очереди позволяет управление составообразованием на сортировочных станциях.

Дальнейшее исследование очередей на железных дорогах позволит формализовать влияние неравномерности на все процессы эксплуатационной работы и использовать выявленные закономерности:

• при проектировании станций, участков, грузовых фронтов и др.;

• при разработке нормативно-технологических документов (графика движения, плана формирования поездов, технологических процессов работы предприятий);

• при техническом нормировании эксплуатационной работы;

• при оперативном планировании и управлении поездной и грузовой работы.

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TRAIN QUEUING AT RAILWAYS

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ABSTRACT

Insufficient consideration of irregularity of train traffic causes lack of tracks at the stage of designing and reconstruction of stations, underestimation of resources during development of technical specifications, and underestimation of indices during development of technological processes etc. In order to evaluate irregularity of train traffic the article proposes to use the queuing theory that permits adapting necessary documents used for design and establishing of technological standards. The research used simulation to study real process of train operations, to obtain features of train queuing, to analyze changes of indices that depend on traffic intensity growth. The achieved results can contribute to increase of veracity and validity of decision-making, operation planning and freight and train operation management.

ENGLISH SUMMARY

Background. *Queues to obtain service are characteristic of all the spheres of human activities, and railways don't make an exception. Queues at Russian railways were first mentioned at the end of 19th century [3], when bottlenecks happened yearly from autumn to spring during the period of forwarding of grain towards southern and Baltic ports. Later the same situations repeated due to expectation of acceptance of goods intended for forwarding, to delays in technological operations, in train departures, in bringing up of trains for loading etc. But still this problem was not studied.*

Almost a half of time that the cars spend at modern classification yards is explained by interoperation demurrage, which causes non-productive extra costs, inefficient use of rolling stock and of transit capacity of railways.

Now the organization of rail cars' flows is accomplished on the basis of the plans of train making-up. Practicability of making up of trains intended to go to certain destinations within those plans is determined by surplus of reduced savings received from making up of trains which go directly to their destination without handling at transient classification yards as compared to costs of cumulating of trains at the station where making up of trains is accomplished [4]. It is assumed that all the made-up trains afterwards strictly respect the schedule and their time in transit for the same destination is always the same. And the time spent by trains of different destinations isn't taken into account.

During station and track section designing, technical regulation, developing of standards one usually groundlessly proceeds from the assumption that traffic process is regular. As the result the article notes deficiency of station tracks, lack of transit capacity at important mainlines, loading of freight handling facilities over optimum level, deficiency of handling capacity of classification yards, and that scheduled volumes of train traffic exceed present capacity of railway sections, the number of made-up trains exceeds the number of available locomotives.

The general cause of emerging queues is the inconformity of cargo, cars», trains' flows with capacity to rend relevant services. Even when mean daily volume of flow does not exceed transit, handling, unloading capacity, its irregularity and fluctuations of service time cause queues.

The studies of irregularities of traffic process were begun in 1968 by professor A. C. Ugrumov [5]. Then an important number of publications showed the objective character of that phenomenon. For instance only 20% of cars are unloaded during the first half of a day. But declaration of evident irregularity has not yet changed the situation. Reality differs from regulations.

Objectives. *The objective of the research was to reveal main laws and to determine the impact of irregularity of traffic process on different aspects of organization of train and freight operations.*

Methods. *The main method that was used for research was mathematical simulation (supported by some tools as for instance approximation by linear function).*

As the train operation is a typical system of waiting (queuing) theory, then some of its characteristics were used to assess train traffic:

– incoming flow of trains is determined by intensity of making-up of trains and distribution of intervals of arrival of the trains;

– communication devices regarding train traffic (service mechanism), which determine intervals between trains, duration of service (occupation of blocks, stages) and distribution of inter-train intervals;

– organization of train traffic (service discipline) that determines priorities of trains.

Results. *The most simple flow is a regular incoming flow when demands come one after another at the moments with time interval t. Intensity of the flow is equal to $\alpha = 1/t$ per time unit. It can be shown at example of train schedule strictly respected by passenger trains.*

The most widespread is a flow when demands come stochastically. But during long periods of time there are changes in intensity of trains' traffic (Pic. 1). So the traffic on a regular predetermined basis, defined by schedule, is a probabilistic process. The flow of this kind is called recurrent and is a generalized form of two previously described forms.

The conditions of trains' transit by the sections can be assessed with service characteristics. The first characteristic is the time of transit per block and per whole section (duration of service). The second characteristic is transit capacity of a section (maximum number of trains that can transit the section per time unit). The third feature is availability of service and railway sections are completely accessible systems.

Duration of occupation by trains of blocks and stages depends on moving speed. In order to obtain the determined speed and to respect other norms of the schedule the trains should have green light in front of them and continue going with green light of light signals, the signals should not be changed in front of them. This condition is respected when the distance between the trains is more than three blocks within the system of 3-digits blocking. Less is the density of the flow, freer are the drivers, and then higher speed is achieved.

Decoding of speedometer bands has shown that drivers of freight trains always go with a speed that is less than the planned speed and is under established speed restrictions (Pic. 2). When the distance between the trains is more than three blocks the speed is 20% less than the calculated speed, and 8% less than the scheduled speed. If the distance between the trains is more than 2 but less than 3 blocks, and a train cover a part of the itinerary with yellow light, then the mean speed is 46% and 38% less respectively, and after passing yellow light the speed is 63% less. The real speed of trains differs from the calculated speed in a wide range of values from 0,2 through 1,2. The big dispersion is explained by different skills of drivers, differences in their reaction to the lights, that sometimes causes premature braking.

Practice shows that drivers drive the trains with a maximum permissible speed only in exceptional cases and for a short time, as it is associated with overstrained working of a railway team, locomotive devices and increased consumption of electricity and fuel. Significant amendments to the actual range of speeds make weather conditions, profile and plan of a track, the state of the locomotive.

Any reduction in train speed as compared to calculated speed for this section, and even more interruption of train service lead to losses in use of transit capacity and subsequently to economic losses. Train delays at station-to-station blocks are caused by: non-synchronism in train traffic, untimely opening of signals at stations, malfunctioning of the rolling stock, presence warnings about speed limits and transit of passenger trains, coming late.

In case of non-synchronism in traffic trains run at yellow and often red signal instead of green one. So, if the bunch of trains goes with a 6- minute inter-train intervals and one of the locomotives will reduce the speed against mean scheduled speed by only 5 km / h, the following train in 1,5 min. approaches the traffic lights with yellow signal. Non-synchronism in traffic occurs because drivers use the train schedule, which indicates only the travel time at station-to station blocks. Speed of movement on the various elements of the track`s profile is determined by experts, selection of motion mode depends again on the qualifications of drivers.

Train delays during malfunction of cars, locomotives, tracks, signaling arrangements and communication systems, catenary system, etc. are affected by communications on the train traffic, the number of main tracks, type of traction, inter-train interval and the number of passenger routes. Failures in technical devices reduce available transit capacity of sections to 15%.

The actual number of established speed restrictions of train traffic at many sections of the network is larger than it is provided for by the schedule. Total distance, covered by train with a speed limit $l_{огр}$ is equal to the sum of the extension of established speed restrictions $l_{пр}$, train length $l_п$ and the distance covered with underspeed $v_{огр}$ considering deceleration and acceleration of a train to and after the place where the speed is restricted. Distance with a speed restriction is on average 2,5 times larger than track length with warning about speed restrictions. Analysis of speedometer bands has shown that the actual speed is below limited speed by on average 20–25% Number of trains that are affected by the speed limit on the approach to its place of action:

$$N = \frac{(v_{ср} - v_{огр}) l_{огр}}{v_{огр}(v_{ср} I - l_{П} - p L_{б-у})} - 1,$$

where $v_{огр}$ – mean train speed, km/h; I – inter-train interval, h; p – minimum number of block-sections, delimiting trains, which ensures stable movement on the green signal of traffic light (for three-digit automatic blocking p = 3);

$L_{б-у}$ – mean length of block-section, km.

Transit of passenger trains coming late delays 10–15% of freight trains.

Along with the factors that adversely affect fulfillment of a schedule, there are also positive factors, especially power reserve of locomotives when going with underweight trains. In fact, the average weight of trains is 10–15% less than set by norms, which allows them to go at larger speed than scheduled one. But analysis of speedometer bands shows that due to the lack of interaction of station operators with locomotive crews this opportunity is not realized.

Other possibilities to reduce the impact of delays on the fulfillment of the schedule are reduction in standing time of make-up of trains at service stations (some trains may do not need repairs at all), and use of free graphs of schedule to accelerate the train transit. Changing the order of train transit on single-track lines reduces the number of train crossings and the parking period at stations as compared to the maximum schedule.

Optimization control of loading at sections and stations is of crucial importance for reduction in train delays.

Desire to transit more trains than the section is able to transit according to the norms leads to the opposite result (Pic. 3) [6].

Initial section of this dependence can be approximated by a linear function and it corresponds to its positive response to an increase in the intensity of the incoming flow of trains, i. e. any increase in the incoming flow leads to an increase in the outgoing flow. The section retains a positive response so far, until it reaches a state of saturation of trains. Thereafter, further increase in the intensity of the incoming flow substantially does not lead to an increase in the outgoing flow. When the state of oversaturation is reached, any increase in the intensity of incoming flow of trains reduces the size of outgoing one.

But apart from the incoming and outgoing flows, there is also a flow of trains approaching the section (Pic. 4).

Simulation of train traffic made it possible to look deep into the train operation. A gradual increase in intensity (decrease in inter-train interval) of a train flow approaching the section has been studied (Pic. 5). At small sizes approaching, incoming and outgoing flows are equal and increase linearly.

Reaching a point of saturation of trains (I in Pic. 5), a further increase in the intensity of the flow of trains on the approach and entrance to the section continues to increase linearly up to the point II. Then with further reduction in inter-train interval flow of the trains, approaching the section, increases linearly, and the incoming flow, although also increases, but nonlinearly, and by a smaller value. Outgoing flow of trains after the point I slows its growth nonlinearly to reach its maximum value at the point III, after which it begins to decrease linearly.

Returning to the real section, the author considers the change in the flow of trains value and characteristics of their queue on approach, entrance and exit from the section.

While reducing inter-train interval on the approach to the section:

- the intensity of the train on the approach to the section increases linearly (Pic. 6);

- the intensity of the incoming flow of trains increases linearly to the point II, after which the nonlinear increase in the intensity slows (Pic. 7);

- the intensity of the outgoing flow of trains increases linearly to the point I, after which a nonlinear increase slows down to point III (the maximum size of the movement in the section), and then the flow of trains decreases nonlinearly (Pic. 8);

- the average queue length of trains on the way to the section (Pic. 9) and the maximum queue length (Pic. 10) increase;

- mean queuing time of trains (Pic. 11);

- loading of the section increases (Pic. 12).

When trains' saturation of the section increases, their influence on each other grows, and they go at yellow and red signals of traffic lights more often. As a result speed of movement reduces. Time for occupation of block-sections by trains raises, queue to pass the section occurs.

The section under review has 6-min inter- train interval.

In the simulation, queue of trains before the section has already occurred by inter-train intervals, which have been equal to 8 min. Inter-train interval, which is smaller than in practice, has been modeled, but then loading of the section has not reached 1 (Pic. 12). It is explained by the fact that the flow of freight trains with similar specifications as well as locomotive drivers with the same driving skills cannot be found. In addition, in case of high traffic intensity train flow becomes extremely unstable.

Conclusions. *For a better use of available transit capacity of sections «back» of trains is required, i. e. their turn on the approach. For each section, there is a rational length of trains' queue, which should be considered in operational planning and standardization of train operation. Management of trains' making up at classification yards allows optimizing the queue length.*

Further research on the railways queues will allow formalizing the uneven impact on all processes of field operation and using regularities identified:

• in designing stations, sections, freight fronts and others;

• in development of regulatory and technical documents (schedule, train formation plan, technological processes of enterprises);

• in technical standardization of field operation;

• in operational planning and management of the train and freight operations.

Key words: railway, traffic control, queuing theory, traffic irregularity, trains' flow intensity, saturation and oversaturation of the section, station and section designing, regulations.

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