STOCHASTIC TIMETABLE DISTURBANCES IN HEAVY HAUL AND EXTRA-LONG TRAIN TRAFFIC

DOI: 10.36724/2072-8735-2025-19-2-53-60

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Manuscript received 12 January 2025;
Accepted 10 February 2025

Keywords: *timetable disturbances, train delays, stochastic disturbances, heavy haul train, extra-long train, train interval, virtual coupling*

This work is aimed at studying the stochastic assessment of the timetable accuracy of heavy haul and extra-long trains in real traffic conditions. The timetable accuracy is dependent on several factors, including climate conditions, rolling stock specification, railway track profile, fails of equipment, speed limitations, etc. These factors affect every train movement on the section at the observation time. However, the timetable accuracy may be drastically reduced depending on specific train features, such as type (passenger or freight), weight and length. There are trains of the weight up to 8000 tons and a length up to 2 km on the Trans-Siberian railway and increasing throughput on railroad sections by reducing train intervals is topical. In this case, stochastic timetable disturbances may significantly limit the value of train interval and section throughput. In the study, a mathematical modeling of train delays on a railroad section based on the statistical data of timetable execution is developed. It is shown that the train disturbances and malfunctions can be considered using a stochastic approach. The way to estimate timetable disturbances by distributions of chi-square, Erlang, Gamma and Weibull is found in this contribution. The research results may be used for the simulation models development and timetable planning, especially for the design of timetable robustness.

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Для цитирования:
Польянов В.В., Атучин В.В., Бессоненко С.А. Стохастические отклонения от графика движения тяжеловесных и длинносоставных поездов // T-Comm: Телекоммуникации и транспорт. 2025. Том 19. №2. С. 53-60.

For citation:
V. V. Polyanov, V. V. Atuchin, S. A. Bessonenko, "Stochastic timetable disturbances in heavy haul and extra-long train traffic," *T-Comm*, 2025, vol. 19, no. 2, pp. 53-60.

1 Introduction

The process of planning on the railway transport is aimed at accounting the distribution of freight and passenger trains, local work execution, reducing infrastructure faults, meeting the standard weight and length of trains, etc. The development of optimal routes in freight traffic requires increasing the throughput in railway sections [1]. At the same time, developing a robust timetable is an important task for the railway efficiency increase, especially in the Traffic Management System (TMS) development.

TMSs are advanced systems that help increase the throughput of railways by reducing of train interval to 4 minutes or less instead of 8-10 minutes typical in the case of automatic block systems [2,3]. According to the results reported in [4,5], the telecommunication infrastructure on railway sections is ready for the implementation of virtual coupling on the sections of Trans-Siberian Railway. However, the effectiveness assessment and optimal section selection for testing the technology can be carried out only based on safety and specific conditions, such as traffic characteristic, infrastructure limitations, climate, track numbers, electric traction, rolling stock capacity, human factor, etc. For example, in accordance with the timetable standard [6], the proper running time on a railroad section is dependent on rolling stock conditions, locomotive power, load capacity of catenary, safety requirements of train traffic, dynamic loads, etc.

One of specific conditions of the Trans-Siberian Railway is heavy haul and extra-long train traffic. The efficiency of heavy haul transport can be increased with changing optimal train intervals by a virtual coupling implementation. At present, researches propose programming models, such as the train service plan problem, train timetabling problem model and simulated annealing algorithm [7, 8]. These approaches allow obtaining a train service plan by minimizing the operation cost and maximizing the transportation volume of special heavy haul railway lines. The distance headway scheme for heavy haul trains, sometimes, is not efficient to reach a virtual coupling of freight trains. In [9], the virtual coupling was studied for heavy haul freight trains, and it was proposed to set the follower train to be a certain time behind the schedule of the leader train rather than the distance headway. The disturbances in heavy haul lines may especially occur in virtual coupling sections. In [10], the virtual coupling-based timetable rescheduling method was proposed to reduce the delays under disruptions and increase the line capacity by the mixed-integer linear program (MILP) model.

The Trans-Siberian railway is a passenger-freight collinear railway. The accuracy of timetable execution for freight trains is comparatively low because of high priority of passenger trains. It leads to significant fluctuations in reference to a proper timetable and crew plan in the presence of disturbances. The problem of rescheduling the train timetable and crew scheme in the presence of disruptions on a passenger-freight collinear railway was considered in [11]. The mixed-integer linear program model was developed considering the distinctive priorities of passenger and freight trains, as well as crew operations in order to minimize train delays and fluctuations in the crew schedule, while maximizing the delivery rate of freight trains at the railway. The robust railway design considering freight train traffic fluctuations was implemented in [12]. The optimization model of the robust version of strategic timetable is developed as discrete scenarios. At the same time, the uncertain freight train demand is modeled using optional trains, which can be inserted in the resulting timetable.

Another reason of freight trains timetable fluctuation is infrastructure limitations. The severe fluctuations in the traction power may depend on the train operation stability. Researches tried to account for operation conditions in mountain railways and reveal the ways for the train timetable optimization of mixed passenger/freight railways to reduce their impact on weak power grids [13, 14]. The electromagnetic compatibility limitations on the railway transport, as emissions from power lines to nearby lines and signal circuits, were reported in [15, 16].

In accordance with the train interval calculation methodology [17], the motion on the railroad section is described as a stationary process. It does not consider any stochastic fluctuations from the proper timetable. However, there are train delays occurred in real traffic conditions, which may lead to a change of train interval, running time on the section and the throughput. Timetable disturbances caused by a wide range of factors related to the functioning of railway units or induced by external factors are difficult to take into account. Train delays caused by the direct influence of an interfering factor are called primary delays, and secondary delays appear due to the delays of earlier trains [18]. Nowadays, topical is to increase robustness at the timetable level for heavy haul and extra-long train traffic, especially in TMS conditions. It allows increasing the throughput of railways by setting an optimal train interval. That is why the main purpose of the work is to reveal and estimate the timetable disturbances on a railroad section planned to be implemented by the virtual coupling technology.

One of the approaches used by researchers to consider the timetable disturbances is stochastic modeling. It presents the data on complex processes and predicts the outcomes that account for certain levels of unpredictability or randomness, especially in combination with stochastic interference. Stochastic microscopic simulation models allow recognizing the capacity and stability of timetable depending on the TMS type (such as radio-based control systems) implemented on the railroad section. The evaluation by this algorithm is based on simulation experiments [19]. The results of modeling allow changing priority lines for a possible installation of advanced train interval systems based on the capacity and operational conditions. The model of primary train delays allows creating a robust timetable by discrete probability distributions. In [20], the exact symbolic simulation method is used to compute the impact of delays in railway systems. To reach that, the method of computing exact probabilistic quantities was proposed. The delay probability distributions, expected delays for timetable trains or expected capacity use of infrastructure elements may be estimated by stochastic algorithms. These approaches allow recognizing infrastructural problems and increasing the timetable robustness. In [21], a two-step stochastic optimization model was used to allocate the supplements and buffers with the objective of minimizing the real-time schedule fluctuation from the planned timetable. This approach is one of the easiest to realize and implement the calculations, but it is not precise when a complex environment is considered.

In order to estimate the efficiency of TMS implemented on the Trans-Siberian railway, it is necessary to introduce stochastic disturbances in the simulation model. Accordingly, the present study is aimed at describing timetable disturbances for a train flow on a selected railroad section by the optimal mathematical function. Furthermore, as the timetable execution accuracy may be dependent on train conditions (weight, length, kind of haulage etc), the created stochastic model should be able to account the freight train traffic for different train categories, especially for heavy haul and extra-long trains. The implementation of stochastic approach for analyzing timetable may describe the disturbances observed across the Trans-Siberian railway and establish the reasons of delays. The timetable disturbances are estimated as fluctuations from a proper running time on the railroad section Oy-Mos of the Trans-Siberian Railway. The position of the railroad section Oy-Mos on the topographic map is shown in Figure 1.

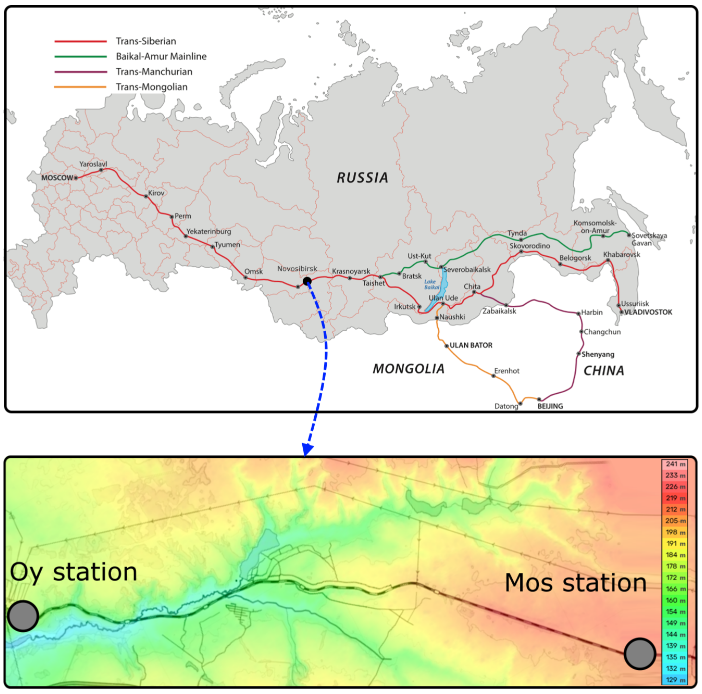

Fig. 1. Scheme of railroad section Oy-Mos

The Oy-Mos railroad section is a passenger-freight collinear railroad part with heavy haul and extra-long train traffic. Special conditions of the section include curves and long hilly parts inclined up to 10.8‰. Average percent of trains delayed more than 1 minute on this railroad section is 98% per month.

The study is based on the timetable execution data collected from automated train motion monitoring system during 240 h. The train departure and arrival data were recorded using automatic block signaling and interlocking devices (on the occupation of block section circuits). The train category is identified by the number which is assigned for the transportation route. It allows recognizing the train category in statistical data including heavy haul and extra long trains. The reliability of the data is ensured by synchronization automatic block system devices with the NTP server. In accordance with the methodology for processing train timetable statistics [22], the timetable execution data are recorded with an accuracy of ±1 min.

2 Methods

The process of the train motion along a railway section may be described using the following differential equations [23]:

$$\begin{cases} \frac{ds}{dt} = v \\ \frac{dv}{dt} = a \end{cases}, \qquad (1)$$

where s is the railway section distance of the train relative to the railway station, v is the train speed and a is the train acceleration. But the problem of this approach is in recognizing the fluctuations of kinematic parameters of a moving train in real traffic. As transportation is the process of transfer trains between stations, it is possible to consider disturbances from the timetable execution data.

The study includes an analysis of the data on real train traffic using probabilistic statistical methods. A hypothesis was put forward about the possibility of describing a statistical sample using the known distribution laws. The statistical hypothesis was tested on the compliance of the assumed distribution law with the theoretical law at a significance level of 0.05 using the Chi-square criterion.

A mathematical model of train flows via a railway station was proposed in [24]. The mathematical model is based on the collected statistical data on the Trans-Siberian railway. The timetable fluctuations of freight trains are considered on the stochastic approach. The obtained modeling results show the distribution laws of train delay values for passenger and freight trains. However, such specific track and traffic conditions as heavy haul and extra-long trains were not considered in [24].

3 Timetable execution accuracy on the railroad section

The statistical data of timetable execution were collected during 10 days of January. The running time on the railroad section is analyzed in accordance with the following conditions:

– running time fluctuations of up to 0.1 min are discarded;

– r nning time fluctuations more than 0.1 min up to 1 min are accepted as 1 min in accordance with the Train Timetable Guide [25] and Regulation for the Timetable Data Analysis [22];

– train delays in the railroad section more than 1 h for freight trains and more than 6 min for passenger trains are not considered as a stochastic delay. It is topical because such timetable fluctuations are caused by the failure of technical facilities in accordance with the terms of the regulation for the failures analysis in the railway infrastructure [26].

The length of railroad section Oy-Mos is 23.1 km. The proper running time on the observed section is 21 min for freight trains and 17 min for passenger and suburban ones. Negative values (ahead of timetable) are not taken into account. The results of the statistical data of timetable execution are shown in Table 1.

Table 1

Running time fluctuations on the railroad section
Oy-Mos by train categories

	Total	Heavy haul trains	Extra long freight trains	Regular freight trains	Passengers and suburban trains	Other trains
Number of trains	1013	238	190	245	220	120
Running time fluctuations	896	233	189	238	40	96
Percent of timetable accuracy	12%	2%	1%	3%	82%	20%

Evidently, there are large timetable fluctuations on the railroad section. The lowest running time accuracy occurs for freight trains, including heavy haul and extra-long freight trains (1-3%). In Figure 2 is the time distribution of timetable fluctuations from the proper running time on the railroad section.

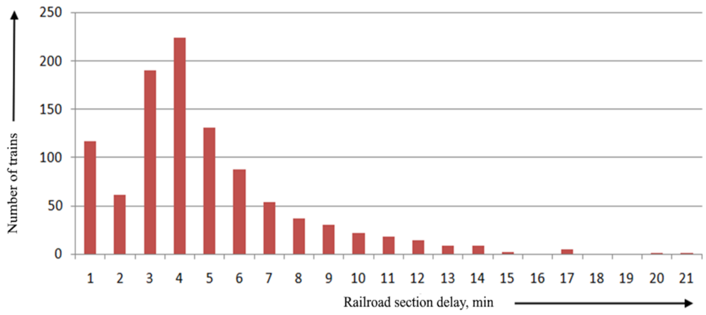

Fig. 2. Distribution of timetable delays on the railroad section

A lot of factors should be taken into account to find and the key causes of the timetable disturbances. For example, a special condition of the Oy-Mos railroad section is the presence of long hilly and curvy sections. Heavy haul trains (up to 7000 tons) on such sections lose their speed at a hilly rise. It may lead to reduction of a train interval and a switching of an automatic block signal to yellow or red one. Moreover, a sizable portion of the disturbances is related to occidental external factors, including weather conditions, visibility conditions, third party influence etc. The values of timetable delays on the railroad section are shown in Table 2.

Table 2

Values of running time fluctuations
on the railroad section Oy-Mos

	Total	Heavy haul trains	Extra long freight trains	Regular freight trains	Passengers and suburban trains	Other trains
Total trains	1013	238	190	245	220	120
Fluctuations (min)	3804	1010	786	1005	141	462
Average fluctuation per train (min)	3.8	4.2	4.1	4.1	0.6	3.9

The largest fluctuations belong to freight trains (4.1-4.2 min), including heavy haul and extra-long ones, and the smallest fluctuations belong to passenger and suburban trains (0.6 min). There are neither technical failures nor speed limitations that occured on the section during the data collection. Thus, the reasons for the observed delays are stochastic disturbances which have to be described in timetable modeling tasks. The train running time depends on many factors, and they are all difficult to taken into account. For this reason, the running time on the railroad section is considered as a random variable, and, in the present study, this variable is described by the stochastic approach.

According to the statistical data, the timetable disturbances analysis is performed by train categories separately. Special attention is paid to heavy haul and extra-long freight trains. The data of timetable fluctuations on the railroad section correspond to the Chi-square, Erlang, Gamma and Weibull distribution laws. The statistical hypothesis verification about the distribution law is carried out at the significance level of 0.05 using the Chi-square criterion. The significance level of 0.05 means that there is a 5% probability of incorrectly rejecting the null hypothesis when it is true [27]. This level strikes a balance between minimizing false positives and detecting real effects.

3.1 Heavy haul train delay distribution

In order to analyze the timetable disturbances for heavy haul trains, the data are distributed over the range from 0 to 20 min by intervals of 1 min. It includes 238 heavy haul train observations out of the available 1013 of the total trains number. The horizontal axis shows the time of delay in minutes and the vertical axis shows the number of trains. Chi-square, Weibull, Erlang and Gamma functions are used for fitting to reveal the optimal distribution law of the general population. The train delays histogram and its approximation by selected functions are presented in Figure 3.

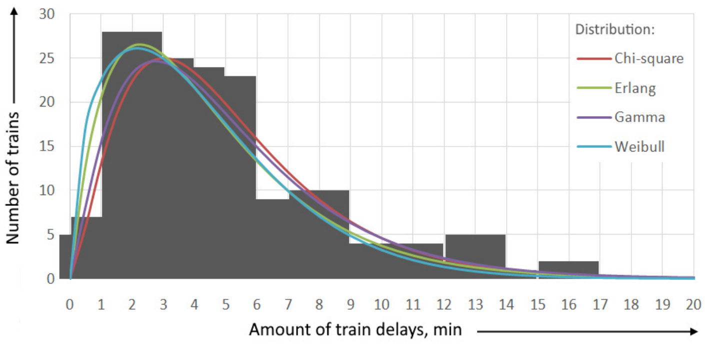

Fig. 3. Statistical distribution of heavy haul train delays

In Figure 4 are the cumulative distribution functions according to Chi-square, Weibull, Erlang and Gamma distributions.

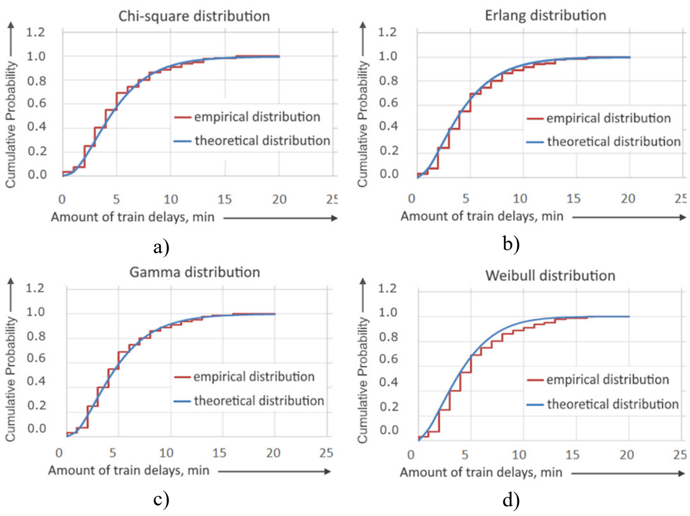

Fig. 4. Approximations of heavy haul train delay cumulative distribution functions by: a) Chi-square; b) Erlang; c) Gamma; d) Weibull dis ibutions

The hypotheses test is performed using the chi-square criterion. The sample shows that the delay values from 13 to 20 min should be combined into one interval. That is why this interval is extended to a large value. The calculated results of theoretical distributions are given in Table 3.

Table 3

Calculation results of the delay distribution for heavy haul trains

Time interval [a,b)		Number of delays by				
		Observation data	Chi-square distribution	Erlang distribution	Gamma distribution	Weibull distribution
0	1	5	6.06434	12.0295	7.9855	16.0307
1	2	7	18.3742	24.3386	20.0869	24.8379
2	3	28	24.1638	26.235	24.296	25.7615
3	4	25	24.3923	23.6175	23.5539	23.3833
4	5	24	21.6328	19.4882	20.5039	19.5815
5	6	23	17.7651	15.2735	16.7452	15.4631
6	7	9	13.8637	11.5692	13.1093	11.651
7	8	9	10.4336	8.55356	9.95882	8.43737
8	9	10	7.64178	6.21041	7.39717	5.90165
9	10	4	5.48028	4.44618	5.39933	4.00149
10	11	4	3.86455	3.14759	3.88647	2.63717
11	12	4	2.68794	2.20791	2.7658	1.693
12	13	2	1.84826	1.53698	1.94968	1.06057
13	20	8	3.78736	3.34578	4.36195	1.55962

The results of distribution assessment indicate that the general population is well approximated by the Chi-square function. The Chi-squared distribution is a continuous distribution determined by equation [28]:

$$f(x) = \frac{1}{2^{\frac{v}{2}}\Gamma(\frac{v}{2})} \exp\left(-\frac{(x-m)}{2}\right)(x-m)^{\frac{v}{2}-1}\ , \qquad (2)$$

where *m* is the minimum x-value and ν is the shape parameter.

The parameter ν is a number of degrees of freedom which are equal to the mathematical value expectation.

According to the Chi-square criterion at significance level of 0.05, there is no reason to reject the hypothesis since $X^2_{observed} < X^2_{critical}$ ($X^2_{observed} = 18.03$, $X^2_{critical} = 21.03$). Thus, the distribution of stochastic timetable disturbances of heavy haul trains is well described by the chi-square law.

3.2 Extra-long train delay distribution

The timetable disturbances for the data of extra-long trains are constructed in the range from 0 to 20 min by intervals of 1 min. In Figure 5 is the histogram of train delays and distribution functions. The statistical data includes 190 extra-long train observations out of the available 1013 of the total trains number (19%).

The horizontal axis shows the time of delay in minutes, and the vertical axis shows the number of trains. Chi-square, Weibull, Erlang and Gamma functions are employed for fitting to put forward a hypothesis about the distribution law of the general population.

The hypotheses test is performed using the chi-square criterion. The sample shows that the delay values from 13 to 20 min should be combined into one interval. That is why this interval is extended to a large value. The results of theoretical distributions are given in Table 4.

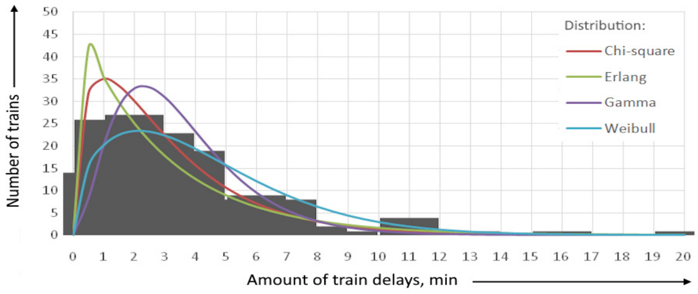

Fig. 5. Distribution of extra-long train delays

In Figure 6 are the empirical distribution and theoretical distributions according to Chi-square, Weibull, Erlang and Gamma functions.

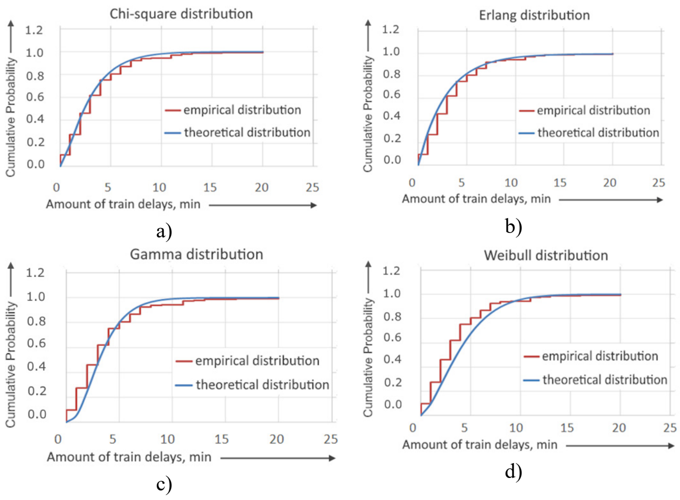

Fig. 6. Approximations of the extra-long train delay cumulative distribution functions by: a) Chi-square; b) Erlang; c) Gamma; Weibull distributions

Table 4

Calculation results of the delay distribution for heavy haul trains

Time interval [a,b)		Number of delays by				
		Observation data	Chi-square distribution	Erlang distribution	Gamma distribution	Weibull distribution
0	1	14	28.8185	42.2974	8.78858	14.3485
1	2	26	33.1826	29.959	28.1361	22.2315
2	3	27	26.2133	21.2198	32.7682	23.0582
3	4	23	18.8734	15.0298	27.2639	20.9295
4	5	19	13.0017	10.6455	19.2306	17.5266
5	6	8	8.7271	7.54016	12.2966	13.8405
6	7	9	5.75831	5.34065	7.36796	10.4284
7	8	8	3.75348	3.78275	4.21532	7.55196
8	9	2	2.42452	2.67929	2.3297	5.28234
9	10	1	1.55509	1.89773	1.25349	3.58158
10	11	0	0.99184	1.34415	0.66014	2.36043
11	12	4	0.62969	0.95205	0.34163	1.51534
12	13	1	0.39825	0.67433	0.17424	0.94927
13	20	3	0.67231	1.63735	0.17368	1.39595

The results of distribution assessment allow putting forward a hypothesis about the Weibull distribution of the general population. The Weibull distribution is a continuous distribution determined by equation [28]:

$$f(x) = \frac{\alpha}{\beta}((x-m)/\beta)^{\alpha-1}\exp\left(-([x-m]/\beta)^{\alpha}\right), \qquad (3)$$

where m is the minimum x-value, α is the shape parameter > 0 and β is the scale parameter > 0. The distribution parameters λ and β are determined from the following equations:

$$\begin{cases} EX = \lambda\Gamma\left(1+\frac{1}{\beta}\right) \\ DX = \lambda^2(\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma\left(1+\frac{1}{\beta}\right)) \end{cases}, \qquad (4)$$

where EX is the mathematical expectation of stochastic disturbances, DX is the dispersion and Γ is the Gamma-function.

According to the chi-square criterion at a significance level of 0.05, there is no reason to reject the hypothesis since $X^2_{observed} < X^2_{critical}$ ($X^2_{observed} = 16,52$, $X^2_{critical} = 19.68$). As obtained, the extra-long train traffic is characterized by Weibull distribution of stochastic timetable disturbances unlike the heavy haul one. Thus, considering disturbances by a train category may increase the accuracy of train delay simulation models.

4 Discussions

The results of statistical data analysis show that the lowest running time accuracy occurs for freight trains, including heavy haul and extra-long freight trains (1-3%). However, in [24], the opposite results were provided for the delay analysis in the Ural region of the Trans-Siberian railway. In this case, 41.4% of freight trains were observed on the proper timetable. Such results are due to some approach differences. In the statistical data of the Ural region of the Trans-Siberian railway, the freight train was considered as delayed if its departure was on the timetable or up to 5 min later. This is because the absolute train delay (from the moment of train formation) was considered. However, the most important for the TMS implementation is not the absolute value of delay, but the delay observed just on the railroad section. It allows taking into account primary and secondary delays caused by stochastic disturbances.

In the present study, the distribution laws of train delays were determined based on the results of theoretical distribution laws using the chi-square criterion at the significance level of 0.05. The distribution of timetable disturbances for heavy haul trains on the Oy-Mos section obeys the chi-square law. The distribution of timetable disturbances for extra-long trains on the Oy-Mos section obeys the Weibull law. However, in [24], the Gamma distribution was stated as the best for freight train delays. That is why the distribution law should be proved for each railroad section model.

The average delay value per train on the railroad section Oy – Mos is 4.2 min for heavy haul trains (21% delay from the proper railroad section timetable), 4.1 min for extra-long trains (20.5% delay) and 0.6 min for passenger trains (3.5% delay). Such delays are commensurate to the values of minimal virtual train coupling interval (3-5 min). This condition significantly complicates the task of throughput increase by reducing the train interval. The analysis of the real traffic train interval under the condition of simultaneously operating both the virtual coupling and automatic block system was carried out in [3]. The average train speed was 56 km/h, and the train interval was 9-12 min. The obtained results show the low efficiency of the virtual coupling technology for the throughput increase.

The analysis of real timetable data in the Swedish Railways was carried out in [18]. This allowed using empirical data as input ones for the simulation model. The data were divided on the train type, namely, local, regional and long-distance passenger trains, as well as freight trains. In total, 99.4% of the deviations in running and dwell times were in the range of ±10 min, 92.7% in the range of ±3 min and full 75% in the range of ±1 min. The accuracy of the schedule between Helsingborg and Karlskrona on the Swedish Railways is higher than on the Oy-Mos section. However, the data cannot be objectively compared due to the different type of traffic. It is also necessary to take into account the infrastructure conditions, such as electrification, length of the section, presence of hilly and curvy sections etc. Despite this, the stochastic analysis in both researches creates conditions for further analysis of primary and secondary delays.

The human factor also cannot be excluded in affecting the timetable accuracy, especially under difficult conditions of hilly sections and heavy haul trains. In Figure 6 (a) is the scheme of heavy haul train movement to the rise.

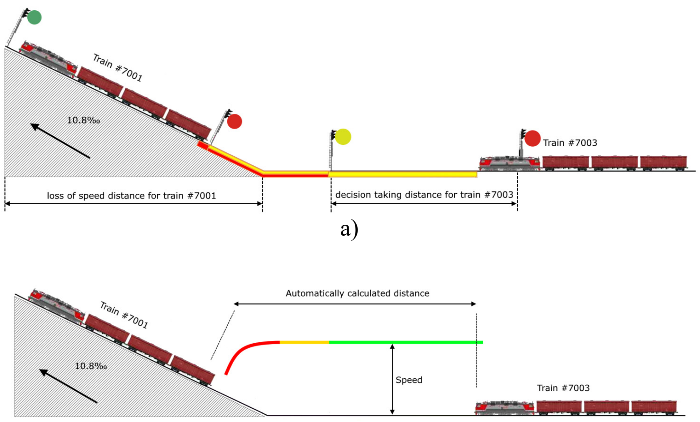

Fig. 7. Train movement on the hilly section: a) on an automatic block system section and b) on virtual coupling section

The heavy haul train has to move at a speed of at least 50 km/h in the foot part of the rise. The movement at a speed less than 50 km/h creates a risk of stopping at the rise. In this case, the train cannot overcome the rise without assisting by a supporting locomotive. If the train driver sees a yellow signal, he is driving in a state of uncertainty. It is necessary to make a decision about an appropriate speed value in the absence of speed data of the train going ahead. In many cases, a rational decision is to reduce the speed on a flat section and save the distance. It allows accelerating up to the required speed (50 km/h) when the green signal comes on. Such decisions lead to an increase of disturbances due to the human factor. The TMS and virtual coupling allow increasing the timetable accuracy, as shown in Figure 6 b). In the case of virtual coupling, the distance and speed of train #7003 are automatically calculated based on the kinematic data of train #7001. It may increase the timetable accuracy by reducing the influence of human factor.

To increase the traffic robustness, researchers add a buffer time and minimum headway interval to their calculations to reduce or prevent the propagation of delays when a train is late. In [29], they modeled each buffer time as an object whose value is determined according to commercial and operational criteria, and whose size is calculated based on a disturbances value. The stochastic analysis of the train timetable by train categories on the Oy-Mos railroad section allowed arranging trains into a timetable package by the deviations magnitude (e.g. train category). The separation of such packages by buffer times may increase the reliability and stability of the schedule.

5 Conclusions

A common timetabling problem is description and evaluation of disturbances. This study presented an analysis of stochastic disturbances from the train timetable on the railroad section Oy – Mos of the Trans-Siberian Railway. The approach for describing the disturbances distribution may be used for delays estimation on any section for the TMS implementation. In general, freight trains are characterized by a low percentage of timetable accuracy. It is evident from the analysis and may be associated with train characteristics (weight, length) and track conditions (hilly and curvy sections). The timetable disturbance value varies from 0 to 20 min per train on the railroad section. Since the problem of reducing the train interval may occur, for example, when virtual coupling or another TMS will be implemented on the railroad section. However, reducing the planed train interval may lead to an increase of secondary delays. The first way of further work is the analysis of stochastic disturbances for other railroad sections with different conditions, including climate, traffic intensity, passenger to freight trains ratio, etc. The mathematical modeling of stochastic disturbances allows increasing the reliability of the timetable at the planning stage, for example, by the calculation of optimal minimal train interval or including a buffer time in the timetable.

The distribution law of stochastic disturbances may be introduced in simulation models to solve practical problems depending on the infrastructure and other specific conditions. That is why the second way of further work is developing the robust timetable on railroad sections of heavy haul train traffic. The research results of delays distribution for train categories will be useful for the simulation. It also allows implementing the obtained results in a real train timetable.

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СТОХАСТИЧЕСКИЕ ОТКЛОНЕНИЯ ОТ ГРАФИКА ДВИЖЕНИЯ ТЯЖЕЛОВЕСНЫХ И ДЛИННОСОСТАВНЫХ ПОЕЗДОВ

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Аннотация
Работа направлена на стохастическое исследование точности выполнения графика движения тяжеловесных и длинносоставных поездов в реальных условиях движения. Точность выполнения графика зависит от ряда факторов, включая климатические условия, характеристики подвижного состава, профиль железнодорожного пути, отказы оборудования, ограничения скорости и т. д. Эти факторы влияют на движение каждого поезда на участке. Однако точность выполнения графика движения может существенно изменяться в зависимости от конкретных характеристик поезда, таких как категория (пассажирский или грузовой), вес и длина. На Транссибирской магистрали курсируют поезда весом до 8000 тонн и длиной до 2 км. При этом актуально повышение пропускной способности участков железной дороги за счет сокращения интервалов движения поездов. Стохастические нарушения расписания могут существенно ограничить значение интервала движения поездов и пропускной способности участка. В исследовании проведено математическое моделирование задержек поездов на участке железной дороги на основе статистических данных графика исполненного движения. Показано, что отклонения от графика и задержки поездов можно описывать с использованием стохастического подхода. В работе применен способ оценки отклонений от графика с помощью распределений Хи-квадрат, Эрланга, Гамма и Вейбулла. Результаты исследования могут быть использованы при разработке имитационных моделей и планировании отказоустойчивых графиков движения.

Ключевые слова: *отклонения от графика движения, задержки поездов, стохастические отклонения, тяжеловесные поезда, длинносоставные поезда, межпоездной интервал, виртуальная сцепка.*

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