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Optimising Train Speed

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ABSTRACT

The importance of the train speed is considered relative to activity of railways, presenting a wide panorama of influence, on the one hand of speed on the process of transportation of goods and passengers, and, on the other hand, of rolling stock, infrastructure, and organisation of transportation on speed.

The objective of the article is to extend the ideas about the speed on railways with the help of analysis of Russian and international history of development and results of the study of the train speed.

Despite, it would seem, all the certainty of speed of movement, the history of its development testifies to a wide range of opinions and non-obviousness of estimates. The historical review contains opinion on the development of the problem and interaction between the speed and other parameters.

The interaction of train speed with all components of the transportation process is described by various dependencies. Therefore, the economic efficiency from increasing speed of trains can be obtained only with a system approach.

Analysis of modern research shows the potential capacity to increase the speed. The results of the author's research reveal the in-depth possibilities and expediency of increasing train speed.

Keywords: railways, speed, interaction of speed with other indicators, regulation, performance, train weight, system approach, train traffic intensity and density, speed distribution.

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INTRODUCTION

Speed has excited humanity since time immemorial. This direction of scientific and technological progress has made it possible to master the surface of the planet, near-earth space, and in the near future will help to travel beyond the limits of the Solar system. And, nevertheless, the point has not yet been made in the study of the issues of speed of movement with regard to railway transport. The factors influencing train speed and the influence of speed on weight of trains, fuel consumption and transit capacity are known. But so far there is no complete picture of speed of the transportation process.

Train speed is associated with time of delivery of goods [1]. But in the transportation process, movement of goods in trains is less than a third of the delivery time. The rest of time of delivery, the goods are at the stations and are subject to cargo, technical and technological operations. And the time when cargo remains at stations and at loading facilities is not associated with speed and is called «time of stay» and «execution of operations». As a result, on a part of the cargo transportation route, there is a struggle for acceleration, measured in minutes, and on other parts of this route, there is downtime, measured in hours.

Train speed is the maximum allowable, estimated, running, technical, speed at the section, route speed, and at the stations it is called «stay» and «downtime». To move, infrastructure, rolling stock, fuel is needed, and for downtime at the stations, nothing is needed except ... «third party's» cars.

Speed, like all elements of the transportation process technology, have two sides of the coin. One is associated with regulatory and technological documents regulating speed, the other is their implementation. Currently, much more attention is paid to development of regulatory and technological documents than to their implementation. As it were, it is assumed that the main thing is to develop a timetable, a plan for train assembling, etc. and they will automatically implement their capabilities. But the level of respect of the traffic schedule, especially for freight trains, is far from 100 %. Or, the automated system for monitoring execution of the train assembling plan looks quite absurd if it completely ignores operational adaptation of organisation of car traffic to real situations through considering fluctuations in size of wagon flows, accumulation time of trains, loading of stations, possibility of timely provision of trains with locomotives, etc.

Therefore, we will also consider the problem of speed from the aspects both of regulation and of implementation possibilities.

Of all the variety of indicators of operational work, weight and speed of trains have the most systemic impact on organisation of the transportation process. It is impossible to consider speed of movement in isolation from weight of trains. Both these indicators are derived from the capabilities of rolling stock and infrastructure. Great changes are constantly taking place in the technical equipment of railway transport, which can be used either to increase weight or to increase speed of trains. Weight and speed are not constants, but the most important parameters for regulating the network operation mode, which determine quality of transport product [2].

Increasing speed of freight and passenger trains is an important opportunity to increase transit capacity of railway lines, accelerate delivery of goods, reduce travel time of passengers, and increase efficiency of using locomotive crews and locomotives. At the same time, a system approach to the conditions and organisation of the transportation process and to its indicators requires considering, first, that under the conditions of limited technical and technological capabilities of the railway network, simply increasing the established speeds is not always effective. Secondly, there is an inversely proportional relationship between speed of movement and weight of trains, therefore, an increase in speed with unchanged technical equipment causes a decrease in weight of trains and an increase in the number of trains on the section. Thirdly, an increase in train speeds is associated with an increase in consumption of fuel and energy resources. Fourthly, speed affects the efficiency of using locomotive crews and locomotives, as well as accelerated delivery of goods. Fifthly, increase in speed causes additional costs for infrastructure maintenance. Sixthly, there is a share of wagons and goods requiring speed limits. Seventhly, faster pace of development of the passenger complex restrains and limits speed of freight transportation, which constitutes the main income of JSC Russian Railways. Eighthly, speed of movement is influenced by the shortage of transit and processing capacity, temporarily suspended freight trains, maintenance of an excess of the working fleet of wagons and oversaturation of sections with trains. Therefore, an isolated consideration of increase in train speeds, separate from other parameters, indicates an unsystematic solution to the issue.

The length of the main tracks on which speed of movement of freight trains of 90 km/h is allowed (in accordance with Rules of technical operations) is less than 10 % of the operational length of the railway network. A few years ago, there were no sites with such a maximum permissible speed at all.

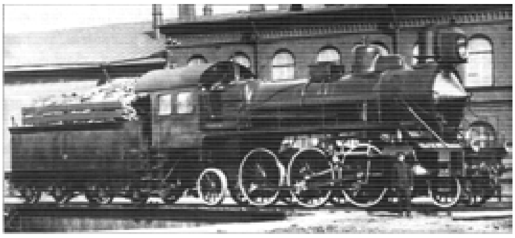
Increasing only the governed speed of freight trains without taking measures aimed at increasing technical, route and delivery speeds, speed at section is ineffective. The implementation of measures to increase the governed speed on the network sections, for example, from 80 to 90 km/h, with strengthening of the railway infrastructure, but without considering traction properties of the locomotive, may not lead to an increase in technical speed and speed at sections [3].

Considering the ways to increase the governed train speed, it is necessary to develop comprehensive measures to strengthen track facilities and power supply along with traction calculations to determine the possibilities for locomotives to follow the set speed, considering the passage of the estimated climbs at the rated speed without overheating of the traction equipment. The system approach also requires considering the possibility of increasing the route speed and speed at section by reducing downtime at stations.

HISTORICAL OVERVIEW.

Domestic Experience of Increasing Speed

The history of development of Russian railways witnesses a consistent increase in speeds. At the beginning of 20th century, several steam locomotives were created, which served fast and courier trains. Back in 1901, on St. Petersburg–Moscow railway, courier trains operated at a maximum speed of 110 km/h. In 1910, a high-speed steam locomotive was built at Sormovo plant, it received the C index and was recognised as one of the best European locomotives of its time (Pic. 1).



Pic. 1. Steam locomotive of the type 1-3-1, one of the first in C series.

In 1913, in trial trips, a steam locomotive of the C series attained the speed of 125 km/h, and in 1915, a steam locomotive of the L series reached the maximum speed of 117 km/h.

From the beginning of 20th century, professor N. L. Schukin had been hatching the idea of putting speed trains into operation between St. Petersburg and Moscow, but the outbreak of war did not allow these plans to be realised.

In 1938, for the first time in the USSR, speed of 177 km/h was reached on Moscow–Leningrad main railroad when testing a steam locomotive manufactured by Kolomna plant with an axial formula of 2-3-2 (pilot wheelsets, locomotive drivers, rear supporting wheelsets) and axle load 20,5 t. Trips (experimental and operational) were carried out on rails weighing 43,6 kg/m.

In the post-war period, the USSR implemented an unprecedented General Plan for technical re-equipment of the railways based on electrification. In the 1960s, a set of experimental trips was carried out between Moscow and Leningrad, then the maximum speed reached 220 km/h.

In 1972, experimental trips of a passenger car with a turbojet engine at a speed of 240 km/h were carried out in the USSR.

The first projects of Moscow–Leningrad speed line were developed back in the 1930s (K. N. Kashkin, G. D. Dubiler, I. V. Romanov). The most famous speed train was Krasnaya strela [Red Arrow]. The first express train departed from Leningrad on June 9, 1931. However, in reality, work on organising railway traffic at increased speeds started only at the end of the 1950s.

One of the first documents that defined the program for increasing speed of trains on Oktyabrskaya railway was the order of the Ministry of Railways dated May 29, 1957 «On preparation of Moscow–Leningrad line for movement of passenger trains at increased speeds». In the same year, the first TE7 diesel locomotives were delivered to Oktyabrskaya railway, they played a significant role in development of speed traffic. The maximum speed of passenger trains reached 140 km/h. The whole trip from Moscow to Leningrad lasted 5 hours 54 minutes.

After laying a continuous track made of R65 rails, replacing turnouts, completing electrifica-

Table 1

Main indicators of some speed railways at about 1965

Country	Section (line)	Length of the section, km	Name of the express train	Maximum speed, km/h	Route speed, km/h
USSR	Leningrad–Moscow	650	«Aurora»	160	130,4
Great Britain	London–Lester	169,5	«Midland Pullman»	140	112
Italy	Rome–Naples	210	« Freccia del Vesuvio (Vesuvian arrow»	140–160	120
USA	Los Angeles - Chicago		«Super Chief/El Capitan»	160	132
France	Paris–Marseilles–Nice	314	«Mistral»	160	131
Germany–Switzerland	Duisburg–Geneva	570	«Rheingold»	160	107 (136,2 km/h in 1964 on the section Freiburg-Carlsruhe)

Data based on various sources differ significantly. The table contains some of them as illustrative information since in-depth study of the issue is beyond the scope of the article.

tion, in 1964 on Moscow–Leningrad line, the daily Aurora express train was put into circulation with a route speed of 130,4 km/h, it was trained by electric locomotives of the ChS2 series.

The results achieved in speed traffic on Leningrad–Moscow line by the mid-1960s were comparable to those of speed railways in Japan, France, Italy, the USA, and other countries leading in this area, as can be seen from Table1.

The first in the USSR ER 200 speed train («Electric train Rizhsky»), with a maximum speed of 200 km/h, was developed and manufactured in 1968–1974. Since 1984, the ER 200 electric train has been operating on Moscow–Leningrad line. The travel time of the train between the end points was 4 hours 30 minutes, the route speed was 144 km/h. Simultaneously with the ER 200, development of another speed train was carried out. It was called the Russian Troika and was designed for a speed of up to 200 km/h. The train was supposed to be of a permanent composition including RT 200 cars of Kalinin (since 1990 Tver) car building plant and the ChS 200 electric locomotive (produced in Czechoslovakia). Eight experimental cars were manufactured, showing good results in tests, however, the Russian Troika train has never been commercially operated.

Since 1994, a sectoral program for development of speed traffic has been implemented in Russia, following it, projects have been implemented to create special rolling stock for maximum speeds of up to 200 km/h, speed passenger electric locomotives EP 100 DC and EP 200 AC, passenger cars of various classes for speed traffic.

In 2009, express Sapsan trains, produced in cooperation with Siemens, began to operate on Moscow–St. Petersburg line. The maximum speed of these trains is 250 km/h. The distance of 650 km is covered in 3 hours 45 minutes. In the first year, 2 million passengers were transported. In the summer of 2010, Sapsan trains started operations on Moscow–Nizhny Novgorod route.

In December 2010, Allegro speed trains, manufactured by Alstom, began regular service between St. Petersburg and Helsinki. The maximum speed of the new electric train in Russia is 200 km/h, in Finland – 220 km/h. Travel time on this international route has been reduced from 6 hours 18 minutes to 3 hours 30 minutes.

One of the strategic directions of innovative development of JSC Russian Railways is expansion of high-speed passenger train traffic. The decree «On measures to organise high-speed rail in the Russian Federation» signed by the President of the Russian Federation on March 16, 2010, testifies to the importance attached to high-speed passenger train traffic.

The Issue of Choosing Optimal Speed

At the very beginning of 20th century, engineer B. D. Voskresensky in his work «Theory of railway trains' operation» proposed as the main criterion for solving the question of the most advantageous weight and speed for freight trains to determine the value of *max* QV_x at an equivalent climb and came to the conclusion that on the sections with a light track profile, it is more profitable to drive heavy trains at lower speeds, and on sections with a difficult track profile, it is advisable to drive trains of lighter weight, but with higher speeds.

Professor A. L. Vasyutinsky, proceeding from the calculations of the cost of transportation associated with operation of rolling stock, came to the opposite conclusion that as the equivalent rise increases, it is more expedient to increase train weight and to reduce speed.

Engineer V. N. Shcheglovitov [4] rightly raised the question of finding not $max\ QV_x$, but the value of $max\ QV_{sec}$ since the carrying capacity of a section is determined by the speed at section (at that time it was called commercial speed. – *auth.*), and not by the running speed, and with an increase in the number of trains on a single-track section, the section speed decreases. Hence, it was concluded that for single-track sections the largest train is the most advantageous.

In the 1920s, it was proposed to determine the economic assessment of speed by the influence of power of locomotives on the cost of transportation:

$$E = A + \frac{B}{Q},$$

where E – full operating costs;

A – costs that do not depend on train weight;

B – costs depending on train weight;

Q – train weight.

Professor I. I. Vasiliev in work [5] concluded that to obtain the minimum fuel consumption per 1 t•km of transportation and to achieve the maximum transit capacity of the section, train weight and speed must correspond to the point of intersection of the curves corresponding to limitation of the traction force for steam traction as far as adhesion and boiler thrust are concerned.

Professors A. M. Babichkov and V. F. Egorchenko in the book [6, P. 247] noted: «For freight trains, estimated speed on the ascent is usually taken as the highest speed at which the traction force of the locomotive is fully utilised as far as coupling, generator or engine is concerned, in other words, it is the speed corresponding on the diagram $F_k = f(V)$ to the intersection point of line of traction according to adhesion with line of tractive force according to generator or the engine. This speed is sometimes called the threshold speed or speed of reaching the automatic characteristic since on the diagram $F_k = f(V,z)$ it corresponds to the break point of the thrust force curve». Thus, the authors consider the best use of the traction force of the locomotive to be the initial criterion in establishing train weight, and that also determines the minimum value of the cost of transportation.

Professor V. N. Orlov [7] concluded that the most advantageous running speed with a constant train weight has a minimum cost of transportation, and at ruling gradient it has the lowest cost of transportation for a given size of freight turnover.

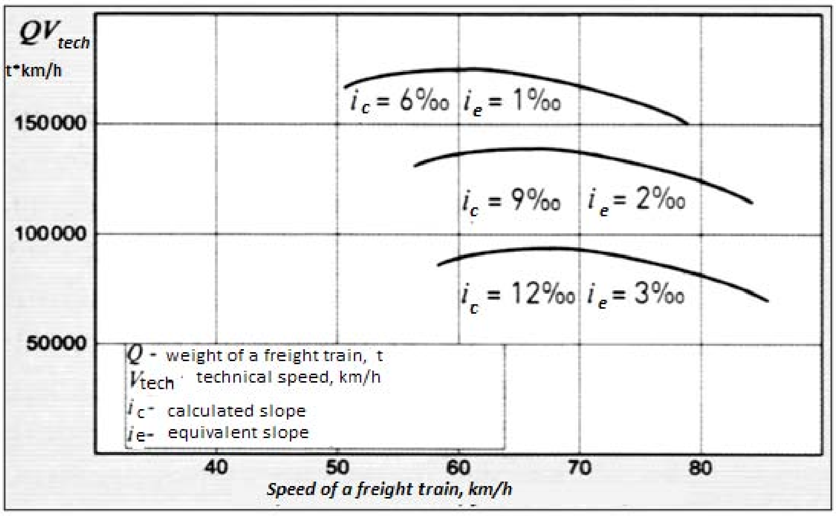
Professor A. I. Ionnisyan [8] argued that with an increase in the maximum permissible speed for powerful locomotives, it is also necessary to increase estimated speed at the ruling gradient. The speed when climbing at the ruling gradient should be set in accordance with the conditions for achieving the minimum cost of transportation.

Professor A. E. Gibshman [9] proposed a method for direct calculation of the types of steam locomotives being compared based on preliminary construction of a special grid and contoured lines for the dependence of costs on train weight and speed for various sizes of freight turnover.

In the Rules of traction calculations for train operation, published in 1956 and 1985 [10], it is proposed to determine train weight and speed based on the conditions of the full use of the power of locomotives and the kinetic energy of the train, i.e. to proceed from the principle of using the greatest possible train weight in terms of locomotive power.

Back in the middle of 20th century, Academician T. S. Khachaturov studied the problem of the dependence of performance of locomotives on speed of freight trains and established this dependence for various values of ruling and equivalent gradients (Pic. 2). For the given ruling and equivalent gradients, the initial weight of the freight train was taken, for which the distance travelled in 1 hour was calculated. Then train weight was increased step by step. Initially, the train travelled the calculated distance with the maximum possible speed. With an increase in train weight, its speed decreased, and performance of the locomotive increased due to the increase in train weight. With a further increase in train weight, the decrease in speed was no longer compensated by the increased train weight, and productivity of the locomotive began to decline.

Professor B. E. Peysakhzon [11] researched and developed a methodology for choosing the optimal values of weight and speed of trains for various types of traction, which made it possible



Pic. 2. Dependence of productivity of the locomotive on technical speed.

to select new types and use existing locomotives based on operational requirements and technical and economic calculations.

Foreign Experience of Increasing the Speed

The history of development of railway transport has many achievements in the field of increasing traffic speed, often they were a kind of technical sensations. Back in 1847, in England, on one of the sections of the Great Western Railway, 92 km long, passenger trains reached a speed of 93 km/h. By the end of 19th century, in Great Britain, France, Germany, and the USA, passenger trains attained a speed of 70–80 km/h. In 1890 the steam locomotive «Crampton» in France with a train weighing 157 tons reached the speed of 144 km/h. The speed limit of 200 km/h was overcome for the first time by a German electric train. In 1903, on Marienfelde–Zossen section, a speed of 210 km/h was reached during tests.

In 1955 in France, for the first time, the threshold of 300 km/h was exceeded, and a speed record was set, it reached 331 km/h. This record was improved on February 28, 1981, with the TGV train reaching the speed of 380 km/h.

The ongoing work in this area shows that the traditional wheel–rail transport system has not exhausted its capacity. In 1988, in Germany, when testing an experimental ICE train, a speed of 406,9 km/h was reached. But this milestone was soon surpassed: in 1989 the TGV train in France reached a speed of 412 km/h, then 482,4 km/h, and finally, in May 1990, an incredible speed record was set, that of 515,3 km/h.

For the first time in the world, the idea of high-speed rail traffic was implemented in Japan (Pic. 3) between the cities of Tokyo and Osaka, where in 1964 the high-speed Tokaido railway with a length of 516 km was put into operation. The maximum speed on the new line was 210 km/h, and the trip from Tokyo to Osaka took 3 hours 10 minutes.

High-speed trains have gained wide acceptance among the population due to their high speed and comfort. Within 5 years, passenger transportation on this line more than doubled and reached 70 million people per year. This significant amount of operations provided a solid foundation for cost-effectiveness of the high-speed line and allowed Japanese railways to plan further construction of such lines.

In 1970, Japan passed a law to establish a nationwide high-speed rail network called Shinkansen. This gave a new impetus to development of high-speed traffic. In 1975, Sanyo high-speed line was put into operation. Having crossed the strait, this line reached the city of Fukuoka, connecting two islands – Kyushu and Honshu.

1982 saw the opening of two more new high-speed lines (HSR): the Tohoku Line north of Tokyo linking Omiya and Morioka, and the Joetsu Line, which crosses Honshu Island from the Sea of Japan to the Pacific Ocean with Omiya–Niigata route. In the early 2000s, the length of the high-speed rail network in Japan,

Pic. 3. The first high-speed electric train (Japan).

which included six main lines, exceeded 2100 km, and the maximum speed of trains running along it was 240–260 km/h (Pic. 4).

Shinkansen main lines are intended for passenger traffic only. Unlike conventional railways, which have a narrow gauge, the gauge of high-speed lines complies with the European standard and is 1435 mm. As a result, Shinkansen-type trains are forced to operate in a closed system. High-speed main lines go directly to the centres of cities and settlements, crossing them through overpasses 25–30 m high.

When creating the Shinkansen network, Japanese specialists solved a number of complex engineering problems associated with choice of a track structure, creation of new rolling stock, engineering structures and other technical tasks.

Traffic safety devices occupy a special place in these developments. The principle of their work is that in case of any malfunction or violation of the operating mode that poses a threat to safety, the train stops immediately. For land transport, this means eliminating the hazard. Practices have proven high efficiency of the applied safety and security systems. During the entire operation of the Shinkansen lines, not a single accident or crash occurred, not a single passenger was killed or injured. By the end of the 1990s, about 3 billion people had been transported.

Every day, 427 high-speed express trains run along the Shinkansen main line, carrying more than 440 thousand people.

A lot of work is underway to create new-generation trains with the aim of achieving a speed of 300–350 km/h on the existing Japanese high-speed rail network. Since the permanent devices of this network were designed for speeds up to 250 km/h, it was necessary to significantly reduce the axle load. This was achieved: in the experimental train, axle load is less than 8 tons.

France is the ideologist of high-speed rail systems in Europe. After two years of theoretical development, in 1976 the National Society of Railways (SNCF) began construction of Paris–Lyon high-speed railway, and in September 1981 the high-speed TGV train saw the green light on the line (Pic. 5). The design of the TGV system was carried out in such a way that trains could run on the new line at a speed of 270 km/h and switch to the regular rail network. Due to this, an accelerated railway connection between Paris and the south-eastern regions of France was provided. Currently, TGV trains operated on the south-eastern direction serve more than 50 settlements with 56 % of the country's population. The length of the TGV-South-East network is 2487 km, of which 417 km are on the new line.

The commercial speed of movement has sharply increased. On Paris–Lyon route, it was 213 km/h, and the travel time between these cities was reduced to 2 hours.

Based on the first successes, the SNCF proposed, and the President of the Republic and the government decided to build a new high-speed line TGV–Atlantic, which was put into operation in September 1989. The total length of the line is 285 km.

As well as TGV–South-East line, the new high-speed line is intended exclusively for passenger transportation. A new generation of high-speed TGV–Atlantic trains has been created for the Atlantic line, with a maximum speed of 300 km/h for commercial operation on newly constructed sections, and 220 km/h on conventional railway lines.

Pic. 4. Japanese high-speed electric train of 300 series.

Pic. 5. French high-speed double-decker electric train TGV Duplex.

Then the northern high-speed rail serving ways to Belgium and to the tunnel under the English Channel (332 km); HSR bypass around Paris, connecting high-speed lines of France and several European countries (102 km) into a single network were put into operation. By 2014, the total length of the French HSR had attained almost 1500 km, and the construction of several more lines continued.

The French concept of high-speed rolling stock provides for creation of permanently assembled trains with locomotive traction. Two electric locomotives are placed at the ends of the train, and passenger cars are located between them. A special feature of the French TGV train is the use of coupled cars on intermediate bogies.

In Germany, the first HSR line appeared in 1991, today the length of such lines is 800 km (Pic. 6). In Spain and Italy, high-speed lines with a length of 471 and 236 km, respectively, were introduced in 1992.

In 1992, trains consisting of cars with forced tilting of bodies began to run in Sweden. These trains reached the speed of 220 km/h. Up to 20 types of such cars have already been created in different countries.

In the UK, three main routes are being improved: London–Glasgow, London–Newcastle–Edinburgh and London–Bristol–Cardiff to achieve speeds of 225 km/h.

Following Europe and Japan, high-speed traffic is developing in the United States, where road and air modes of transport have played a major role for a long time. There were seven projects in the USA to build high-speed rail systems. Some of them are under consideration, others have undergone scientific research and pre-project development. Currently, the highest speed (240 km/h) for passenger trains has been attained on a section in the so-called North-East corridor on Washington–New York segment. On the new main lines, the speed will reach 270–300 km/h.

Work on the creation of ultra-high-speed railways is being carried out on almost all continents. Australia announced plans to build a high-speed line between Sydney and Melbourne. High-speed trains for it will be supplied by the leading manufacturers in France and Germany, which have succeeded in creating trains of the TGV and ICE types. German enterprises are to supply Australia with bullet-speed locomotives, and French ones with cars. The new 870-kilometer line will be operated with 30 pairs of trains with an average speed of 292 km/h and a maximum speed of 350 km/h.

Pic. 6. German high-speed electric train ICE 3.

This review in the context of the article does not cover the latest HSR developments, comprising improvements in infrastructure, construction of new HSR lines, technology of new rolling stock since there are numerous research papers dedicated to the issue, including fast HSR developments in China, focusing on evolution of train speed. But it is impossible to neglect some interrelated aspects.

On high-speed lines, the track design, signalling and communication devices basically keep the traditional principles.

However, they are becoming qualitatively new in terms of science intensity, reliability, and maintenance methods. Their essential elements include microprocessors and computers, diagnostic and information sensors, devices of fine sensitivity for detecting earthquakes, snowfalls, and other emergency situations. All this together with double and sometimes triple redundancy ensures 100 % traffic safety.

The main trends in creation of new types of high-speed electric trains are maximum reduction in the weight of the cars, reduction of energy consumption due to high aerodynamic performance, the use of computers and microprocessor devices, as well as new, more economical, and reliable systems, electrical equipment for traction.

At present, the HSR system has been technically, technologically, and economically tested. High-speed lines have already been built, are under construction or being designed in many countries of the world for almost 50 years. The high efficiency of HSR has been proven, and therefore, today any country, if there are necessary economic conditions for this, can design and build HSR using well-known technical and technological solutions.

Modern Research

Increasing and optimising train speed is a priority task for JSC Russian Railways. Practically the entire scientific potential of the industry is engaged in solving these problems.

Ph.D. (Economics) A. V. Kudryavtseva [12] investigated the long-term dynamics of weights and speeds of freight trains from the point of view of innovative development of railway transport and generalised the resulting economic effects caused by grown values of these indicators.

Specialists of JSC IERT [3], when analysing the increase in speed of freight trains on Barabinsk–Tatarskaya–Moskovka section from 80 to 90 km/h, concluded that economic efficiency indicators depend on the presence (or absence) of infrastructure transit capacity reserves, the possibility of attracting additional volume of freight traffic or optimisation of the transportation process by switching (returning) cargo flows to the shortest routes, the presence of an additional cargo origin sources, confirmed by an appropriate forecast, the size of traffic on the section under consideration, the cost of measures aimed at increasing traffic speed.

Specialists of JSC VNIIZhT [13] investigated the possibilities to streamline the technology of freight trains by updating the timetable developed using ELBRUS hardware and software complex, which made it possible to increase the route speed and speed at sections on Isilkul–Chelyabinsk segment of the South Ural railroad.

Specialists of Far-Eastern State Transport University [14] with the help of the network planning and control system and the ERA software complex investigated the dependence of technical speed and speed at the sections on the governed permissible train speed. Calculations have shown the economic efficiency of increasing average travel speeds by planning and controlling the increase in allowable train speeds within the network.

Specialists of Samara State Railway University [15] analysed the interaction of train speed with other volumetric and economic indicators on the network routes Kuzbass–Chelyabinsk–Syzran–n.a. M. Gorky–Tikhoretskaya–ports of Azov-Black Sea basin. The relationship between train speed and the transit capacity of the section was obtained. But the nature of the curve indicates a constant length of block sections, while with an increase in train speed, the length of block sections should increase, and with high-speed traffic this even leads to a decrease in transit capacity.

Specialists of Rostov-on-Don State Transport University [16] investigated the effect of increasing speed of freight trains on assessment of income and expenses. The factors influencing speed were analysed. The expediency of separation of freight and passenger traffic is considered. For the North Caucasian railway, a relationship has been established between the working fleet of wagons, speed at the section and budget indicators.

In recent decades, guidelines of JSC Russian Railways, programs, methodological recommendations, and projects aimed at increasing speed of trains have been developed and implemented.

TRAIN SPEED ANALYSIS

With maximum traffic and minimum inter-train intervals, the flow of trains becomes unstable, and the process of movement becomes unsteady. Different qualifications of drivers, modern design of speed meters and other factors do not allow the maximum permissible speed to be achieved.

The decoding of speedometers' tapes showed that freight train drivers almost always travel at a speed less than the calculated one or set by the limit warning. When trains are running under a green light of a railway traffic light, i.e. when the distance between trains is more than the length of three block sections, the calculated rate of running speed is not fulfilled on average by 20 %, and the scheduled speed rate – by 8 %. When the distance between trains is less than three or more than two block sections and they follow part of way having a yellow light, the average speed is, respectively, by 46 and 38 % lower than the estimated standard rate, and travelling having a yellow light they have a speed by 63 % lower. The actual speed of train differs from the calculated one in a wide range from 0,2 to 1,2. The wide spread of speeds is explained, first, by the different skills of drivers, who react differently to the readings of traffic lights, often performing premature braking.

An increase in average train speeds usually results in an increase in specific consumption of electricity or fuel following increase in main resistance to movement and energy losses in brakes. Increase in average speeds provides the greatest economic effect with a lean mode of train driving, which, if strictly respecting the schedule, causes the lowest specific consumption of electricity or fuel. The complexity of the development and practical use of reasonable modes of train driving lies in the fact that they are different for different operating conditions, with electric traction, voltage in the contact network is subject to change; depending on the technical condition, the characteristics of electric machines on locomotives differ. The maps of train driving modes compiled for some average operating conditions on the same sections for different drivers have deviations both up and down from the established rate of specific consumption of electricity, fuel. The desire of drivers to save energy or diminish fuel consumption leads to a decrease in speed of freight trains.

Any decrease in train speed in comparison with estimated speed for a given section, and even more an interruption in traffic, lead to losses in the use of capacity and, accordingly, to economic losses. Delays of trains on hauls are caused by out-of-sync train movement, untimely switching of opening signals at stations, malfunctions of rolling stock and technical devices, oversaturation of sections with trains, speed limit warnings and overpassing by delayed passenger trains.

If train traffic is out of sync, the trains go, instead of the green one, at the yellow, and often at the red light of the traffic light. So, if a pack of trains runs with six-minute inter-train intervals and one of the locomotives reduces speed against the average schedule by only 5 km/h, the train following it will approach a traffic light at a yellow light in 1,5 minutes. The lack of synchronisation is explained by the fact that train drivers use the train schedule, which indicates only travel time per stages.

The speed on various elements of track profile is determined expertly, the choice of the mode of movement largely depends on skills of drivers.

According to some estimations, train delays due to untimely reception by technical stations constitute about 1 million train hours per year, and there are also great delays in front of connecting points due to untimely reception of trains by neighbouring railroads and their operating divisions.

Train delays in case of malfunctions of cars, locomotives, track, signalling and communication devices, contact network, etc. are influenced by traffic communication means, the number of main tracks, the type of traction, the inter-train interval, and the number of passenger trains. Failures in operation of technical devices reduce the available transit capacity of sections by up to 15 %.

The increase in density of train traffic leads to an increase in the number of trains going forward at the yellow and red traffic lights, and this causes a decrease in running speed and an increase in delay time of trains on stages.

Analysis of speed meters' records allows establishing the mode of train movement on the section at different density and intensity of train traffic, ratio of different readings of traffic lights and of automatic locomotive signalling system of continuous operation (ALSN) and speed of movement on them, as well as setting technical and section speeds of freight trains. The readings of speed gauge tapes can be used both independently and as initial information for simulating movement of trains on the section. In the latter case, in contrast to the results of traction calculations, the human factor is considered (driver's influence on the mode of train driving).

To compare records of train speed, obtained using traction calculations and speed meters' tapes, it is advisable to use their ratio when trains are going at different traffic lights or at different ALSN readings.

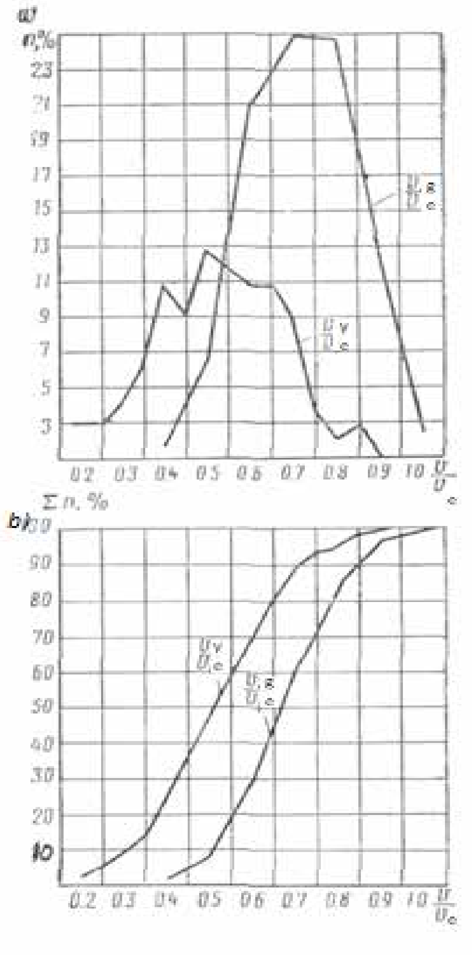
$\frac{v_g}{v_e}$, $\frac{v_y}{v_e}$, $\frac{v_{ry}}{v_e}$ is the ratio of actual and estimated train speed, respectively, when going at green, yellow and after passing at yellow light of the track traffic light (Pics. 7, 8).

On different sections, different drivers implement permissible train speeds in different ways. But while the specific values of train speed differ, their distributions and ratios have a general form (Pics. 7, 8). The general pattern was that trains were going at green traffic light on one half of the block sections at a speed 20–25 % lower than the estimated one and on the other half of block sections they were going at a speed almost two times less than that obtained by traction calculations. On the second half of the block sections, such a decrease in speed is associated with the presence of speed limits and consequent acceleration after passing them, which was carried out more slowly compared to the estimated mode. The decrease in ratio values $\frac{v_y}{v_e}$ is explained by the speed limit set on railways when going at yellow traffic light and by premature low effective braking. Moreover, in 75 % of cases, when trains were going at a yellow light, the traffic light indication turned to a green indication and there might be no registered braking at all.

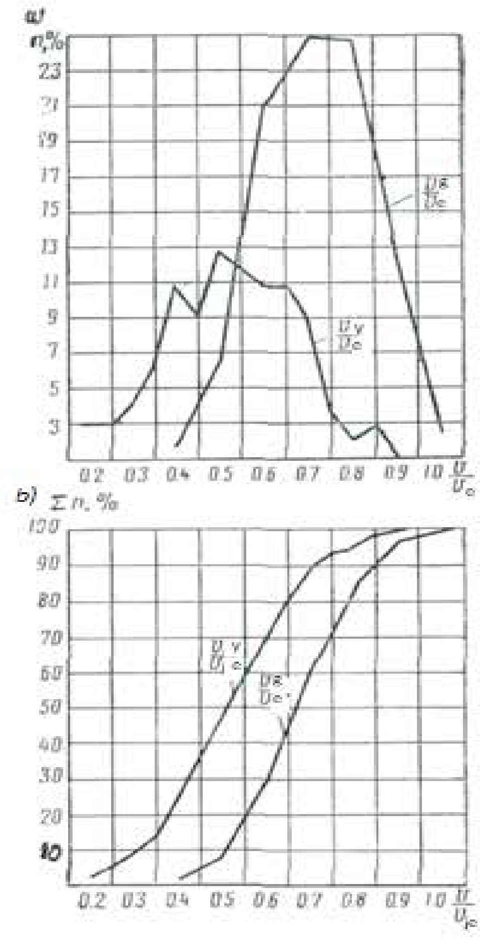
The actual train speeds were considered in relation to speeds obtained by traction calculations. But the standard traffic schedules use speeds that are below the estimated ones. On the considered electrified sections, the traffic schedule provides for running speed of freight trains v_{fr} = 57,7 km/h that is lower than the estimated one by 8,7 km/h. Therefore, the ratio of speeds v_g, v_y and v_{ry} to the standard running speed stipulated in the schedule is 66,4: 57,7 = 1,15 times (Table 2). When trains are going at green traffic light, running speed is 20 % lower than the estimated one, and the scheduled speed is 8 % lower. Trains move at yellow traffic light at a running speed, respectively, 46 and 38 % lower. After passing the traffic lights at yellow light, it is 63 % lower.

The results obtained on the sections with diesel traction are shown in Table 3. The difference in ratios of speeds in odd (loaded) and even (empty) directions is explained by the weight of empty trains which is almost half lower, slow acceleration of loaded trains after passing sections with speed limits and higher speeds of empty trains at green and yellow traffic lights.

The ratio of actual speeds of train movement to the estimated ones when trains pass through intermediate stations along the main track, when there is a green light at the entrance and exit



Pic. 7. Differential (a) and integral (b) curves of distribution of speeds when trains move at different lights on an electrified section.



Pic. 8. Differential (a) and integral (b) curves of distribution of speeds when trains move at different traffic lights on a section with diesel traction.

traffic lights, on electrified lines is on average 0,78, on sections with diesel traction it is 0,75, which is 7–8 % or 5–6 km/h lower than on stages.

The actual number of speed limit warnings on many sections of the network is greater than their number provided for by the schedule. The total distance travelled by a train with a speed limit l_{lim} is equal to the sum of the distance along which warning is effective l_{warn}, train length l_{tr} and the distance travelled at a reduced speed v_{lim}, considering deceleration and acceleration of a train before and after the location where speed is limited. The actual distance travelled by a train with a reduced speed is on average 2,5 times more than the length of the track where the limit warning is valid. Analysis of speedometers' tapes showed that the actual speed is lower than the speed set by the speed limit warning on average by 20–25 %. The number of trains affected by the speed limit when approaching to the area of its action:

$$N = \frac{(v_{av} - v_{lim})\,l_{lim}}{v_{lim}\,(v_{av} I - l_{tr} - pL_{b-s})} - 1,$$

where v_{av} – average train speed, km/h;

I – inter-train interval, h;

p – minimum number of block sections that delimit trains so that with this number stable movement at a green traffic light is ensured (for a three-digit automatic interlocking $p = 3$);

$L_{b\text{-}s}$ – average length of a block section, km.

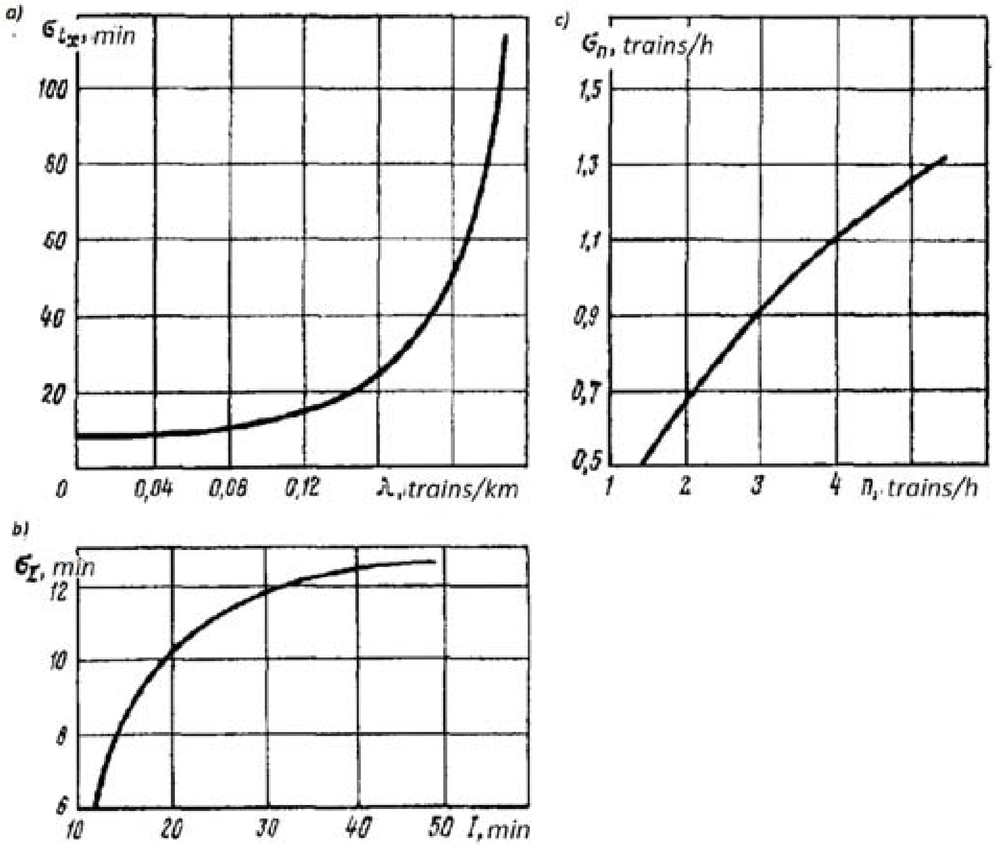
The actual train speed in areas where warnings are in effect is by 2,7 ÷ 5,6 km/h less than set by the speed limits.

Studies have shown that an increase in density of the train flow leads to an increase in average time needed for them to pass through the section. For the scattering estimate (absolute

Table 2

Ratio of actual speeds to the estimated and scheduled ones on electrified sections

Automatic interlocking signals	Number of cases	$\frac{v}{v_e}$	$\frac{v}{v_{fr}}$
At green traffic light	1795	0,80	0,92
At yellow traffic light	543	0,54	0,62
After passing at yellow traffic light	125	0,32	0,37



Pic. 9. Dependence of the standard deviation of train travel time on flow density (a), inter-train interval (b) and train traffic intensity (c).

Table 3

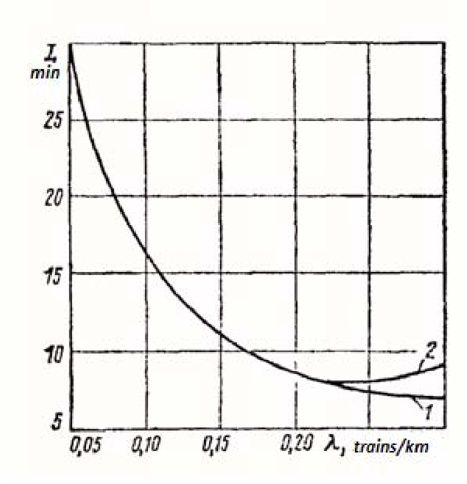
The ratio of actual speeds to the estimated and scheduled ones on sections with diesel traction

Automatic interlocking signals	Odd direction		Even direction	
	Number of cases	$\frac{v}{v_e}$	Number of cases	$\frac{v}{v_{fr}}$
At green traffic light	1060	0,77	778	0,85
At yellow traffic light	140	0,55	77	0,67
After passing at yellow traffic light	–	–	29	0,46

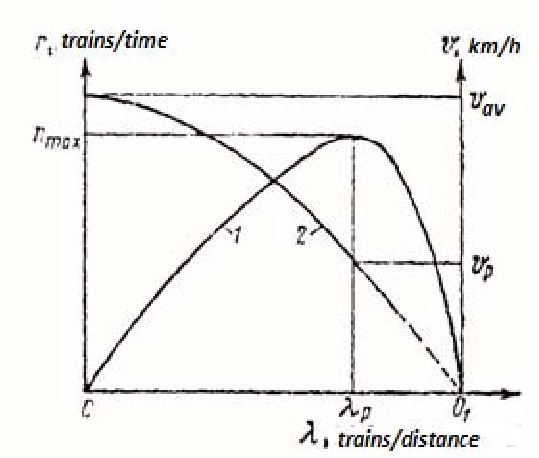
Table 4

Change in train speed depending on the distance between trains

Space interval between trains	Ratio S_1: S with the length of block sections, km			Speed v_1, km/h	
	1,5	2,0	2,5		
$3 \cdot l_{bl}$	1,0	1,0	1,0	80	70
$2,75 \cdot l_{bl}$	0,92	0,92	0,92	73,6	64,4
$2,50 \cdot l_{bl}$	0,83	0,83	0,83	66,4	58,1
$2,25 \cdot l_{bl}$	0,75	0,75	0,75	60,0	52,5
$2 \cdot l_{bl}$	0,67	0,67	0,67	53,6	46,9



Pic. 10. Influence of train flow density on average interval between trains at the entrance (1) and the exit (2) from the section.



Pic. 11. Diagram of train flow: 1 – n(λ); 2 – v(λ).

dimensions of fluctuations) to have the dimension of a random variable, we use the root-mean-square deviation and calculate its values for train travel time along the section (Pic. 9*a*), inter-train intervals (Pic. 9*b*) and train traffic intensity (Pic. 9*c*).

The presence of scattering of possible values around the average value of the train flow characteristics indicates non-synchronisation of train movement, which is present even with free movement of a single train and increases with growing load at the section. Asynchronous movement causes such an influence of trains on each other that the average actual inter-train interval is greater than the calculated one and the traffic flow of trains at the exit from the section is less than at the entrance.

When trains approach each other, their estimated speed v decreases to v_1 and the use of transit capacity decreases. In this case:
$\frac{Tv}{60S} = \frac{Tv_1}{60S_1}$, hence $\frac{v_1}{v} = \frac{S_1}{S}$ and $v_1 = \frac{S_1}{S}$.

To prevent a decrease in the use of transit capacity, trains' speed can be reduced in proportion to reduction in the distance between trains (Table 4).

When the inter-train interval is reduced by half of the length of block section, speed decreases by 11,9–13,6 km/h as compared with estimated standard value and so constitutes 0,83 of the estimated one. Further reduction of the inter-train interval to $S_1 = 2l_{bl}$, when the train goes at the yellow traffic light, makes speed be equal to 0,67 of the estimated one. The analysis of speed gauge tapes confirmed that with an increase in density of the train traffic, speed decreases significantly. This speed reduction decreases the use of transit capacity to n_1, then:

$$\frac{n_1}{n} = \frac{60Tv_1S}{60TvS_1} = \frac{v_1S}{vS_1}.$$

The reduction in the use of transit capacity with v_1 and S_1 is determined by:

$$\Delta n = \left(1 - \frac{v_1S}{vS_1}\right)100\ \%.$$

Studies of the sequential increase in the traffic intensity on the section have shown that with an increase in saturation of the section with trains, their influence on each other increases, and they more often pass at yellow and red traffic signals. As a result, train speed decreases. Time of occupation by trains of block sections increases, queueing to pass through the section appears and increases.

Simulation of train traffic has established that an increase in the flow density causes a difference in intervals between trains at the entrance and exit from the section (Pic. 10).

Graphs of dependences $n(\lambda)$ and $v(\lambda)$ of changes in the flow intensity and in speed on density are presented in the train flow diagram (Pic. 11). It shows many properties of the traffic flow, especially the space-time relationships and the possibility of interference with train traffic.

At points 0 and 0_1, the traffic intensity is zero, i.e., there is essentially no movement, or the flow of trains is in a state of congestion (immobility). As the train flow's density increases, its speed decreases, high speed values can be obtained only at low density values, i.e., under the conditions of relatively free movement of trains. This is of great practical importance. When standardising the performance indicators, during operational planning and regulation of train traffic, it should be borne in mind that an increase in the flow density (traffic size) causes a decrease in speed of trains, and if the sections are oversaturated with trains, it also results in decrease of the use of available transit capacity.

INTERACTION OF SPEED WITH OTHER INDICATORS OF TRAIN FLOW

Based on the main characteristics of the train flow, the transit capacity of the section can be described by the formula:

$$n = \lambda v, \qquad (1)$$

where n – traffic intensity, trains/h;

λ – flow density, trains/km;

v – speed of trains, km/h.

If two of these three variables are known, then the third is uniquely determined. Among the variables under consideration, there is no one that depends on only one parameter. However, since intensity is a quantitative characteristic of the transportation process, and speed reflects the level of technical equipment of sections and development of rolling stock, then they should be considered as independent variables, and the density should be deemed dependent variable. Ratio (1) can be visualised as a surface in three-dimensional space. In addition to the already listed average values, determination of the following values is of great practical and theoretical importance:

n_{max} – maximum traffic intensity;

v_{free} – speed of trains in free conditions (in accordance with traction calculations or traffic schedule);

v_p – speed, at which traffic intensity is maximum ($n = n_{max}$);

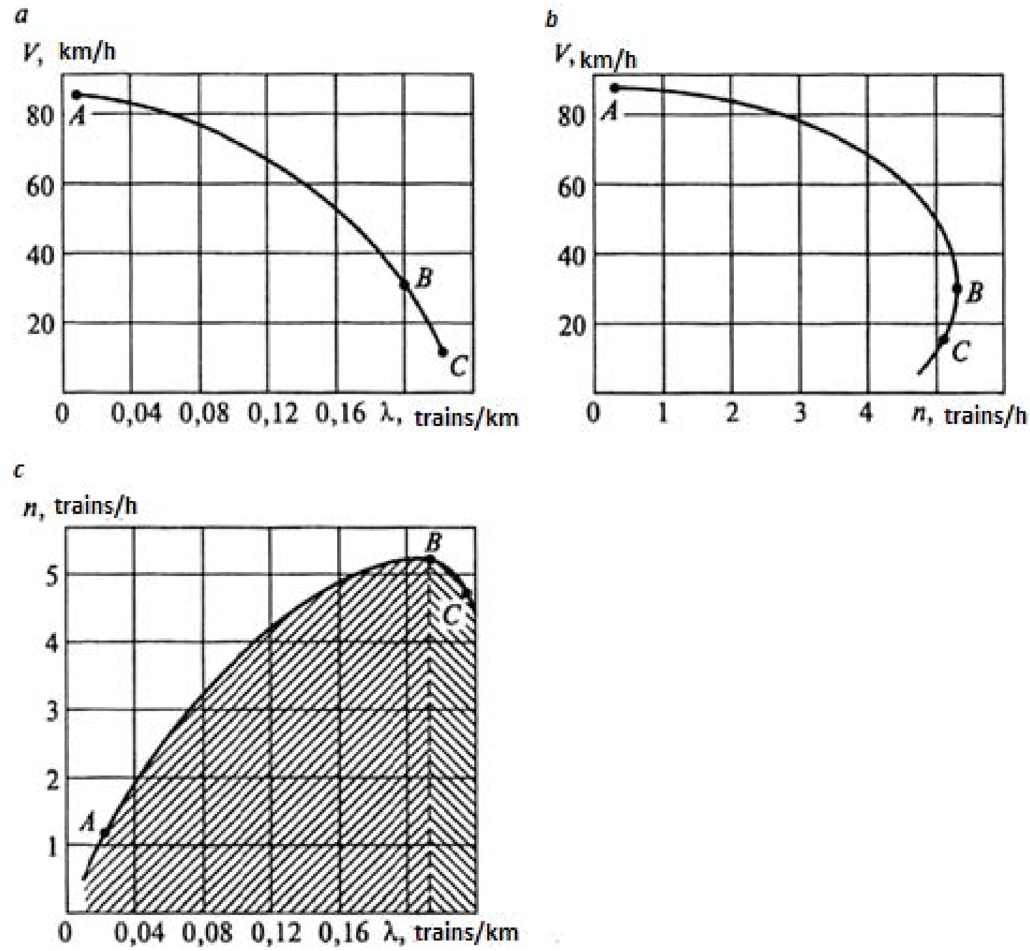
λ_{max} – maximum density, at which train movement is impossible ($v > 0$);

λ_p – density, at which traffic intensity is maximum ($n = n_{max}$).

The intensity-density relationship (Pic. 12) is the main train flow diagram. With an increase in the train flow density, the intensity increases to the maximum value n_{max} corresponding to the available transit capacity of a section (point *B*). Starting from this point, an increase in intensity at the entrance of the section does not lead to its increase at the exit, as evidenced by a decrease in intensity with a further increase in flow density. The vertical dashed line drawn from point *B*, as it were, separates the conditions of train traffic without delays (left) and with delays (right). Point *A* is typical for free conditions of train traffic without delays. Point *C* is within the area of traffic conditions with delays and shows that the same intensity can be achieved with a much lower flow density (0,16 trains/km), i.e., an excess in the working fleet of wagons does not lead to an increase in quantitative indicators, but, on the contrary, reduces them and worsens qualitative indicators of operational work. If on a specific section (Pic. 12) it is necessary to increase intensity, then density of the train flow should be increased to 0,214 trains/km.

To characterise the use of the section's capacity, we will use the load rate, which represents the ratio of the achieved traffic intensity n to the maximum traffic intensity n_{max} of the section, i.e., $\gamma = n/n_{max}$. With the help of this concept, it is possible to obtain comparable characteristics of the flow of trains on different sections, since γ is a dimensionless quantity and can take any values from 0 to 1.

Depending on the flow speed and its density (see Pic. 12), the initial section of the curve corresponds to free movement of trains. With an increase in flow density, speed of movement decreases due to a decrease in average inter-train interval and an increase in influence of trains on each other. Point *A* corresponds to the speed of movement v_{free} in free conditions. This speed is determined by traction calculations. The depen-



Pic. 12. Dependence between speed of train flow, traffic intensity and density.

dence does not cross the vertical axis but approaches it asymptotically. The qualitative state of the train flow can be characterised using the concepts of the speed coefficient and the rate of saturation of the section with trains.

The coefficient of speed u is the ratio of the maximum permissible speed v_{per} at the achieved density to speed of free movement v_{free}:

$u = v_{per}/v_{free}$.

The coefficient of speed allows to evaluate the effect of different flow densities on speed. The quantity u is dimensionless and can take any values in the range from 1 to 0.

The saturation rate of the section is the ratio of the flow density at various traffic sizes λ_{traf} to the maximum density λ_{max}:

$\varsigma = \lambda_{traf}/\lambda_{max}$.

As intensity increases to the maximum value n_{max} corresponding to point B, speed decreases (see Pic. 12). The part of the curve located above point B corresponds to normal traffic conditions without train delays, the lower part of the curve corresponds to traffic conditions with delays. Points A and C on «speed–intensity» curve correspond to similar points on «intensity–density» curve. Dependencies in Pic. 12 are obtained based on computer simulation of train traffic.

The most important characteristic of the sections is the maximum train traffic intensity (transit capacity). The satisfaction of the needs of cargo owners and the population in transportation of goods and passengers largely depends on the use of capacity and optimisation of its development.

Density of the flow of trains can be taken as hourly, daily, monthly, annual and for the corresponding period capacity will be obtained, but formula (1) is correct only with a small load of the section by trains. Since an increase in density of the flow of trains leads to a decrease in speed of movement, the correct functional form of expression (1) will be:

$n(\lambda) = \lambda v(\lambda)$. (2)

Train speed is distributed within a certain range (see Pic. 13), therefore it is advisable to determine two types of average speeds (spatial and temporal) and, accordingly, two density distributions of speed v.

The spatial density of distribution of speeds $f_s(v)$ is determined for trains occupying the section at a given moment of time, the temporal density of distribution of speeds $f_t(v)$ – for trains passing a given point of the section during a given time interval. Then the average spatial and temporal speeds are:

- for double-track sections:

$$\bar{v}_s = \int_0^{v_{max}} v f_s(v) dv \; ; \qquad (3)$$

$$\bar{v}_t = \int_0^{v_{max}} v f_t(v) dv \; ; \qquad (4)$$

- for single-track sections:

$$\bar{v}_s = \int_0^{v_{max}} |v| f_s(v) dv \; ; \qquad (5)$$

$$\bar{v}_t = \int_0^{v_{max}} |v| f_t(v) dv \; . \qquad (6)$$

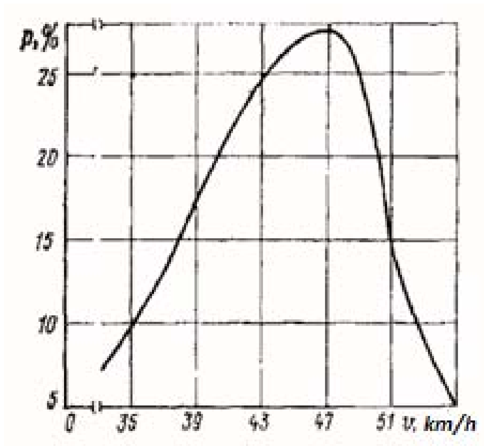
In formulas (3) and (4), the lower limit is assumed to be zero since there is no oncoming traffic along each separate track of a double-track section. The lower limit in formulas (5) and (6) shows that on single-track sections, trains move both in forward and backward directions.

For the theory of train flows, harmonic average speeds $'v_s$ and $'v_t$, based on the corresponding distribution densities, are of interest; for example, for a double track section:

$$'v_s = \frac{1}{\int_0^{\infty} \frac{1}{v} f_s(v) dv} \; ; \qquad (7)$$

$$'v_t = \frac{1}{\int_0^{\infty} \frac{1}{v} f_t(v) dv} \; . \qquad (8)$$

The necessity of using harmonic average speed in some cases will be illustrated by a simple example, which shows what difficulties arise when considering the flow of trains. Let us assume that three trains have covered a 10 km stage at speeds of 40, 50 and 60 km/h respectively. Obviously, average speed is 50 km/h. Similarly, the average travel time is 0,206 h. However, these values (10 km, 50 km/h, 0,206 h) do not satisfy the equation $s = vt$.



Pic. 13. Distribution of running speed of train movement on the section.

The reason is that this equation is valid for mean values only if the harmonic mean is taken for speed, and the arithmetic mean is taken for time, or vice versa. Here, as above, it is assumed that the flow of trains is stationary and that speed of each train is constant during the time interval that determines average temporal speed, or along the section that determines average spatial speed.

Let $\lambda_v dv$ and $n_v dv$ represent, respectively, the differentials of density and traffic intensity of trains which speed lies in the range between v and $v + dv$. Then the following expressions for distribution densities $f_s(v)$ and $f_t(v)$ are valid:

$$f_s(v)dv = \lambda_v dv / \lambda \; ; \qquad (9)$$

$$f_t(v)dv = n_v dv / n \; , \qquad (10)$$

where λ and n are, respectively, density and intensity of the train flow.

From the expression (1) it follows that $n_v = v\lambda_v$.

Using this expression, we get from formulas (4) and (5):

$$n f_t(v) = v \lambda f_s(v) \; . \qquad (11)$$

Then $\bar{v}_s = \int_0^{\infty} v f_s(v) dv = n / \lambda$, since $\int_0^{\infty} f_t(v) dv = 1$.

As a result:

$$n = \lambda \bar{v}_s . \qquad (12)$$

Thus, equation (1) is valid for average spatial speed v_s, even if train speeds are not the same, but are random variables with an arbitrary probability distribution. On the other hand, by substituting equations (12) and (11), we find that:

$$f_t(v) = f_s(v) v / \bar{v}_s . \qquad (13)$$

Equation (13) describes the dependence between spatial and temporal speed distribution densities. By dividing by *v* and integrating both sides of equation (13), we obtain:

$$\int_0^\infty \frac{1}{v} f_t(v)dv = \frac{1}{\bar{\bar{v}}_s}\int_0^\infty f_s(v)dv = \frac{1}{\bar{\bar{v}}_s}.$$

Returning then to equation (8), we notice that $'v_t = 'v_s$. Thus, average spatial speed is equal to average harmonic temporal speed.

Then we consider the relationship between $\bar{v}_t$ and $\bar{v}_s$. Let's substitute equation (13) in (4):

$$\overline{v_t} = \int_0^\infty v^2 f_s(v)dv \,/\, \overline{v_s}.$$

If we determine dispersion of average spatial speed as:

$$\sigma_s^2 = \int_0^\infty (v - \overline{v_s})^2\, f_s(v)dv = \int_0^\infty v^2\, f_s(v)dv - v_s^2,$$

then we get:

$$\overline{v_t} = \overline{v_s}\left[1 + (\sigma_s / \overline{v_s})^2\right].$$

Thus, for large values of σ_s, the difference between average spatial and average temporal speeds also becomes large.

SUMMARY

The widespread practices of changing only a single component shows that in a dynamic and internally connected complex system of railway transport, this results in a change in many other components. The results of the study of interaction of train speed with other indicators of the transportation process have confirmed this statement.

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