Intelligent centralized traffic management of a rapid transit system under heavy traffic

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Abstract. Aim. *In today's major cities, increased utilization and capacity of the rapid transit systems (metro, light rail, commuter trains with stops within the city limits) – under conditions of positive traffic safety – is achieved through smart automatic train traffic management. The aim of this paper is to choose and substantiate the design principles and architecture of such system.* **Methods.** *Using systems analysis, the design principles and architecture of the system are substantiated. Genetic algorithms allow automating train traffic planning. Methods of the optimal control theory allow managing energy-efficient train movement patterns along open lines, assigning individual station-to-station running times following the principle of minimal energy consumption, developing energy-efficient target traffic schedules. Methods of the automatic control theory are used for selecting and substantiating the train traffic algorithms at various functional levels, for constructing random disturbance extrapolators that minimize the number of train stops between stations.* **Results.** *Development and substantiation of the design principles and architecture of a centralized intelligent hierarchical system for automatic rapid transit traffic management. The distribution of functions between the hierarchy levels is described, the set of subsystems is shown that implement the purpose of management, i.e., ensuring traffic safety and comfort of passengers. The criteria are defined and substantiated of management quality under compensated and non-compensated disturbances. Traffic management and target scheduling automation algorithms are examined. The application of decision algorithms is demonstrated in the context of uncertainty, use of disturbance prediction and genetic algorithms for the purpose of train traffic planning automation. The design principles of the algorithms of traffic planning and management are shown that ensure reduced traction energy consumption. The efficiency of centralized intelligent rapid transit management system is demonstrated; the fundamental role of the system in the digitalization of the transport system is noted.* **Conclusion.** *The examined design principles and operating algorithms of a centralized intelligent rapid transit management system showed the efficiency of such systems that ensured by the following: increased capacity of the rapid transit system; improved energy efficiency of train traffic planning and management; improved train traffic safety; assurance of operational traffic management during emergencies and major traffic disruptions; improved passenger comfort.*

Keywords: *centralized management, autonomous systems, intelligent management, functional levels, subsystems, energy efficiency, disturbance prediction, genetic algorithms.*

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Introduction

Rapid transit systems conventionally include subways and a light rail systems separated from road traffic. Later, the commuter rail systems with stops within the city limits were included in the classification as well. In particular, the Moscow Central Circle (MCC) and the Moscow Central Diameters [1, 2] are classified as rapid transit. Given that the organization of traffic in metros, light rail and commuter rail has the same goal of providing comfortable and safe transportation of passengers, as well as the similarity of the underlying technologies, a centralized rapid transit traffic management system should be developed based on a single set of principles.

Centralized traffic management. Functional management levels. Management level subsystems

When traffic is heavy, which is typical for the rapid transit systems of major cities, designing autonomous unmanned vehicle control systems with automatic control of each train according to a predefined traffic schedule is not effective, as in such case the position of other trains on the line is not taken into account. "Harmful" mutual interaction of trains only takes place when it starts affecting the movement patterns automatically selected in the train control system [3]. Unlike autonomous systems, centralized systems receive information on the arrival and departure times of all trains across all stations, compare this information with a defined traffic schedule and condition control commands for each train, including the required station dwell times and travel times for the open line ahead. Such commands are implemented by unmanned vehicles. This mode of centralized systems operation is called disturbance-compensated management, when a deviation from the target schedule can be mitigated using available travel and station dwell time budget. We shall call compensated disturbances "minor faults". In this case, when the travel and station dwell time budget is not sufficient to mitigate the disturbances, unscheduled train turnovers are performed at stations with passing loops, if necessary, along with unplanned removal of trains to the yard, which leads to changes in the train pair count and sequence. Such situations are commonly called "major faults" [3, 4, 5]. In cases of major faults, algorithms are initiated for centralized fault management and traffic recovery upon elimination of the causes of the fault [5, 6], while traffic management is carried out based on the operational schedule. The purpose of post-fault management is to restore train traffic according to the initial target schedule, which enables the required night arrangement of trains [6, 7]. Thus, two functional management levels can be distinguished within the centralized system, i.e., upper and lower.

At the upper level, in accordance with the target or operational schedule and the received information on the arrival and departure of trains, the required travel times and dwell times for each train are calculated. At the lower level, the commands of the upper level are implemented. The most important upper-level management function is generating commands for train turnaround at terminals and stations with no passing loops. Such commands are delivered through centralized traffic control to the station interlocking system that controls the point operation. The operation of the upper functional level is supervised by the traffic controllers who receive information on the train locations through the supervisory control system. In addition, the traffic controllers are able to receive information from CCTV cameras at stations, turnaround points, etc. The role of the traffic controllers is especially important when major faults occur. At the upper functional level, a management scenario is automatically generated and its execution is approved by a traffic manager [6]. A mode is required, in which the traffic manager takes control. Traffic safety is ensured by track circuit-based systems (ARS in the Moscow metro) [8], or communications-based (CBTC-like) systems [9]. The advantage of the communications-based systems consists in the absence of position quantification of the "tail" of the train ahead (positioning of the "tail" of the train ahead based on the occupied track circuit), reduced operating costs associated with the maintenance and adjustment of track circuit equipment. In the case of communications-based train control, the positioning of the "tail" of the train ahead accurate to the length of the overlap determined by the maximum errors of travelled distance and speed measurement allows reducing the allowed headway [10], which is essential when traffic is heavy. At the same time, communications-based train control systems (like CBTC) do not ensure rail integrity control (the so-called "control mode"). Therefore, the application of CBTC-like systems requires additional equipment enabling rail integrity control [10]. Additionally, while deploying automatic traffic management systems on active lines it is important to ensure operational continuity of traffic safety systems. Therefore, the development of hybrid algorithms and equipment enabling the advantages of track circuit-based and communication-based systems appears to be promising. The commands of the traffic safety system are given the highest priority.

The upper functional level comprises the following subsystems:

– subsystem for minor faults, major faults, post-fault management [3];

– target schedule and turnover construction subsystem [11, 12];

– subsystem for selecting energy-optimal modes of train control with set specified travel times [13] and energy-optimal distribution of travel times [14]. The outputs of the above subsystems are used in the construction of target train schedules. It should be noted that solving the problem of energy-optimal train control for various travel times allows obtaining for each open line a dependence of traction power consumption as a function of the travel time that is required and sufficient for energy-optimal distribution;

– subsystem for archiving train orders and train sheets;

– database of failures and results of diagnostics of technical assets that enable train traffic, including rolling stock diagnostics data;

– subsystem for automatic management of rolling stock turnover at stations with passing loops;

– passenger information subsystem;

– subsystem for training of personnel involved in the traffic organization, a personnel training software and hardware system [15];

– subsystem for advanced training of traffic controllers, a traffic controller simulator [16, 17, 18].

The relevance of those software and hardware systems is much more significant than their direct purpose. Those systems include detailed line simulation models that are used in the analysis of new algorithms. The results of such simulation determine the effectiveness of their implementation. The simulator includes a system for calculating the performance criteria of the control system and an open library of control algorithms. Of special significance is the matter of integration of staff training systems of various services, which would allow using common criteria for training quality and methodology evaluation. The simulation models allow using machine learning for predicting hazardous failures of various system components [19].

Let us note a few advanced features of the upper functional level that allow using the term "intelligent system". The upper-level algorithms require generating commands for the trains on a line under uncertainty. The (n+1)-th train must be given the departure command and required travel time in such a way as to let it perform its movement with no interference on the part of the safety systems. Developing this solution requires knowing the deviation from the target value of the next

station dwell time of the previous, n-th train while it has not yet arrived to the station. In this situation, an intelligent disturbance prediction algorithm is implemented that uses the delay statistics of previous trains [20]. A genetic algorithm is used for automatic construction of train and turnover schedule [21, 22]. Therefore, the term "intelligent system" is correct. The integration of various system functions, including management itself, collection and processing of diagnostic information, analysis of facility performance indicators and operation planning, archiving, etc., can be implemented using Big Data and artificial intelligence algorithms. In turn, the system's open architecture, availability of a database for collecting diagnostic information allows regarding it as a foundation for the digitalization of urban transportation systems.

At the lower functional level, the onboard control system solves the following tasks:

– train traffic safety;

– energy-optimal train control with the observance of all specified restrictions (including traffic safety indications) that ensures the observance of upper-level inter-station travel times;

– targeted stops at stations;

– enforced permanent and temporary speed restrictions;

– closing and opening the doors, movement initiation, passenger information.

One of the vital tasks associated with ensuring safe and efficient traffic management is the measurement of traffic parameters, i.e., train speed and travelled distance. In subways, this problem is solved using wheel-mounted frequency-pulse rotation sensors and correction sensors installed on tunnel walls or in the track. In this environment, infra-red sensors have shown their efficiency. On the tunnel wall, an angle reflector is installed, while trains are equipped with infra-red transceivers [3]. The beam of the transmitter is directed toward the tunnel wall. It is reflected from the angle reflector and is received on the train, resetting the measurement error of the wheel-mounted frequency-pulse sensor. When two sensors are installed at a fixed distance from each other, the onboard computer calculates the wheel radius, thus enabling reduced error when measuring the travelled distance and speed outside the strobing signal points [3]. There is experience with RFID sensors installed between rails. The advantage of such sensors consists in the ability to transmit the sensor number, its coordinate, the number of the open line. At the same time, due to the bell-shaped direction diagram of the radio signal, the position of the detected correction point depends on the

speed of the train. The latter causes train positioning error. Reducing the train speed at the location of the RFID sensor when approaching the station in order to reduce the effect of the bell-shaped signal wave-form on the detection error results in longer traction time at a constant travel time and, therefore, overconsumption of traction energy. On average, a 1-second increase of braking time causes a 1-percent increase of traction energy consumption. The combined use of two types of sensors allows improving the dependability of the distance measurement link and to take advantage of the strengths of both sensors, i.e., the accuracy of correction point detection of the infra-red sensor and large amount of communicated information of the RFID sensors.

A technical vision system is required for detecting obstacles in the unmanned control mode in open areas accessible to people, animals, other modes of transport [23]. Control inputs generated by such system have the highest priority.

The presence of advanced computing facilities onboard the trains allows integrating the functions of automatic train control, train protection, collection of diagnostic information that is radioed to the station and further to the upper functional level.

Improving the energy efficiency of management processes

Let us focus on improving the upper-level traffic management algorithms. The main criteria for efficiency at the top level of the train management algorithm are:

– improved accuracy of target schedule performance with disturbance compensation;

– minimum time of target schedule recovery upon elimination of the causes of a major fault.

The minimization of the above criteria is to be achieved subject to the additional condition of minimized traction energy consumption.

In case of unmanned driving, the onboard travel time control facility can achieve the predefined range of travel time with high accuracy. This capability is used for improving the energy efficiency of management operations in the event of minor faults. The travel time of the $(n+1)$-th train across the open line ahead required for compensating for the late arrival of such train to the $(j+1)$-th station is chosen subject to the restrictions on the minimum dwell time in such a way as to enable the minimum headway based on the restrictions of the train control systems. The distinctive feature of the traffic management algorithm with disturbance compensation is the consideration for the dependence of the restrictions on the system status

and predicted deviations of the dwell times of the train ahead based on the previous train delay statistics [20]. The dependence of the restrictions on the system status is defined by the regulating characteristic of the j-th open line $T_{uminj}[n+1] = [T_{xj}[n+1], T_{xj}[n]] + T_{cj}[n]$, where $T_{uminj}[n+1]$ is the minimum departure interval of the $(n+1)$-th train to the j-th open line from the $(j-1)$-th station, whereas the n-th train does not affect the operating modes of the $(n+1)$-th train through the traffic safety system; $T_{xj}[n]$, $T_{xj}[n+1]$ is the the travel times of the n-th and $(n+1)$-th trains across the j-th open line respectively; $T_{cj}[n]$ is the dwell time of the n-th train at the j-th station. When control is selected, the values $T_{cj}[n] = T^r_{cj}[n] + \Delta T^{pr}_{cj}[n]$, where $T^r_{cj}[n]$ is the dwell time of the n-th train at the j-th station according to target schedule; $\Delta T^{pr}_{cj}[n]$ is the predicted deviation of actual dwell time from the target value. The travel time of the $(n+1)$-th train across the j-th open line is chosen by the algorithm in such a way (provided that the requirements for the value $T_{uminj}[n]$ are met) as to enable the restriction on the allowable minimal dwell time and the minimal possible delay of the $(n+1)$-th train arriving to the j-th station. That also allows reducing the number of speed restrictions and stops of the following train between stations. Such algorithm, on the one hand, improves traffic safety by reducing the probability of trains running dangerously close to each other, and, on the other hand, reduces traction energy consumption not only by reducing the number of stops between stations, but also by increasing the running time of the following train.

Upon the elimination of the causes of a major fault, the control algorithm chooses – out of a variety of fastest-acting control algorithms – the one that minimizes the traction energy consumption through energy-optimal distribution of the travel times along the line. The problem of energy efficiency is taken into account while scheduling train traffic not only, as previously stated, by means of optimal distribution of travel times, but also by changing the way the number of trains on the line is increased at the beginning of to the peak hours. In conventional target traffic schedules, such transitions involved extended dwell times that ensured increased headway for the purpose of adding new trains to the operation. In the planning algorithm under consideration, the same effect is achieved through planned extension of travel times, which allows reducing the traction energy consumption. Thus, the energy efficiency of target train schedules is achieved by associating the traction energy consumption with the travel times under the selected energy-optimal control modes, distribution of train running time along the line, replacement of extended dwell times with increased travel times in transition mode.
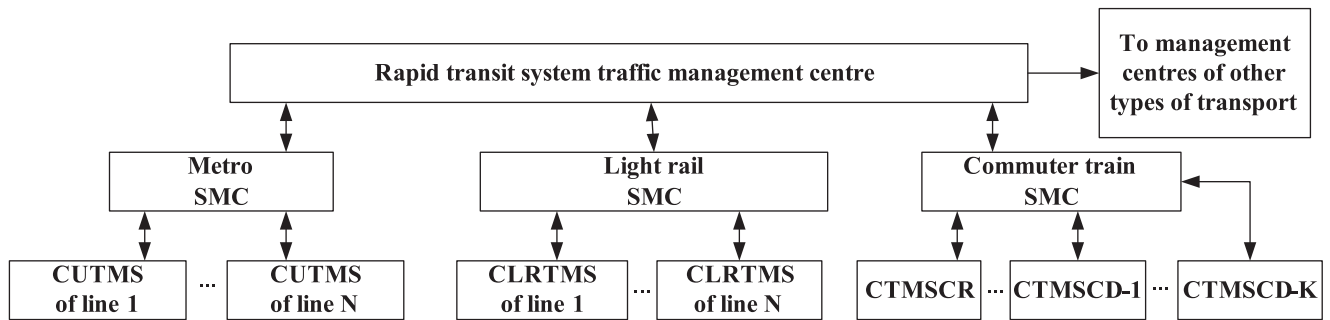
Fig. 1. System structure

The matters of information communication network design as part of centralized management systems, information protection are extremely important and define system efficiency. Such issues are not addressed in this article and require individual consideration.

Structure of the rapid transit traffic management system

A rapid transit traffic management system was examined above. The integration of such systems with the addition of a higher level of management is illustrated in Fig. 1, where the following designations are used:

– SMC, situation management centre;

– CUTMS of lines 1, …, N, centralized underground traffic management system of lines from 1 through N;

– CLRTMS of lines 1, …, M, centralized light rail traffic management system of lines from 1 through M;

– CTMSCR, centralized traffic management system of the central ring (MCC in Moscow);

– CTMSCD, centralized traffic management system of the central diameters from 1 through K.

The situational management centres (SMC) of various types of rapid transit receive information from subsystems of the upper functional level of centralized traffic management, in particular, from the hardware and software systems of line-level traffic management facilities. In normal mode, the received information is "compressed" and in a generalized form is displayed in situation management centres. If a train deviates from the target schedule by a fixed amount of time, the centre's personnel is informed accordingly by changing line colour and a tonal signal. They can then display a detailed image of the operational situation available to the traffic managers. The functionality of the situation management centre and its design principles were developed by the Russian University of Transport (RUT/MIIT) and the Moscow Metro [24]. Aggregated information from the SMC of various types of rapid transit systems is delivered to the metropolitan rapid transit management centre. At this level, the collected information will allow managing urban transportation in emergency situations, making coordinated advance managerial decisions in cases of planned closure of certain line sections. The metropolitan rapid transit management centre is to be associated with other transportation management centres. The concept of its construction requires considerable elaboration.

Conclusion

The examined design principles and operating algorithms of a centralized intelligent rapid transit management system showed their efficiency that is defined by the following:

– increased capacity of rapid transit systems through strict adherence to the target train schedule;

– improved energy efficiency of traffic planning and management through energy-efficient train management patterns, traction energy-optimal distribution of train running time along the line, replacement of the target train scheduling with extended station dwell times with the scheduling with modifiable target train running times during the periods of train pair count changeover, improved centralized management algorithms that take into account the dependence of control restrictions on the system state and prediction of possible disturbances, increased station-to-station train running times for the purpose of implementing the allowed headway by means of train separation systems;

– improved traffic safety through reduced probability of "hazardously close" distance between trains with stricter observance of station-to-station train running times and dwell times;

– operational traffic management during emergencies and major traffic disruptions through efficient algorithms of centralized management during traffic disruptions and after the elimination of their causes;

– improved passenger comfort through accurate execution of the traffic schedule.

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References

1. [Passenger traffic on the MCC has reached 550 thousand people per day]. (accessed 18.03.2020). Available at: https//wwwm24.ru/news/transport/07122019/99787. (in Russ.)

2. Romensky D.Yu, Vakulenko S.P., Kozlov A.V. [Choice of the conceptual solution for organizing commuter rail traffic across the Moscow railway centre]. Molodye uchyonye razvitiyu natsionalnyy tekhnologicheskiy initsiativy 2020;1:568-570. (in Russ.)

3. Baranov L.A., Golovicher Ya.M., Erofeev E.V., Maximov V.M. Baranov L.A., editor. [Modern computer-based train separation systems for EMUs]. Moscow: Transport; 1990. (in Russ.)

4. Baranov L.A., Kozlov V.P. [Managing a subway line affected by traffic disruption]. VNIIZHT Scientific Journal 1992;5:29-31. (in Russ.)

5. Balakina E.P. Principles of algorithms construction of system of support decision making for a train dispatcher. *Science and Technology in Transport* 2008;2:23-26. (in Russ.)

6. Balakina E.P. Automatic devices function as traffic controller. World of Transport and Transportation 2008;2:104-109. (in Russ.)

7. Balakina E.P., Shcheglov M.I., Erofeev E.V. Metro line operational control algorithm for restoration traffic on a planned schedule. *Science and Technology in Transport* 1;1:23-25. (in Russ.)

8. Bestemiyanov P.F., Romanchchikov A.M. Traffic control using coordinate mode. World of Transport and Transportation 2008;1:104-108. (in Russ.)

9. IEEE 1474.1-2004 – IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements; 2004.

10. Baranov L.A. Evaluation of metro train succession time for safety systems based on radio channel. *World of Transport and Transportation* 2015;2:6-19.

11. Sidorenko V.G., Safronov A.I. [Constructing a target traffic schedule for a subway]. *World of Transport and Transportation* 2011;3:98-105. (in Russ.)

12. Iskakov T.A., Safronov A.I., Sidorenko V.G., Kyaw M.A. Approaches to quality assessment of subway traffic planning and management. *Automation on Transport* 2020;8:38-63. (in Russ.)

13. Baranov L.A., Melyoshin I.S., Chin' L.M. Energyoptimal dispatching of a regenerative braking train at the account of restrictions on phase coordinate. *Science and Technology in Transport* 2010;4:12-23. (in Russ.)

14. Baranov L.A., Kuznetsov N.A., Maksimov V.M. [Energy-optimal vehicle control]. *Electrical Engineering* 2016;9:12-18. (in Russ.).

15. Loginova L.N. The role of the system of automated knowledge test of train traffic controllers of metro in improvement of training quality. *Science and Technology in Transport* 2011;1:62-65. (in Russ.)

16. Baranov L.A., Sidorenko V.G. [Application of simulators in the improvement of the qualification of traffic department employees]. *Avtomatika, sviaz, informatika* 2003;2:17-20. (in Russ.)

17. Baranov L.A., Sidorenko V.G. [Simulator for train dispatchers of the Moscow Metro]. *Rail International* 2002;8:64-69. (in Russ.)

18. Baranov L.A., Balakina E.P., Sidorenko V.G. [Train dispatcher simulators in railway transportation]. Proceedings of the XVIII All-Russian Research and Practice Conference Train Traffic Safety. Moscow: MIIT; 2017. (in Russ.)

19. Shubinsky I.B., Zamyshliaev A.M., Pronevich O.B., Platonov E.N., Ignatov A.N. Application of machine learning methods for predicting hazardous failures of railway track assets. *Dependability* 2020;2:45-53.

20. Baranov L.A., Balakina E.P., Ikonnikov S.E., Antonov D.A. Centralized train traffic operation of urban railways of a modern megalopolis. *Science and Technology in Transport* 2020;1:30-38. (in Russ.)

21. Sidorenko V.G., Zhuo M.A. Application of genetic algorithms for underground electric trains scheduling problems. *Electronics and electrical equipment of transport* 2016;6:13-16.

22. Sidorenko V.G., Zhuo M.A. An investigation into the possibilities of genetic algorithm application to solve the underground electric rolling stock scheduling problem. *Electronics and electrical equipment of transport* 2017;6:37-40.

23. Okhotnikov A.L. Technical vision systems: development trends. *Zheleznodorozhny transport* 2020;9:44-51. (in Russ.)

24. Ershov A.V. Principles of construction of the situational centre on the Moscow underground. *Science and Technology in Transport* 2006;1:27-33. (in Russ.)

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The authors' contribution

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Sidorenko V.G. Train planning tasks, genetic algorithms.

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Conflict of interests

The authors declare the absence of a conflict of interests.