

railway stations; simulation; ergatic model; finite-state automate

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## FUNCTIONAL SIMULATION OF RAILWAY STATIONS ON THE BASIS OF FINITE-STATE AUTOMATA

**Summary.** The general scheme of railway station's model and technique of formalizing the technologic processes at stations are described. To take into account the human impact on station's operation is suggested to use ergatic models. In conformity with concept of stations' ergatic models a person is directly involved into the simulation process and manages the station technological processes acting as a dispatcher. The formalization of technological processes for processing the objects is performed on the basis of deterministic finite-state automaton. Designed model can be used for optimization of technical and technological parameters of railway stations, as well as in computer simulators for training of railway traffic managers.

## ФУНКЦИОНАЛЬНОЕ МОДЕЛИРОВАНИЕ ЖЕЛЕЗНОДОРОЖНЫХ СТАНЦИЙ НА ОСНОВЕ КОНЕЧНЫХ АВТОМАТОВ

**Аннотация.** Приведена общая структура функциональной модели железнодорожной станции и методика формализации технологических процессов станций. Для учета влияния человека на станционные процессы предложено использовать эргатические модели. В соответствии с концепцией эргатического моделирования человек принимает непосредственное участие в процессе моделирования и управляет технологическим процессом станции, выполняя функции диспетчера. Разработанная модель может быть использована для оптимизации технических и технологических параметров железнодорожных станций, а также в компьютерных тренажерах для подготовки диспетчерского персонала железных дорог.

### 1. INTRODUCTION

Railway stations are one of the main elements of the infrastructure of transport network. For their steady operation, stations should have sufficient reserve capacity and processing ability to cope with the peak loads. At the same time, the stations' own expenses should be minimized reducing excessive technical potential. The determination of rational parameters of railway stations is a complex multi-variant and multi-criteria problem. The long-term experience in operating real stations and numerous researches of scientists and engineers were the basis of "Instructions on design of stations and junctions on the USSR railways" (hereafter referred as "Instructions"). It should be noted that this document was until recently the basic standard in the CIS countries governing the requirements to train stations' technical parameters. However, in recent years in relation to the market reforms in the railway transport of Ukraine and other CIS countries, significant changes took place. Changing the range of

products of enterprises, sharp increasing the share of private freight cars, introducing the high-speed traffic on the adjacent lines, making the traffic safety requirements be more strict due to aging the infrastructure and rolling stock led to the situation when many mainline and industrial railway stations have shortages in the capacity and processing abilities, even in the conditions of a general reduction in traffic volumes. It should be noted that the design standards specified in the "Instructions" in many cases do not correspond to the real conditions of operation of railway stations. In this context, the solution of design and technological problems need a modern and effective tool for obtaining reliable quantitative and qualitative evaluation of the planned changes in stations' design and operation technology. The simulation of station processes on the basis of modern computer technology can serve as an effective tool for analysis and assessment of functioning of the stations, their technical-and-technological and economic parameters. The use of simulation models for the stations' operational management as well as for the implementation of project activities would allow making rational decisions to reduce stations' own expenses and increase the profits of transportation by rail.

## 2. LITERATURE REVIEW AND DEFINING THE PROBLEM

A large number of papers are devoted to the development of methods for simulating the operation of railway stations (e.g., refer to [1-8]). However, the analysis shows that in the current models not enough attention is paid to managing the technological processes (TP) of stations and evaluating its quality. In addition, the efficiency of functioning a station is largely dependent on the level of operational management by dispatch personnel. At the same time, the existing station models practically do not take into account the management activity of dispatch personnel that does not ensure the adequacy of such models. Besides, the currently used methods for developing simulation models require a significant contribution of time and labour of highly skilled programmers and engineers and, as a result, they are often not available for a wide range of practitioners to solve specific problems.

To eliminate these drawbacks, the authors have suggested a concept of stations' ergatic models, in which a person is directly involved into the simulation process and manages the station TP acting as a dispatcher. In doing so, one of the main requirements to these models is the simplicity and versatility of providing the input data at the expense of complicating the internal organization of the simulation software systems. This approach would automate the synthesis of models making them available to a wide range of engineering and technical staff.

This article presents a general structure of the railway station ergatic model and a procedure of formalizing the station TP's. In addition, the results of using the developed ergatic model in various applications are given.

## 3. METHODOLOGY

The railway station is a complex system consisting of a number of different elements, which interact closely one to another in the process of operation providing mutual influence. To build the functional station models (FSM), the following generic models are developed:

- model of station trackage;
- model of station automation system;
- model of station technologic process (STP);
- model of operative station management (OSM);
- information model.

These models are developed as separate modules built using an object-oriented approach. Such an organization allows standardizing the integration process for modules into the general FSM for solving problems of different class. In addition, this approach simplifies the synthesis of models of specific stations enabling one to take into account the characteristics of their technical equipment and operation

technologies. The proposed FSM modular structure is shown in Fig. 1.

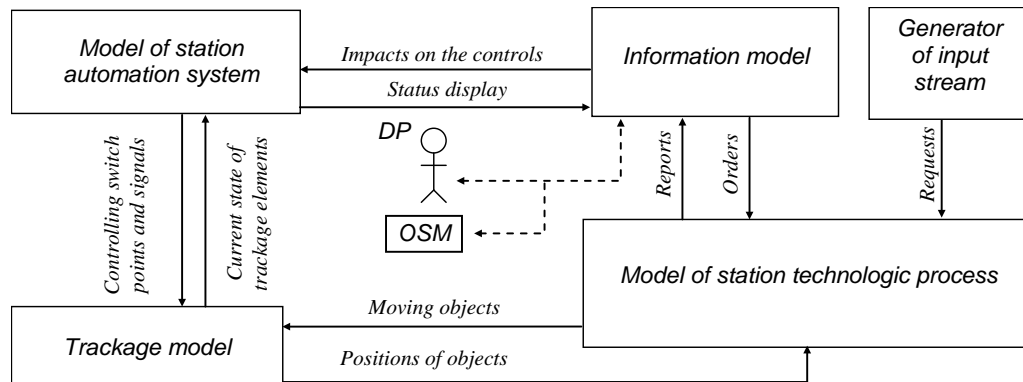


Fig. 1. Structure of functional model of a railway station

Рис. 1. Структура функциональной модели железнодорожной станции

Models of trackage of stations and station automation systems are formalized in the form of weighted directed graphs and presented in [9, 10]. A formal representation of trackage and automation systems in the model of a station allows automating their synthesis, and the availability of data on the actual length of the track sections provides an adequate simulation of train and shunting movements.

One of the main problems arising in the functional simulation of stations is the difficulty of formalizing their technological processes, which may essentially differ at different stations.

In the model developed a station or a separate processing facility is seen as a managed multi-phase multichannel queuing system (QS). In the QS the objects, which need maintenance at the station (trains, sets of cars, locomotives etc.), generate the input stream. The individual technological operations or works (immobilizing of train, technical inspection, breaking up, etc.), which are performed in a specific sequence according to the TP, are service phases. The duration of these operations are to be simulated as random variables, which parameters depend on the characteristics of the object. Executors of technological operations (car inspectors, shunting locomotives, sorting humps etc.) are serving devices. The service discipline is set by the model's dispatching person (DP) or a system of priorities adopted in the OSM. The structures of data used to represent the objects, executors and works in the TP model (TPM) are presented in [11].

The formalization of TP for processing the objects is performed on the basis of deterministic finite-state automaton (FSA) that ensures performing all the complex of technological operations to every object in accordance with their mutual dependence:

$$A = \{X, Z, S, F_z, F_s\}, \quad (1)$$

where  $X, Z$  are, respectively, input and output alphabets;  $S$  is a set of automatic device states;  $F_z, F_s$  are functions of outputs and transitions.

The input alphabet  $X$  of an automaton comprises two subsets of the input signals:  $X = \{X_1, X_2\}$ ; here  $X_1$  are external commands from DM or OSM to initiate certain operations to the object;  $X_2$  are internal signals from the object after termination of each technological operation. Availability of signals  $X_1$  type allows a person to impact on simulation process and realize the concept of ergatic model.

The function  $\Psi_i$ , which is to be performed by FSM at the time of receipt of the input signal  $x_i$  with the FSA, is assigned to each character  $z_i$  from the output alphabet  $Z$ . The functions  $\Psi_i$  comprise command sets of two types  $\Psi_i = \{K_{i1}, K_{i2}\}$ ; here  $K_{i1}$  is a list of initialization commands for individual technological operations with the object;  $K_{i2}$  is a list of commands and messages to be transmitted to structural models of FSM.

Each state of an automaton  $s_q \in S$  corresponds to a certain state of TP for servicing the objects that is characterized by the completion of each technological operation ( $s_q = 0$  – the operation can not be started,  $s_q = 1$  – the operation can be initiated or executed,  $s_q = 2$  – the operation is completed).

A separate FSA is to be developed to simulate processing the objects of different categories (freight trains, passenger trains, shunting trains, etc.) at the station. The TP of servicing an individual object is simulated by a sequence of FSA transitions from one state to another as the provisional operations are performed. At the beginning of simulation of TP for servicing each object, the corresponding FSA is in the initial state  $s_0$  (an automaton is initial). Upon completion of all the operations according to the TP, an automaton transits into the final state  $s_f$ , then the corresponding object is to be removed from the QS.

The functions of outputs  $F_z$  and transitions  $F_s$  of an automaton  $A$  perform the conversion of the input signal sequence  $\mathbf{x}_j = \{x_1, x_2, \dots, x_k\}$  into the corresponding output sequence  $\mathbf{z}_j = \{z_1, z_2, \dots, z_f\}$ . A variety of input sequences  $\mathbf{x}_j, j = 1 \dots r$ , where each one makes the FSA transited from state  $s_0$  into state  $s_k$ , is used to formalize the various technology options for servicing an object; the choice of the sequence  $\mathbf{x}_j$  is to be realized by DP.

An analysis of TP's for servicing various objects at railway stations found that the output and transition tables for the corresponding FSA's are very sparse. In this context, a directed graph is used to represent an automaton. For example, Fig. 2 shows a directed graph of the behavior of automaton simulating the TP for servicing a group of cars in the reception yard; in this process the following technological operations are to be performed: 1 – moving of a group of cars to a reception yard; 2 – immobilizing by rail skates; 3 – uncoupling a locomotive; 4 – protecting; 5 – technical inspection; 6 – commercial inspection; 7 – coupling a locomotive; 8 – removing rail skates; 9 – humping. The DP manages a TP, who for the initialization of individual operations with an object issues the following commands: 101 – "To immobilize", 102 – "To protect", 103 – "To couple a locomotive", 104 – "To humping".

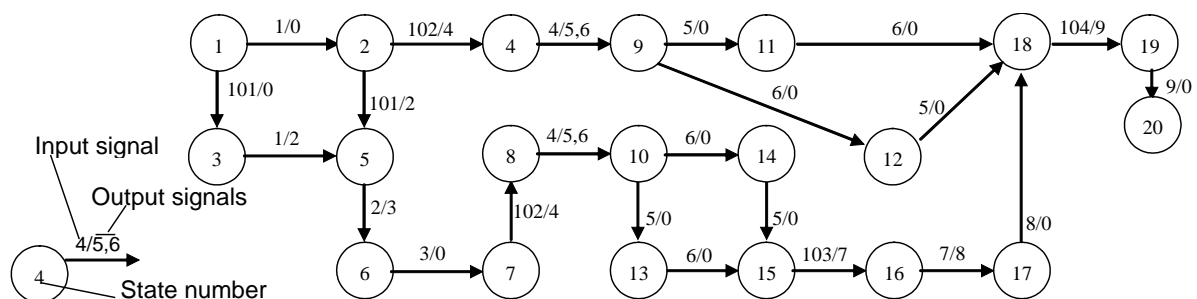


Fig. 2. The FSA transition graph for simulating the technologic process of servicing a group of local cars in the reception yard

Рис. 2. Граф переходов конечного автомата для моделирования технологического процесса обслуживания группы местных вагонов в парке прибытия

The automatic device states 1 ... 20 are assigned to the graph nodes, the possible transitions between them are assigned to the arcs. The graph arcs are marked with characters  $x/z$ . Here  $x$  is an internal signal from the object on the completion of operation with the number  $x$  ( $x = 1 \dots 9$ ) or an external command from the DM ( $x = 101 \dots 104$ ), under which a transition presented by the arc is under realization, and  $z$  is a number of operation that should be started in so doing.

The state 1, which means that a group of local cars is beyond a reception yard, is initial; the state 20, when the cars of this group are directed to marshalling tracks, is final.

An automaton provides two options for servicing the group: with or without cutaway of shunting locomotive at technical inspection of cars. Selecting the service option is to be provided by the DM, who can issue a command 101 or 102 in the state 2, whereas commands 103, 104 enable the DP to manage the queues for breaking up of set of cars.

The FSA transition graph shown in Fig. 2 is the basis for formalization of TP for servicing the object in the FSM (see Fig. 3). In this case, the lists of identifiers of the operations executed, occupied executors and/or ones executing an operation and available commands issued by the DP are assigned to each state of an automaton. The executors in this case are: the reception track – RT, shunting locomotive – SL, yardman – YM, operator of car inspection station - OP, team of car inspectors - CI, team of commercial inspectors– KI, hump - H.

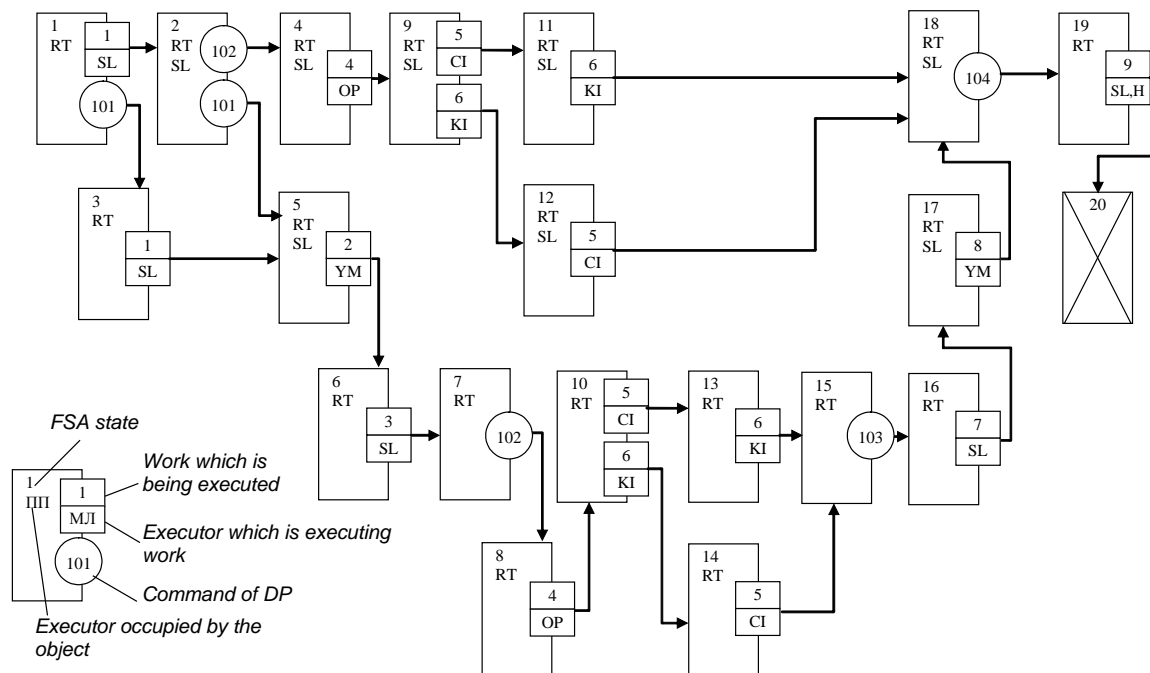


Fig. 3. Fragment of the technological process of servicing local cars in the reception yard

Рис. 3. Фрагмент технологического процесса обслуживания местных вагонов в парке прибытия

#### 4. INVESTIGATION RESULTS

On base of this model the special software for simulation of railway stations was worked out.

To automate the construction of FSA's simulating the technological processes in servicing objects of different categories at station, a special software editor is developed. The mentioned editor enables one to making interactively the required FSA transition graph from the standard elements and commands. The editor window and a fragment of graph constructed with its help are presented in Fig. 4.

The technique developed allows simulating the station TP at any level of complexity and with any degree of detail. In doing so, the use of FSA's allows simulating various options of servicing the objects, which provides the significant flexibility in the model. Furthermore, the formalization of TP in the FSA form allows the interactive human participation in the process of simulating the station operation, and it allows simulating his/her interaction with the performers of technological operations.

Traditionally, a graphic model in the form of daily schedule is used for the analysis of the technical equipment and operation technology of railway stations. This model has a large information capacity and provides a high rate of search and access to the necessary information. The main drawbacks of traditional development methodologies for schedules are the low rate of constructing the graphic image and obtaining the station operation indices, the neglect of random nature of the duration of technological operations, the complexity of replicating, archiving and transmitting the information. In this context, the simulation model developed is augmented with a module of automated construction of the daily schedule of station operation. The chart is constructed automatically during the simulation of

station operation, and the final result is stored in a file format «\*.dxf» supported by graphics packages AutoCAD and CorelDraw.

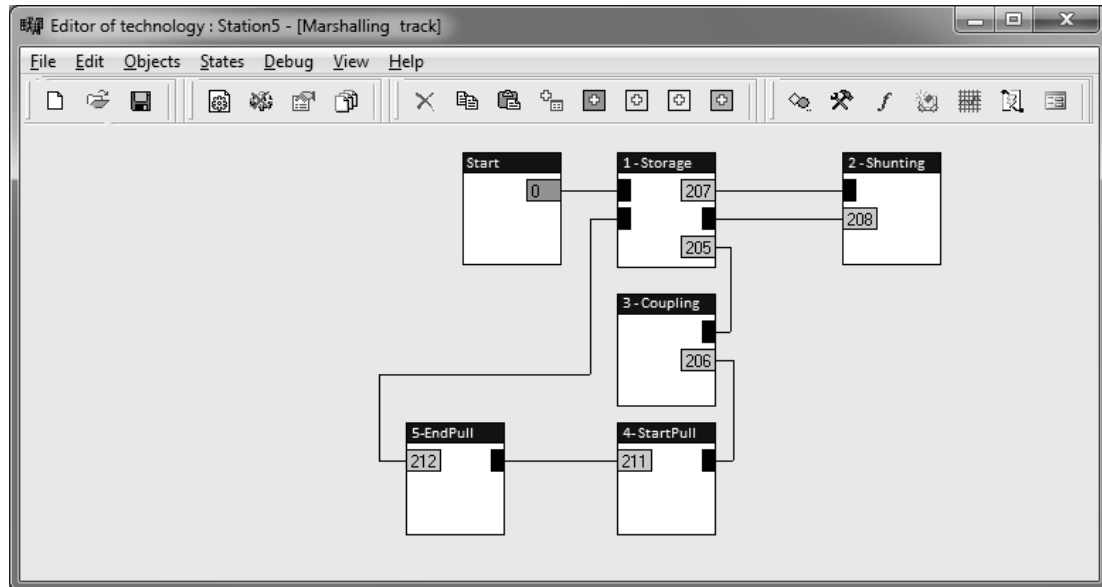


Fig. 4. Editor window of the technological process of station operation  
Рис. 4. Окно редактора технологического процесса работы станции

In so doing, the work performed by a station is displayed on a special grid in the form of various graphics primitives; each of them corresponds to a certain technological operation (train acceptance, technical inspection, breaking up, locomotive motion, etc.). Based on the chart analysis, one can determine the load of station elements and its operating indices as well. A fragment of such a chart obtained by the simulation results for the station operation is presented in Fig. 5.

Approbation of the simulation technique suggested has been performed in the evaluation of design decisions on the reconstruction of a breaking-up subsystem at one of the marshalling stations in Ukraine. To construct the ergatic model, a comprehensive survey of the station is performed; based on the related results, its technical equipment and technology process are formalized, the information model is developed, the parameters of the input stream of requests and time characteristics of performing the individual technological operations are determined. Based on these data, the identification of model of breaking-up subsystem is completed. Evaluation of the model adequacy is executed on the basis of statistical analysis of random variables for staying time of trains in the system obtained at station as a result of chronometer observations and simulating the station operation. Testing the hypothesis of belonging these two samples to the same general set using the criterion of Van der Waerden has confirmed the model adequacy. To get the technical and operational indices, characterizing the operation of breaking-up station subsystem, a series of simulation experiments with its model was carried out. In each experiment 10 replications with different initial values of the random number generator were made. Table 1 shows the trend in the station operation indices with changing the number of reception tracks and the traffic volumes  $N_p$ .

The results obtained are used in a feasibility comparison of the reconstruction variants developed and allows one making operative informed decisions on appropriate changes in technical equipment of the park with changes in workload.

The development of computer simulators for training and testing the station duty officers is another of effective directions of using the ergatic simulation [12]. In this case, a powerful ergatic model of relevant railway station is a basis for each computer-based simulator of such a kind.

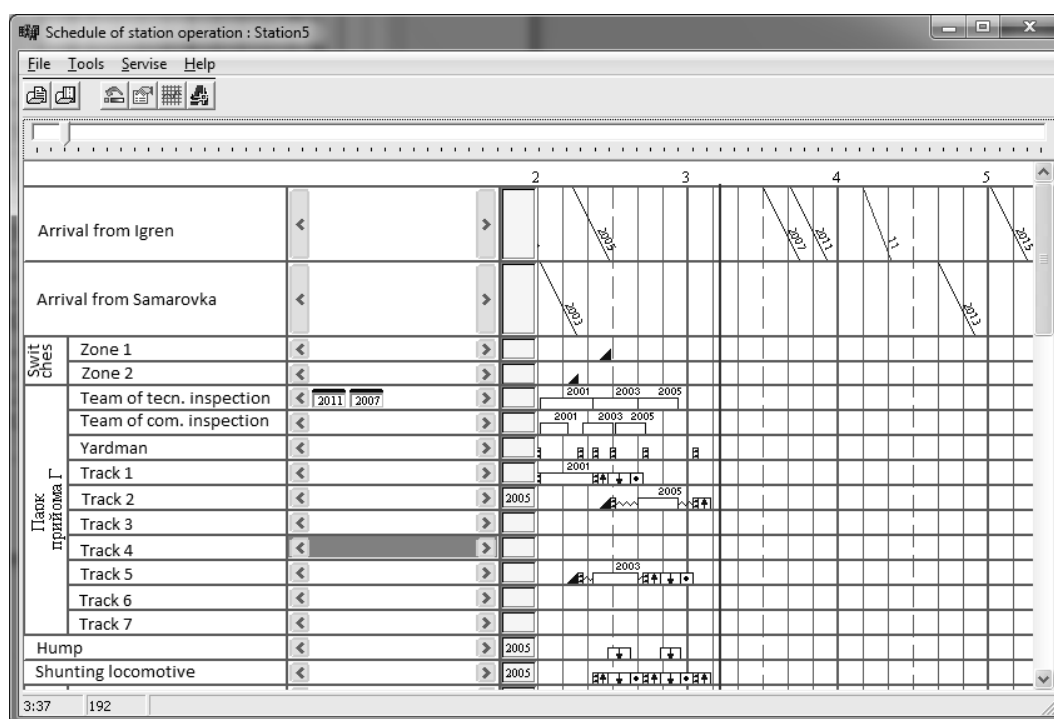


Fig. 5. Fragment of schedule of railway station operation

Рис. 5. Фрагмент графика работы железнодорожной станции

Table 1

Technical and operational performance of the station

Index	Quantity of tracks	Average daily number of trains			
		10	20	30	40
Average waiting time for a train to arrive, [min]	4	0.18	0.7	3.1	9.4
	5	0.18	0.2	0.18	0.3
Average waiting time for a train at the yard, [min]	4	68.7	72.4	83.4	125.6
	5	68.6	70.4	77.46	105.3
Average waiting time for a train locomotive at the yard, [min]	4	5.2	5.3	5.6	6.4
	5	5.2	5.3	5.5	6.2

For the simulators developed, the workplace of a station duty officer, including the station light mnemonic scheme, signal lights, control buttons and arms, and other elements necessary in the operation, is displayed on the computer screen (Fig. 6).

The simulators allow providing the train and shunting routes by switching the switch arms and pressing the traffic light buttons. In doing so, the manipulator "mouse" is in use. During the training process, the technological process of servicing the trains of various categories, taking all provisional operations into account, is simulated in detail. In addition, all train and shunting movements within the station limits and the adjacent track sides are under simulation. In this case, all the movements are shown in the station mnemonic scheme as on the actual consoles. To study and improve the established regulations for information exchange, an imitation of operational negotiations, which a station dispatcher has in operation, is made during exercises. With this goal in hand, the provision is made in the audio and textual output of messages from all employees involved in the technological process. A call of the desired employee is implemented through a system of menus and commands.

The simulators developed also provide the opportunity to work in the conditions of disruption of the normal functioning of station automation. This allows studying the procedures and regulations of the negotiations in emergency situations.

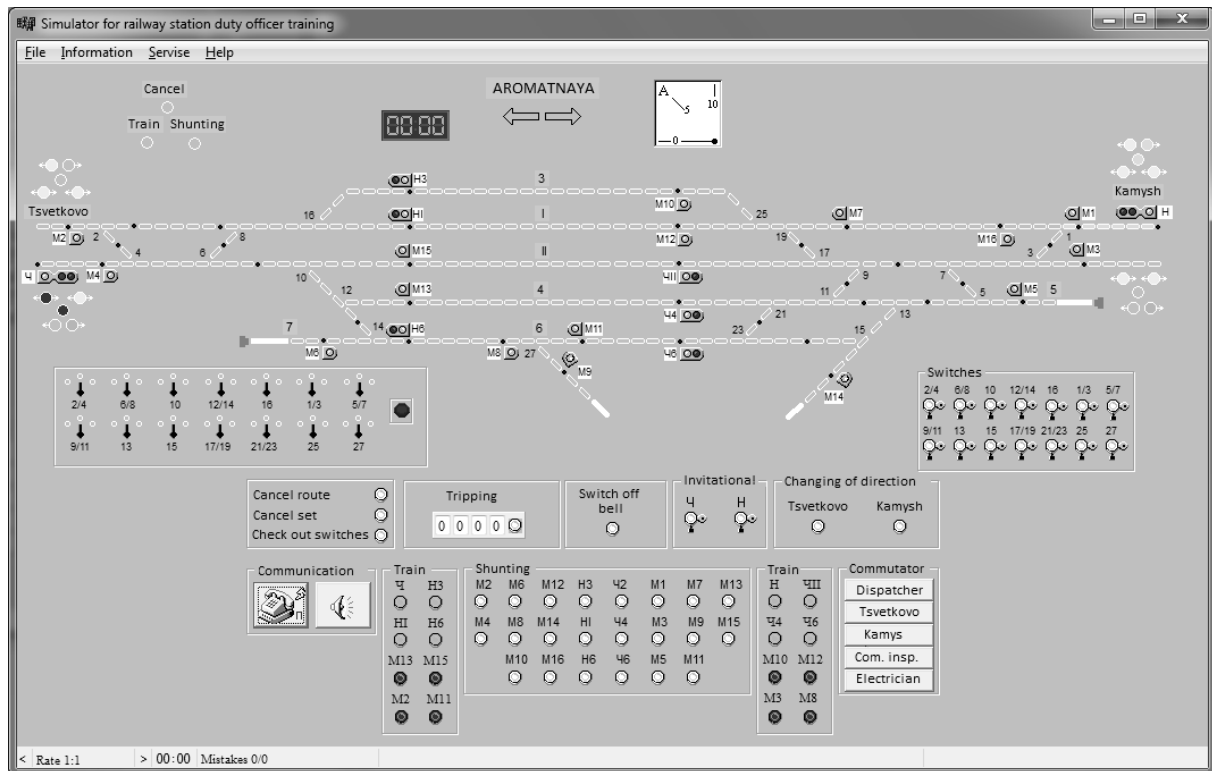


Fig. 6. Appearance of simulator for railway station duty officer training

Рис. 6. Внешний вид тренажера для подготовки диспетчера железнодорожной станции

During the training process, all the errors made are recorded. According to test results, the basic indices enabling one to estimate the level of professional skill are determined. The structure of each training simulator complex also includes the editor of initial conditions that allows us quick creating the training job at any level of complexity. At present the simulators developed are implemented at a number of marshalling yards in Ukraine as well as they have a wide application for study purposes in a number of railway transport universities and colleges.

## 5. CONCLUSION

Thus, the practical implementation of the developed concept of ergatic simulation has confirmed its sufficient high efficacy in both the integrated assessment of options of the design decisions for improving the railway stations' operation and professional training of station dispatchers. Currently the software-and-hardware tools, which greatly simplify and activate the replication of such models and computer simulators for various stations, are developed. The creation of such a complex of models should address a wide range of applications aimed at improving the operation of railway stations.

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