс аралығын 3 минутқа дейін қысқартудың өткізу қабілеті мен қозғалыс кестесінің сенімділігіне әсері бағаланды. 6 минуттан аз аралықтар екінші реттік кідірістердің жинақталуына әкелетіні анықталды, ал 6 минуттық интервал қозғалыс кестесінің тұрақтылығын жоғалтпай, өткізу қабілетін арттыру үшін оңтайлы болып табылады. Аралықты 13 минуттан 7 минутқа дейін қысқарту нормативтік салмақ пен ұзындықтағы жүк пойыздары үшін өткізу қабілетінің 54,2%-ға, ауыр салмақты пойыздар үшін 53,3%-ға, ал ұзын құрамды пойыздар үшін 58,6%-ға артуын қамтамасыз етеді. Ұсынылған әдістеме виртуалды тіркелген пойыздардың қозғалыс кестесін жоспарлау кезінде нақты стохастикалық ауытқуларды ескеріп, жүк теміржол тасымалын оңтайландырудың жаңа тәсілін ұсынады.

Түйін сөздер: виртуалды байланыс, жүк поездары, минималды интервал, стохастикалық бұзылыстар, кесте сенімділігі, дискреттi-оқиғалы модельдеу.

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Стохастическое моделирование распространения задержек в транспортных системах для оптимизации пропускной способности

Исследуется минимальный интервал движения для виртуально сцепленных грузовых поездов в условиях стохастических отклонений графика на Транссибирской магистрали. На основе эмпирических данных участка О-М установлены характерные законы распределения задержек: для грузовых поездов нормативного веса и длины - распределение Эрланга, для тяжеловесных - хи-квадрат, для длинносоставных - распределение Вейбулла. С применением гибридной модели дискретно-событийного моделирования и сетей Петри оценено влияние сокращения интервала (до 3 мин) на пропускную способность и надёжность графика. Установлено, что интервалы менее 6 мин вызывают накопление вторичных задержек, тогда как 6-минутный интервал является оптимальным для увеличения пропускной способности без потери устойчивости графика. Сокращение интервала с 13 мин до 7 мин обеспечивает прирост пропускной способности на 54,2% для грузовых поездов нормативного веса и длины, на 53,3% — для тяжеловесных и на 58,6% — для длинносоставных. Предложенная методика интегрирует реальные стохастические отклонения в планирование графика движения виртуально сцепленных поездов, предлагая новый подход к оптимизации грузового железнодорожного транспорта.
Ключевые слова: виртуальная сцепка поездов, грузовые поезда, минимальный интервал, стохастические отклонения, надёжность графика движения поездов, дискретно-событийное моделирование.

1 Introduction

Increased consumption of coal and other mineral resources makes it challenging for heavy-haul railways to maintain their operational capacity. This transportation method serves as the main system for the bulk transportation on the Trans-Siberian railway. At the same time, the rise of container traffic on railways leads to extra-long train operations. In such freight traffic structure, adjusting the headways for each train category allows increasing the transportation efficiency. The concept of virtually coupled train operation (Figure 1) has been proposed as a promising approach to increase both the flexibility and performance of railway systems [1]. While full-scale VC implementation with safety certification remains under development in operational railway environments, the technology has been extensively studied through simulations, laboratory experiments, and limited pilot trials. On the Trans-Siberian Railway, current automatic blocking systems achieve minimum headways of 9–12 minutes [14], which represents the baseline for evaluating potential VC benefits through simulation-based analysis. Scholars view virtual coupling (VC) as an effective method to boost the rail capacity through the reduction of headway to 2–3 min [2,3]. But the implementation of VC for freight traffic remains challenging because of differences in train weight and length (up to 9000 tons, up to 140 cars), stochastic disturbances and infrastructure conditions. While the theoretical foundations and control algorithms for VC have been extensively developed

[2–9], the technology has not yet achieved full operational deployment with formal safety certification on commercial railway lines.

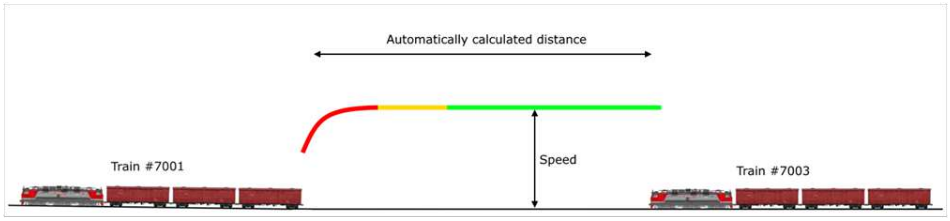

Figure 1: Train separation by virtual coupling.

The VC implementation creates new multiple problems that need to be addressed by the railway industry, such as timetable robustness and safety algorithms. Current studies are focused primarily on finding the minimum safe distance (or headway) between trains as well as the reliability of VC as a control system for stability purposes [4]. The research fields include calculation of spacing for virtual coupled train sets [5], implementation of safe communication protocols and reliable hardware components in interrupted communication [6], predictive control methods which use dynamic train state models to make effective decisions despite the uncertainty in train acceleration and positioning dynamics [7], distributed robust model predictive control research (DRMPC) implementation for the state of adequate stability conditions for the local and string stability in structural uncertainties to minimize distance and velocity tracking errors [8]. Also, the VC faces communication delay impacts which may be demonstrated through simulation experiments while exploring their implications for the railway train operation stability and energy consumption [9]. The research in [10] develops a complete train scheduling and routing system which handles rolling stock constraints by implementing microscopic routing adjustments with variable speeds and track restrictions derived from the braking performance at reference points.

Scientists develop methods for heavy-haul trains to enhance their safety and operational efficiency through a coordinated speed control. A cyber-physical framework for heavy-haul trains, which evaluates longitudinal dynamics alongside with the velocity alignment and appropriate train spacing, is presented in [11]. The cooperative reference velocity control method enables slow adjustments of heavy-haul train speeds to reduce train velocity variations and spacing differences. The safety margin enables both the emergency risk mitigation and increased capacity benefits for VC while maintaining secure train distances even when communication systems fail unexpectedly. The dynamic safety margin may provide this solution [12]. The VC implementation may create the best conditions for the timetable optimization of passenger and freight trains by implementing relative braking distance-based spacing strategies across different train types. Two distinct heterogeneous train operation scenarios, where the maximum braking capacity remains constant and variable between trains, are analyzed in [13].

Today, the VC technology on the Trans-Siberian railway fails to meet the efficiency expectations because it does not reach headways better than 9–12 min [14] instead of 3–5 min. The increased turnover of coal and containers resulted in a traffic bottleneck in some railroad sections. The effectiveness of timetable compliance is contingent upon various elements, including the train weight, length, electromagnetic compatibility, human factor, track conditions of hilly sections, etc. [15, 16]. However, the known railway traffic models fail to determine specific capacity values for freight train categories when they operate virtually coupled. A mathematical framework, which models timetable disturbances for different freight train categories, needs to be established. The common evaluation methods are not allowed to predict the rail network performance of VC in the heavy-haul and extra-long train traffic. Current researches ignore the train movement behavior under real stochastic disturbances in sub-5-minute headways.

The present study is aimed at determining the optimal headway for VC freight trains, ensuring enhanced railway capacity while maintaining the timetable reliability under real-world stochastic disturbances. To reach it, this study bridges the existing research gaps by developing a discrete-event simulation (DES) model grounded in actual operational data, analyzing delay distributions using Erlang, chi-square and Weibull functions for distinct train categories, and modeling optimal headways to balance the railway capacity and timetable robustness. Thereby, critical operational recommendations are provided for global freight rail systems facing similar challenges.

2 Simulation model

The effectiveness of railway transportation depends on multiple essential factors which include infrastructure conditions (climate, track numbers, electric traction etc.), rolling stock capacity, human factor and specific conditions. The problem of optimizing timetables to reduce the infrastructure pressure by shortening both inter-departure intervals and travel durations, and maximizing passenger train capacity utilization is addressed in [17]. The effects of infrastructure conditions produce timetable disturbances which require integration into transportation modeling approaches. The algorithms based on mixed integer programming models are employed in [18, 19] to manage train operations and adjust the timetable while considering stochastic delays. It enables a train delay transmission assessment which improves railway operations to enhance both the timetable reliability and transportation safety. The proposed train trajectory optimization model represents the train initial delay as a random variable with an unknown distribution. The model evaluates delay effects by using specific initial delay values between 0 and 300 s. A mathematical framework grounded in the stochastic process theory to analyze the railway traffic dynamics is introduced in [20]. This framework facilitates the computation of train speeds and distances while considering particular railway constraints. The current challenge requires analyzing how heavy-haul and extra-long train traffic behaves in actual operational settings. The existing research and proposed models are not enough to determine the best VC headway for assessing the efficiency of VC implementation instead of automatic blocking system.

In this section, the steps of creating the simulation model for the calculation of optimal headway are described. The DES model was developed to simulate the train movement for each train category. To accurately represent the movement of freight trains based on their specific categories, the DES was developed with incorporating stochastic timetable disturbances. In this framework, the simulation engine maintains a catalog of planned events that are aligned with the clock of the simulation engine. The DES methodology requires system state changes and decision-making processes to occur only at predetermined intervals.

This work employed the DES under the premise that changes in state occur solely at specific moments in time, allowing the simulation to advance by transitioning from one scheduled event to the other. It allows adjusting headways for freight trains in timetable disturbance conditions. To recognize real traffic disturbances, the timetable execution data were collected from the automated train motion monitoring system of Oy – Mos railroad section during 240 h. The position of the railroad section Oy-Mos of the Trans-Siberian Railway on the topographic map is shown in Figure 2. The Oy – Mos railroad section operates as a combined passenger and freight railway line that supports heavy-haul and extra-long transportations. The section features both curves and an extended hilly terrain that reaches inclines of up to 10.8‰. The observed train delays exceed one minute for 98% of all trains. The 3.3 kV AC electrification provides consistent power delivery, reducing variability in train performance compared to diesel traction, though electromagnetic compatibility considerations remain critical [16]. Terminal capacity at Oy and Mos stations affects train dispatching capabilities, modeled through the control position a_1 in the Petri net framework.

Automatic block signaling and interlocking systems captured the data regarding train departures and arrivals. The train categories (regular, heavy-haul or extra-long) were separated by the number which is assigned in the collected data. The automatic synchronization of block system devices with the NTP server allows guaranteeing the data reliability. The guidelines for processing train schedule statistics specify that the timetable performance data should be recorded with a one-minute precision [21].

The railroad section Oy – Mos is 23.1 km long. The ideal running time for freight trains on the analyzed section is 21 min and, for passenger and suburban ones, it is 17 min. The simulation framework is based on transferring delay durations among trains as they operate at headways. Throughout this process, secondary delays may occur.

2.1 Petri net approach to the model development

The proposed model enables continuous train dynamics through independent train dynamics which only connects through the VC headway control executed by discrete algorithms. Every train operates autonomously and is guided by the limitations imposed by the headway control system and its individual primary delay. However, there may be a situation where secondary delays propagate. In this situation, the trains behavior becomes dependent on each other.

Simplifications implemented in the model during the initial planning are as follows. Trains will not pass each other. Proper running time across railroad section of freight trains is identical. Primary delays are stochastically set and added to the running time of each train. The requirement to ensure the transportation safety is realized by means of the minimal distance condition in case of VC.

The proposed model represented by the Petri net is shown in Figure 3, where p_A is the initial position of train in station Oy, p_1 is the input to the railroad section, p_2 is the output from the railroad section, p_B is the destination position to station Mos, a_1 is the control position, s_2 is the safety supervisor, $t_{A,1}$ is the conditional transition and $t_{1,2}$, $t_{2,3}$, $t_{S,1}$ are the unconditional transitions with delay.

The process of virtually coupled trains movement along a railway section is represented as (P, T, μ). Here, P is the set of positions, T is the set of transitions (events controlling the trains movement), μ is the segment marking: $\mu = (\mu_1, \mu_2, \ldots, \mu_k)$, where $k = |P|$, $\mu_i \in \{0, 1\}$;

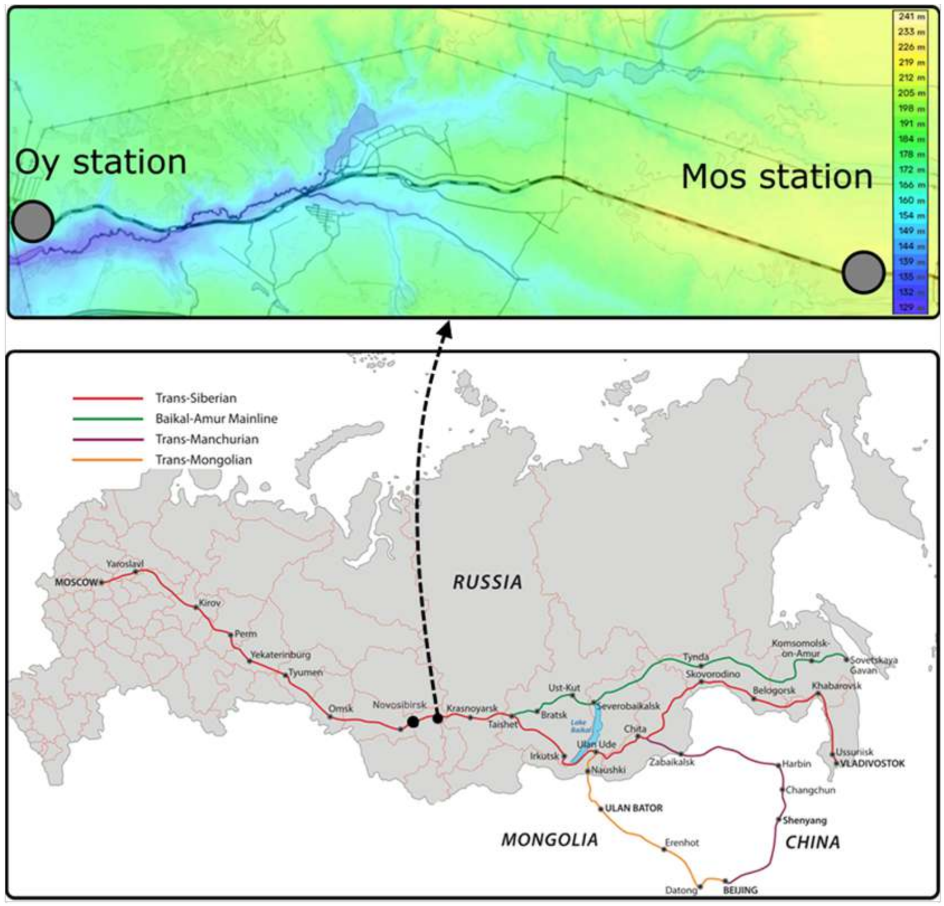

Figure 2: Scheme of railroad section Oy-Mos.

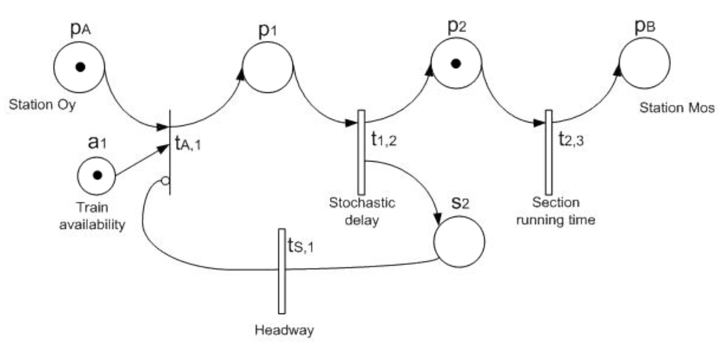

Figure 3: Petri-net model representation.

$\mu_i = 1$ corresponds to the presence of a token (train) in position p_i. The model is based on three constraints. Positions p_A and p_B correspond to boarded railway stations. Positions p_1 and p_2 belongs to the railway section. The value of μ_i is equal to the number of trains in position p_i (the number of trains in the i-th segment). The location of train at position p_A

means that there is the train to depart for the section. Position a_1 is the control position of the network. The state of position a_1 is determined by the value of the corresponding logical variables. The control variable value depends on the route construction system at the station. When the train is prepared for departure and the pathway from the station to the designated section is clear, the variable a_1 receives the value of 1. Subsequently, the train occupies position a_1, thereby establishing the necessary conditions to initiate the transition t_{A1}. As a result, the train moves from position p_A to position p_1 (railroad section input).

The transition $t_{1,2}$ from position p_1 to p_2 occurs with a time delay that corresponds to the stochastic disturbances from the designated timetable, which is governed by the probability distribution of a random variable. The movement from position p_2 to p_b, denoted as $t_{2,b}$, and it occurs within a time frame that corresponds to proper running time for the railroad section. Since the movement of virtually coupled trains on the section is associated with the presence of stochastic deviations from the timetable, a "catch-up" of one train by another is possible. A supervisor is necessary to ensure the compliance with safety regulations and avoid violations. The established safety criterion for dispatching virtually coupled trains traveling in the same direction on a common track requires a minimal train interval that meets or exceeds the value indicated by equation:

$$h \geq t_{\text{run}} + \tau_{\max}, \tag{1}$$

where h is the headway, t_{run} is the proper running time, and $\tau_{\max}$ is the maximum primary delay.

According to the Petri net graph (Figure 3), the train is prohibited from leaving p_A prior to the completion of the specified headway. This requirement is satisfied by the establishment of a safety supervisor. Let positions p_A and p_2 contain trains in the initial state of the network, as shown in Figure 3. Thus, the safety requirement is met in the initial state. When a_1 changes for 1, the transition t_{A1} activates, causing the train located at position p_A to shift to position p_1; however, this action contravenes the safety protocol since position p_2 is already occupied by another train. To prevent the activation of transition t_{A1}, the position p_2 incorporates the supervisor position s_2 along with the blocking arc ($s_2 - t_{S,1} - t_{A,1}$). The presence of train in position s_2 happens simultaneously with the presence of train in position p_2. The transition $t_{S,1}$ is executed within the headway. Thus, $t_{S,1}$ controls the train transition from p_A to p_1 according to headway. This ensures the continuity of the trains movement at a given interval, simulating the trains movement on the section. The number of trains on the railroad section is determined by the number of trains in positions p_i and depends on the headway, proper running time and primary delay values.

2.2 Simulation modeling in the Anylogic software

The DES components within the Anylogic environment can effectively replicate the Petri-net based model. This replication offers several benefits, including streamlined calculations, enhanced result processing, and improved model scalability. That is why the study utilizes the Anylogic software as the primary instrument for performing the simulation modeling. In Figure 4 is the schema of DES.

The "source" block generates trains in time according to headway. The proper running process of trains across the railroad section is realized in the "conveyor" block. On the

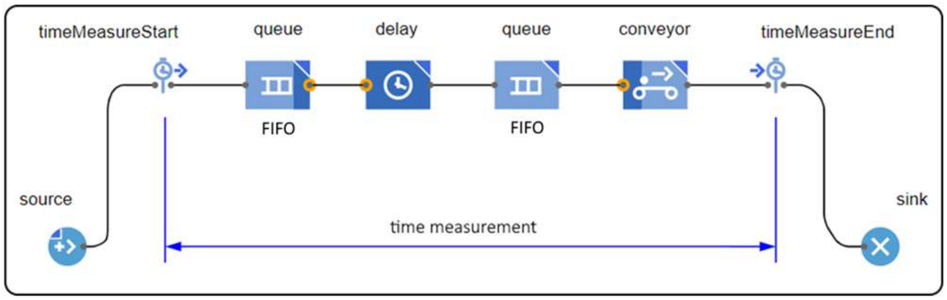

Figure 4: Flow diagram DES module of Anylogic for a single railway track operation.

conveyor system, trains consistently travel the most direct path from their starting point to their endpoint at a specified speed and distance between trains. The "delay" block serves for indicating the postponement of train arrival within stochastic disturbances of a timetable. Each train initiates its motion from the source block, follows a specified headway, gets a stochastic disturbance and ultimately reaches the "sink" block. A stochastic modeling approach employs a random number generator to produce stochastic values that serve as inputs for random variables. The variables that will be incorporated into the proposed simulation model are listed in Table 1. The train operations safety is ensured through a set of constraints illustrated in the flow diagram (Figure 4):

1. The number of trains in the convoy is not limited, but the headway limits the catch-up of trains.

2. Implementing a FIFO queue block prior to the delay block prevents trains from overtaking one another.

3. By placing an FIFO queue block in front of the conveyor block, trains can be stacked up while they wait for the railroad section to be released.

Table 1: Model variables

Variable	**Value**	**Description**
Headway h	3–20 min	Inter-train interval
Running time t_{run}	21 min**	Proper running time
Primary delay τ	Distribution law*	Stochastic delay input
Safety constraint	Eq. (1)***	VC safety criterion

* According to the delay distribution law of the real traffic by the train category.

** According to the standards set for the Oy – Mos railway section.

*** According to equation (1).

The time measurement utility serves for documenting the trains running time. It allows the corresponding modeling of the running time and the proper one by calculating real delays (in minutes). The total train data are used to determine the delay in minutes, which helps assess the performance of various train intervals. By conducting a statistical examination of the train arrival data stream produced from modeling outcomes, one can determine the actual delays experienced by each train at selected intervals, as well as secondary delay propagation and the alteration in capacity within the analyzed segment results from a decrease in train intervals.

The DES methodology is employed in [22] for evaluating the operational capacity of a railway corridor. Evaluating the railway capacity of a hypothetical railway corridor with various train headways was obtained. However, this method has limitations for applications on virtually coupled train sections, as train arrival intervals less than 15 min were not considered. This fact does not allow tracking the propagation of secondary delays associated with the reduction of train interval in the presence of stochastic disturbances in real traffic. In order to analyze operational delays, a stochastic scenario based on the assumption that the time intervals conform to an exponential distribution was implemented for train arrivals. Nevertheless, in [22], it is pointed out that this assumption is not a realistic representation. The probabilistic assessment of timetable reliability for heavy-haul and extra-long trains in real traffic conditions is investigated in [15]. Incorporating actual train delay statistics can enhance the precision and quality of modeling outcomes. To create the incoming flow of train delays, the empirical data regarding the real timetable execution were collected. The primary delays in the timetable data were aligned to the Chi-square, Erlang, Gamma and Weibull distribution laws by the Chi-square criterion, as outlined in the method described in [15].

The determination of the optimal train headway aimed at increasing the railroad capacity is focused on the real timetable stochastic disturbances. A primary train delay arises directly from an event that delays the train operation. Conversely, a secondary train delay refers to a situation where one train influences another train. The selection of optimal headway follows an optimality criterion that includes the following constraints:

$$\begin{cases} N(h) \to \max, \\ E[\tau_{\text{out}}] \le E[\tau_{\text{in}}], \end{cases} \tag{2}$$

where $N(h)$ is the section capacity at headway h, $E[\tau_{\text{out}}]$ is the mathematical expectation of output delays, and $E[\tau_{\text{in}}]$ is the mathematical expectation of input (primary) delays.

A simulation framework designed to analyze secondary delays that emerge from the distribution of input delays, which reflect primary delays, is introduced in [23]. The model utilizes the empirical data regarding the timing performance of Swedish railways as its basic input. To analyze the impact of various factors on the railway capacity and timetable reliability, a comprehensive review of existing methodologies and simulation frameworks is essential. The implementation of DES and creation of a simulation framework to analyze various train arrival situations are carried out in [22]. Additionally, a probabilistic scenario was established to assess timetable disturbances. The integration of DES with the application of the software aimed at optimizing dispatching and planning processes, which facilitates the evaluation of throughput and the formulation of strategies to enhance the dependability of train timetable, is discussed in [24]. The research detailed in [25] introduces a simulation model operating in discrete time, which facilitates the examination of freight and passenger traffic, accounting for train interactions. The research in [26] emphasizes the need for a fundamental restructuring of the signaling systems to enable the implementation of VC technologies. Research on railway capacity analysis conducted in [27–30] provides varied approaches to this issue, though it does not fully address the specifics of virtual coupling. The train delay modeling is addressed in [31, 32].

The concept of increasing capacity by minimizing the headways involves acknowledging the stochastic disturbances in the timetable. Numerous factors influence a deviation from a proper timetable, e.g. track topography, train type, weather conditions, human factors, etc. Therefore, the most accurate results can be reached by putting into the model the real delays on the railroad section over an observation time in order to ascertain the distribution laws of delays in a real train timetable. The model proposed in the present study permits the use of the distribution law associated with real stochastic delays as a dynamic variable in the delay block, thus, resulting in a more accurate examination.

3 Results

3.1 Mathematical modeling of timetable disturbances

The analyzed timetable data include 701 observations of heavy-haul, extra-long and regular freight trains characterized by weight and length (Table 2). To determine the most appropriate distribution law for the general population, researchers commonly use Chi-square, Erlang or Gamma functions. The evaluation of the statistical hypothesis concerning the distribution law occurs at a significance level of 0.05. The histogram of delays for regular freight trains and its corresponding approximation through selected functions are shown in Figure 5.

Table 2: Train category description

Train category	**Weight, tons**	**Length, cars**
Regular freight	up to 4500	up to 70
Heavy-haul	up to 9000	up to 140
Extra-long	>4500	>70

The x-axis represents the delay time in minutes, while the y-axis indicates the train number. The calculated results of theoretical distributions are given in Table 3. Analysis of the sample indicates that delay values ranging from 13 to 20 min should be merged into a single interval, prompting an extension of this interval to encompass a broader range.

Table 3: Calculation results of the delay distribution for regular freight trains

Distribution	χ^2_{obs}	χ^2_{cr}	**Accepted?**
Erlang	18.72	19.68	Yes
Chi-square	21.43	19.68	No
Gamma	20.15	19.68	No
Weibull	22.07	19.68	No

The findings from the distribution evaluation enable the proposal of a hypothesis regarding the Erlang distribution within the overall population. This continuous distribution

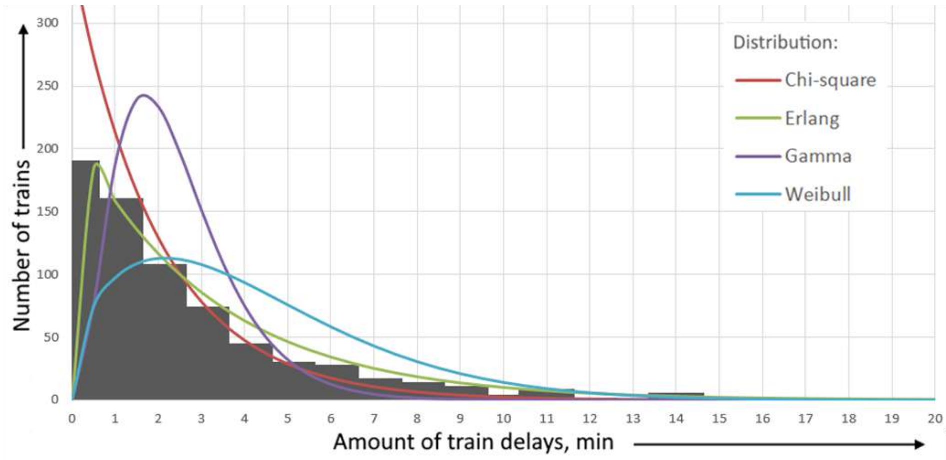

Figure 5: Statistical distribution of regular freight train delays.

is determined by the equation [33]:

$$f(x;k,\lambda) = \frac{\lambda^k x^{k-1} e^{-\lambda x}}{(k-1)!}, \quad x \geq 0, \tag{3}$$

where $k \in \mathbb{N}$, $\lambda > 0$ is the intensity (inverse scale factor). The distribution parameters λ and k are determined from the following equations:

$$k = \frac{(EX)^2}{DX}, \qquad \lambda = \frac{EX}{DX}, \tag{4}$$

where EX is the mathematical expectation of stochastic disturbances and DX is the dispersion. Based on the Chi-square criterion at a significance level of 0.05, the hypothesis remains valid since $\chi^2_{\text{obs}} < \chi^2_{\text{cr}}$ ($\chi^2_{\text{obs}} = 18.72$, $\chi^2_{\text{cr}} = 19.68$). Consequently, the random variations in the timetable of regular freight trains at railroad section Oy – Mos conform appropriately to the Erlang distribution. In accordance with the results reported in [15], the distribution laws of stochastic delays were established separately for heavy-haul and extra-long trains. The description of the train categories and delay distribution laws are given in Table 4.

Table 4: Stochastic delay distribution laws by the train category

Train category	**Distribution law**	**Parameters**
Regular freight	Erlang	$k = 3$, $\lambda = 0.42$
Heavy-haul	Chi-square	$\nu = 5$
Extra-long	Weibull	$k = 1.8$, $\lambda = 7.2$

As the delay distribution law is varied by the train category, it is advisable to conduct a separate modeling for each distinct category.

3.2 Simulation modeling of minimal train interval

To estimate the timetable robustness by the changing of headway, a 2-hour timetable sections were selected as the minimum planning period [21]. The probability and duration of delay for each train added to the model are determined by the distribution law. The 20 min headway was set for the model verification because it is able to level any random delay in the closed interval $[0, 20]$ observed in the general population. Moreover, the value of the 20 min headway is comparable to the estimated train travel time along the line of 20.9 min. It excludes the influence of delays on later trains, i.e. it guarantees limiting the spread of secondary delays. In Figure 6 are the graphs of the travel-time-on-the-section dependence on the duration of observation, obtained from the simulation modeling results. The data are averaged over 100 cases of travel and provide running time distribution in different headways.

Headways of 20, 13, 6 and 4 min were selected to evaluate the timetable reliability. It is expected that decreasing the headway leads to increasing the running time and scattering of values due to the fraction of stochastic delays. Some headway values may not be suitable for creating a reliable train timetable. For example, at an interval of 4 min (Figure 6), a gradual increase in travel time during the observation period is found for all train categories. This indicates the need to establish the minimum duration during which there will be no travel time increase over the 120 min observation window.

It is topical to examine how random delays at model inputs affect the section running time that emerges from the model. The comparison of the input and output delay flow at different headways allows determining the critical value at which the accumulation of secondary delays starts. This is possible by comparing the mathematical expectation of the input and output delay flow. Based on the results of simulation modeling, a set of output train delays $\tau_{i,\text{out}}$ $(i = 1, \ldots, n)$ was obtained. The data are grouped into intervals by 1 min. The simulation results are summarized in Table 5. In accordance with the applications of the central limit theorem, the minimum required sample size with a given accuracy Δ and significance level α is determined according to the expression [34]:

$$n \geq \left(\frac{z_\alpha \cdot \sigma}{\Delta} \right)^2, \tag{5}$$

where z_α is the quantile of the normal distribution of level $1-\alpha/2$, σ is the standard deviation and Δ is the confidence interval accuracy. For a normal distribution $\alpha = 0.01$ and the quantile is determined as $z_\alpha = 2.58$. The interval accuracy is assumed to be $\Delta = 1$ min.

Table 5: Statistical analysis of simulation for regular trains

Headway, min	n	$E[\tau_{\text{in}}]$**, min**	$E[\tau_{\text{out}}]$**, min**	σ**, min**	**Stable?**
20	12	6.0	5.8	2.1	Yes
13	18	6.0	6.2	2.3	Yes
6	40	6.0	6.5	3.1	Borderline
4	60	6.0	9.3	4.7	No

The secondary delays propagation criterion is the excess of the mathematical expectation of the statistical sample over the original distribution. Analyzing the propagation of deviations

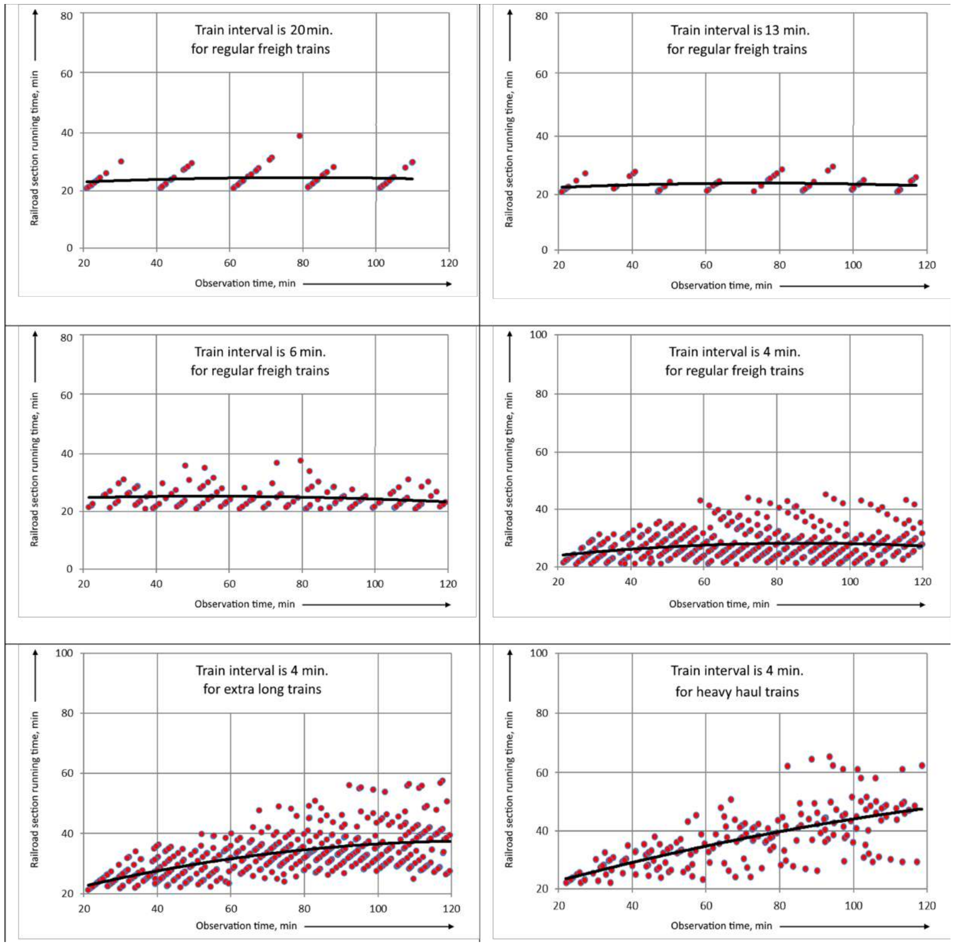

Figure 6: Running time execution on the Oy-Mos railroad section.

from the timetable at different headways makes it possible to determine the minimum permissible interval that does not induce the growth of secondary train delays. In Figure 7 is the dependence of the mathematical expectation of train delay on the size of the headways for different categories of freight trains. As it is seen, the reduction of headway to 6 min leads to the secondary delays accumulation. It is an indicator of the loss of timetable stability.

3.3 Capacity estimation

Despite the accumulation of secondary delays, reducing the headway below 6 min may also increase the railroad section capacity. To assess the efficiency of reducing the inter-train interval taking into account stochastic deviations, the capacity was calculated at different headways. In Figure 8 are the results for the throughput capacities of the section on a 120 min graph segment.

As it is seen, with the headway being reducing, the railroad capacity increases. The shape differences in railroad capacity curves are related to the train category, weight, length of trains and different delay distribution laws.

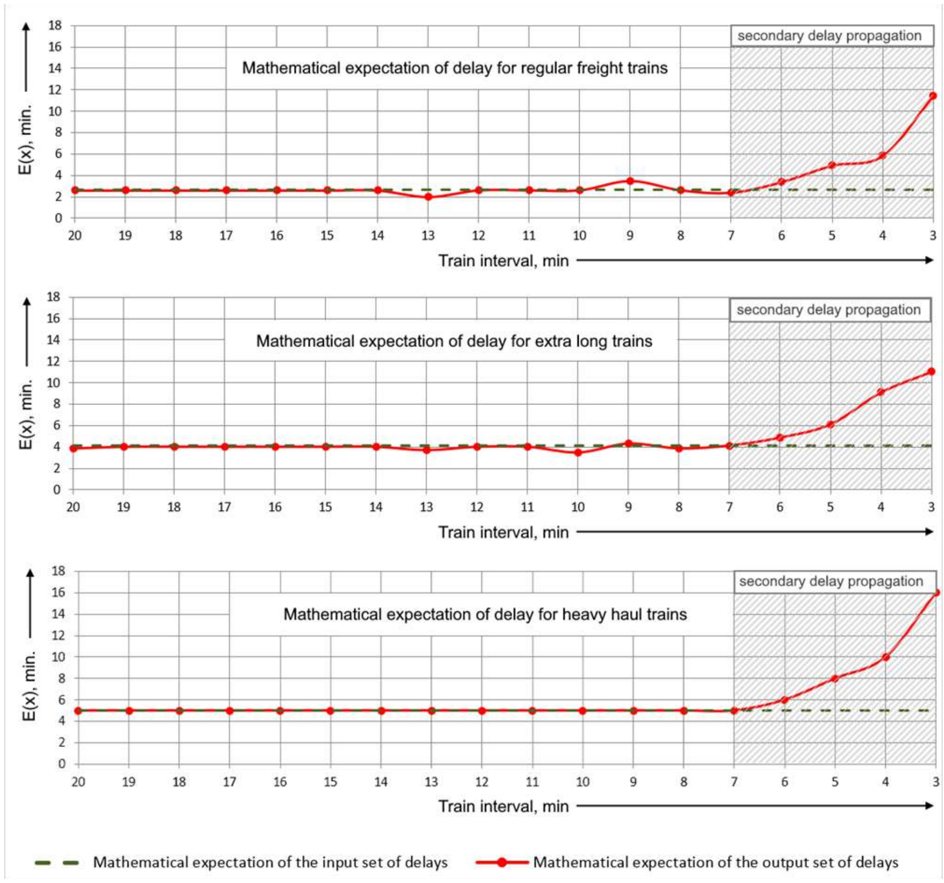

Figure 7: Expectation of delay for different freight trains.

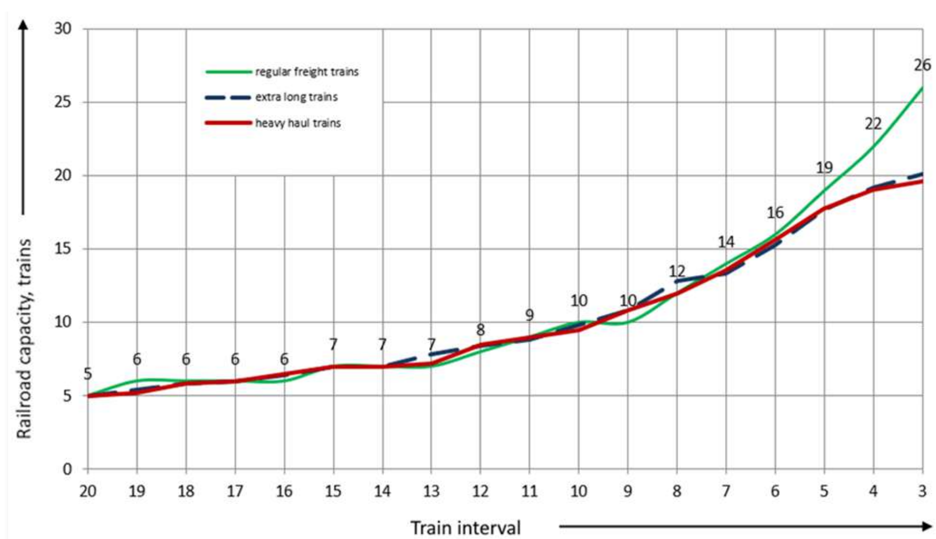

Figure 8: Railroad section capacity dependence on a train interval.

4 Discussion

The investigation presents a new solution to enhance virtual coupling (VC) systems for freight trains on the Trans-Siberian Railway, and it addresses real-world uncertainties from various train types (regular freight, heavy-haul and extra-long trains). The present study makes a unique contribution to this issue by analyzing freight train operations under VC with distributions that match real-world delay patterns for regular freight (Erlang), heavy-haul (chi-square) and extra-long trains (Weibull). The findings are based on the operational data from 240 h of the Oy-Mos section monitoring, which creates robust empirical evidence for better research applicability.

The proposed method, which combines discrete-event simulation (DES) and Petri nets, delivers a superior performance beyond current methodologies. The prior research by Zhang [17] and Corman et al. [20] used multi-agent simulations and stochastic differential equations, yet they maintained generic delay models and idealized conditions without analyzing specific train categories. The study incorporates actual statistical data to analyze the operational patterns of freight trains because they differ in weight (up to 9,000 tons) and length (up to 140 cars). The Petri net modeling of safety constraints with delay propagation helps maintain the system stability under stochastic disturbances and solves a critical problem from the previous contributions that failed to address freight train headway instabilities of less than five minutes.

The research reveals that a 6 min headway represents the most effective interval for balancing the system capacity enhancement (54–58% increase across train categories) and schedule reliability. The studies by Wu et al. [2] and Xun et al. [3] introduced 2–3 min headways for virtual coupling without experimental validation under real freight operations. The research proves that headways shorter than 6 min create additional delay effects which destabilize the system while previous studies about passenger and metro operations failed to show this critical point. Wang et al. [4] studied energy-delay trade-offs for metro trains operating with 40 s switch constraints; yet their results cannot be directly applied to freight operations due to their large-scale and variable nature.

The proposed methodology works for any railway section before the virtual coupling (VC) implementation, especially when minimizing inter-train headways is essential for the capacity increase. The framework can be modified for various rail networks through the integration of empirical delay distributions and safety constraints to optimize headways while preserving the timetable reliability. The proposed method can solve bottlenecks in high-density freight corridors such as the Krasnoyarsk–Irkutsk section of the Trans-Siberian Railway, where coal and container traffic delays occur, and the Australian Pilbara rail network, where heavy-haul iron ore trains face capacity limitations. The proposed method would benefit China Daqin Railway, which transports coal as its main cargo and Europe Rhine-Alpine Corridor, which carries mixed freight by reducing headways and decreasing congestion. The methodology is characterized by the network scalability for multi-section systems because it models complex segment interactions by including specific delay patterns and infrastructure constraints, which results in a powerful optimization tool for worldwide railway systems.

The study addresses heavy-haul and extra-long train operations by delivering practical solutions for optimizing freight under real-world conditions unlike Flammini et al. [26] that ignored freight heterogeneity. The proposed framework combines empirical delay distributions with the safety-oriented DES-Petri net modeling to present a scalable solution which helps global railway operators manage their similar operational challenges. The research indicates that a 6-min adaptive headway produces better results than earlier fixed headway approaches since it reduces delay propagation risks and provides substantial capacity increase. The research contains certain restrictions that need an additional investigation. The model does not allow overtaking. Yet this aspect could be significant for corridors where passenger and freight trains operate together on the same tracks. The current analysis only covers the Oy-Mos section, and, so, a future validation should be performed on different track layouts with different traffic patterns. The indirect modeling approach for human factors and equipment failures through stochastic delays might not accurately represent their actual effects. The proposed framework needs its development to support multi-section networks with incorporated overtaking scenarios and direct modeling of climate and infrastructure variations to enhance the timetable stability and practical application.

5 Conclusions

The research introduces an original solution to deploy virtual coupling in the freight train management that addresses how timetable uncertainties affect minimum operational headways. The research develops the optimal 6 min headway through the DES-Petri net modeling that enhances capacity by 54–58% while ensuring the realistic timetable reliability. This study introduces a novel approach that differs from the previous work focused on passenger or homogeneous train systems because it provides customized solutions for different freight operations. The research findings deliver practical knowledge for developing modern traffic management systems which should focus on dense freight routes like the Trans-Siberian Railway. The combination of actual disturbance modeling and safety constraints creates a new benchmark for the Virtual Coupling implementation which will drive future progress in the heavy-haul railway optimization. Besides, this model can be developed to account such significant factors as overtaking scenarios in mixed passenger-freight operations, climate and infrastructure variability.

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Authors contribution

Conceptualization — VP; Methodology — VP; Software — VP; Formal Analysis — VP; Data Curation — VP; Investigation — VA; Writing – Original Draft Preparation — VP and VA; Writing – Review & Editing — VP and VA; Supervision — VA.

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