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Operational Rationing of Energy Resources for Train Traction using the Method of Artificial Neural Networks

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ABSTRACT

The task of resource saving is relevant for all transport companies and many world communities of scientists and engineers are engaged in search for ways to solve it. World railway companies, and especially large ones such as Russian Railways, are large consumers of energy resources and the problem of saving is the most urgent for them. One of directions for solving this task can be the use of an optimal energy regulation system for traction of each train – an operational rationing system. Such a task can only be solved by modelling the process of movement through the dynamic programming method. In modern conditions of development of engineering and technology, it has become possible to develop such operational standardization systems endowed with important properties: high performance, multitasking, solution accuracy, ease of use and maintenance. These requirements impose certain restrictions on the architecture of the operational rationing system. Typical system architecture should be built around a centralized node, which will act as a solver and storage, nodes for input and output of information can be geographically separated. The method of dynamic programming can be improved by using it in the process of training artificial neural networks, which will form not only a priori estimates of energy consumption for traction, but also an a posteriori estimate of train control (by a train driver or auto-driving system). Also, the use of artificial neural networks will allow us to continuously improve the method due to training using the accumulated amount of data from real trips, which will allow us to clarify the norms of energy consumption and to plan our costs in the future. The prototype of the operational standardization system was developed at the department of traction rolling stock of Russian Open Academy of Transport of Russian University of Transport and the results obtained allow us to state that the chosen approach to solving the problem of energy saving has been chosen correctly.

Keywords: *transport, railway, traction calculations, optimization of traction calculations, rationing of energy costs for train traction, artificial neural networks, automatic vehicle control systems, traction properties of a locomotive, regulation of traction and braking forces.*

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Background. In accordance with long-term development plans of the Russian Railways holding company, it is required to reduce the specific energy consumption for train traction [1]. This task is relevant for all world railway companies and in practice there is a continuous search for a solution to the problem of energy saving and optimal train driving [1–7]. The problem is considered at different levels: for a single train [5], for groups of trains following each other [1], at the level of control of movement of a large number of trains [4]. Domestic scientists and engineers also do not disregard this problem, which is reflected in works on practical use of devices and technologies for resource saving [8–10], and other works [11–13]. The use of traction calculations for operational regulation of energy resources for train traction in order to reduce energy consumption is one of practical applications of applied methods of traction theory. But the existing methods of traction calculations and their implementation, developed on the basis of current rules of traction calculations [14], do not fully comply with the requirements of operational standardization systems. Therefore, it is necessary to look for new approaches to solving the problem of saving energy costs for train traction.

Operational standardization of energy consumption means determination of minimum reasonable energy consumption for train movement through a section. The main requirements for operational standardization systems are: high performance, multitasking, solution accuracy, ease of use and maintenance, high availability. Also, such a system should not only evaluate the energy consumption for a trip a priori, but also make an a posteriori trip estimate indicating the errors of the auto-driving system or the driver.

To implement such a system of operational regulation of energy consumption for train traction, it is advisable to use a set of programs that will effectively use the computing power of computers. This is because of the fact that exact optimal solutions (due to the requirement of accuracy) obtained by the numerical method of dynamic programming [12] are quite expensive in terms of the processing power of the processor. There are methods for finding the optimal trajectory of motion based on Pontryagin maximum principle [11], but such implementations have serious limitations on functional dependencies.

Results.

Architecture of the complex of operational regulation of energy resources

The authors have developed a computationally effective implementation of the dynamic programming method for single-criterion or multi-criteria optimum search. The needs of the program in RAM for one traction calculation can be estimated by the formula:

$$N_{TC} = 5 \cdot \frac{S}{\Delta_s} \cdot \frac{v_{max}}{\Delta_v} \cdot N_U, \quad (1)$$

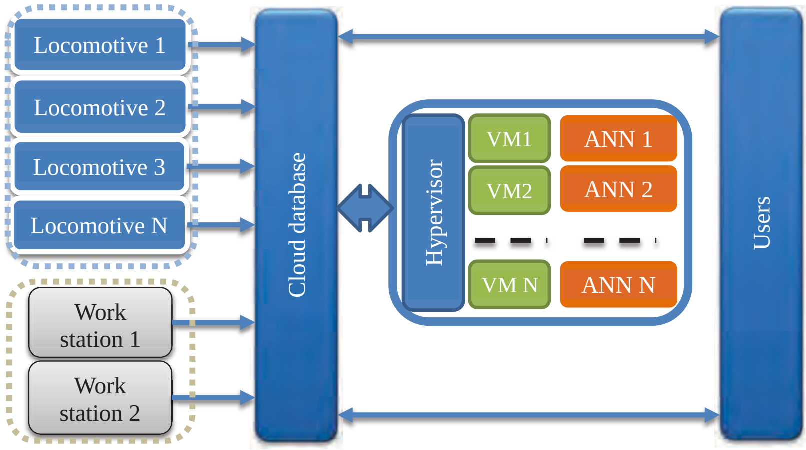
where S – length of the track;

Δ_S – value of the sampling step along the coordinate;

v_{max} – maximum speed;

Δ_v – value of the sampling step for speed;

N_U – number of controls.



Pic. 1. Typical architecture of the complex of operational regulation of energy resources [authored by S. V. Malakhov].

Table 1

Traction characteristics of VL11 electric locomotive for series-parallel connection of TED and complete excitation [authored by S. V. Malakhov].

Speed, km/h	Traction force, kN	Speed, km/h	Traction force, kN	Speed, km/h	Traction force, kN
21,7	557	28,0	239	36,1	106
22,3	513	28,9	217	37,0	100
22,9	468	29,5	196	38,3	93,1
23,5	436	30,4	177	39,8	84,2
24,1	399	31,3	164	41,0	78,3
25,0	355	31,9	154	41,9	75,3
25,9	309	33,1	139	42,8	70,9
26,5	285	34,0	124	43,7	68,0
27,1	261	35,2	114	44,9	65,0

For a typical traction arm of 200 km, only 4 GB of RAM will be required for a trip, which in case of multitask parallel calculation will require serious computing power, for example, for 1000 simultaneous calculations, 4 PB of RAM will be required. Therefore, in order to meet the requirements of high performance, multitasking, it is required to use the task separation approach.

The software package consists of: initial information preparation programs, calculation programs, visualization programs (Pic. 1).

Separation of tasks allows to independently perform: input and updating information on traffic conditions and restrictions, calculations, processing of results. These tasks are performed in parallel, which requires a small number of operators which form the task for calculation and provide input of initial information. Since it is assumed that the consumer of information is a locomotive depot, the results of the software package should be available directly in a particular depot. However, each locomotive depot has a limited number of service areas, and operates certain series of locomotives, so the task of preparing and updating trip information must be solved at a higher level than a single depot.

Preparation and input of initial informaiton

Operators who solve the problem of preparing and updating information must initially fill the database with the required initial information (traction and current characteristics, profile and route plan, weather conditions, etc.), and then update this information, for example, speed limits, weather conditions etc.

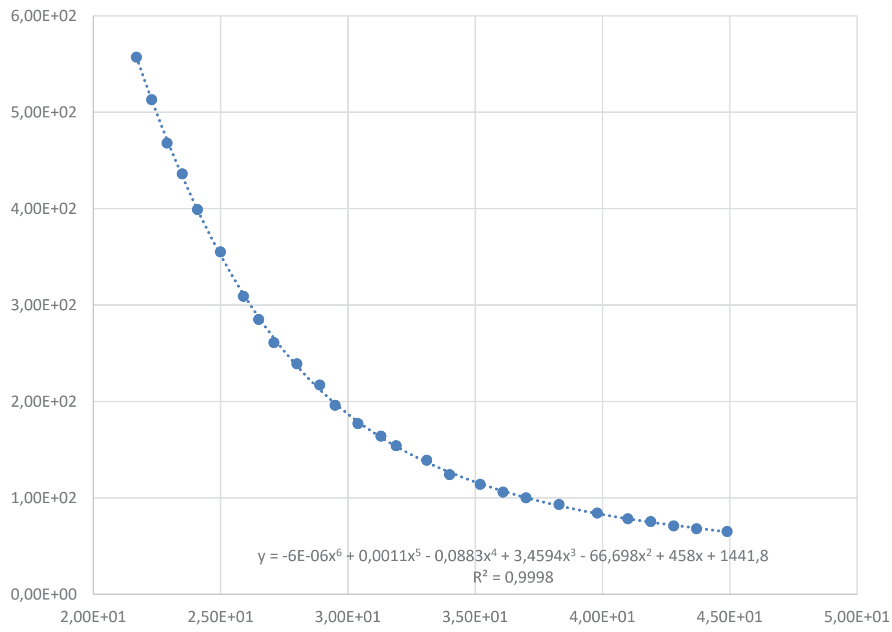
It is advisable to use an application for working with spreadsheets from ready-made free office packages, for example, LibreOffice Calc on Linux operating system, which is open source software, as a program for preparing initial information for calculation. Since the data exchange between the parts of the complex passes through the database (Pic. 1), at the data preparation stage, ready-made software that has versions for all common operating systems should be used.

A profile and a track plan can be entered into a spreadsheet using import options, for example, in MySQL database there is a Load Data Infile statement that can directly load data from a file in delimited text format.

Functional dependencies expressed in tabular data from [14] can also be implemented in LibreOffice Calc or Microsoft Excel. Let's consider an example of obtaining a functional dependence of traction characteristics of VL11, given in tabular form (Table 1).

Data is entered into a spreadsheet, then a diagram is built, a trend line is added, which is regression. For a better approximation, we choose a polynomial dependence of at least seventh order. The result of the procedure is shown in Pic. 2. The value of the coefficient of determination shows a fairly good approximation. The parameters of the approximating function can be selected individually for data. The coefficients of the equation in Pic. 2 can be transferred to the database by pasting it in a predetermined format into the database table. The remaining functional dependencies of the locomotive and the train are introduced in the same way.

Programs in the complex should interact with each other through a database. This is due to the fact that there are ready-made tools for



Pic. 2. Example of approximation of traction characteristics of the electric locomotive VL11 [authored by S. V. Malakhov].

viewing and editing data, for effective multi-user access to data. The database allows to effectively manipulate data within the framework of relational algebra or user scripts and provides reliable structured data storage, including in clustering or sharding mode. MySQL (or analogues of MariaDB, Percona Server) and PostgreSQL are used as such a database. These are free database management systems that are used in network sharing mode. For local testing of the program, the local SQlite database is used, which also provides multi-user access at the local level. In case of real use of a system with a large number of remote users, it is advisable to use one of the network relational databases located on a dedicated server in the cloud. The cloud can be private in the form of its own server or cluster of servers with software based on Linux operating system (OpenStack, Apache Cloudstack) or public (the cloud services platform from Mail. Ru Group, Microsoft Azure platform, Amazon Web Services platform, etc.).

Search for optimal power consumption rate

The automatic traction calculation unit must also be located in the cloud. There are several reasons for this requirement:

• **high performance.** Dynamic programming is chosen as a universal optimization method, since it allows to implement a detailed train model without restrictions on the dependencies between variables. Dynamic programming involves several stages: dividing the task into simpler ones – a matrix of possible train states, obtaining and analyzing possible train trajectories, changing conditions, recalculating a matrix of possible states or rebuilding trajectories, etc. The stages of the algorithm require frequent integration of the equation of train motion, taking into account many constraints (depending on complexity of the model), which can be specified in the form of differential equations or even in the form of systems of differential equations (if dynamic forces in the train are taken into account). To reduce calculation time, servers with several multi-core processors should be used, their number should allow to withstand the load from consumers in case of growth in requests for calculation. Taking into account the fleet of cargo locomotives (about 7500), we can estimate the maximum number of trains and, accordingly, the number of requests for calculation multiple of the number of trains. Therefore, a maximally scalable system is required, which is provided by a cloud solution;

• **requirements for the amount of RAM.** Dynamic programming is a search algorithm of directional search, which, to determine the solution, performs incomplete search of

Table 2

Calculation results [authored by S. V. Malakhov]

Calculation	Power consumption (Bellman method), kV • h	Power consumption (ANN method), kV • h	Running time (Bellman method), min	Running time (ANN method), min
1	2723	2774	61,54	61,33
2	2810	2852	61,61	61,72
3	2858	2860	61,66	61,65
4	2443	2479	61,39	61,47
5	2597	2423	61,66	61,71

variant paths, the number of which is algorithmically limited by a number of conditions. Impossible enumeration options are eliminated at each step, so a complete enumeration is not performed. But even in this case, with a small step along the coordinate and a large length of the traction arm, the number of possible trajectories is 10^{22} or more. Using a cloud environment allows to start the decision process inside a virtual machine, the resources of which can be flexibly managed;

• **network access.** High hardware requirements impose restrictions on the use of a computing program for a large number of consumers. If there are fast communication channels, there is no need to place equipment near the end user. Therefore, the cloud application of the program will save the financial resources of the customer and consolidate the computing load.

A breakthrough solution compared to classical methods is a method that allows to separate the processes of implementation and obtaining solutions. The modern technical level and mathematical apparatus make it possible to make full use of the methods of nonlinear approximation of multidimensional functions offered by artificial neural networks (ANN). Updating is also required only for classical optimization methods, such as Pontryagin maximum principle or Bellman optimality principle, which do not involve training (improving the adequacy) of the model. Such methods are sensitive to accuracy of initial information. If the characteristics of rolling stock change, for example, due to wear and tear of the equipment, the resulting optimal solution does not pretend to be accurate. In contrast to the classical methods, the use of the «black box» of ANN allows for continuous learning and improving accuracy of the norms depending on the amount of information used for training. Over time, the amount of that information will only increase, which will ensure continuous improvement of the result without the use of separate additional techniques or technologies.

The need for the use of such structures arose due to the main drawbacks of classical methods: long-term obtaining of the optimal solution, need for a special increase in adequacy of initial data, an a priori train model that does not take into account the specific features of rolling stock. For the method of artificial neural networks, memory requirements have a significant limitation only in the training mode, which can be performed in parallel with operation of the neural network and is divided in time and space (for example, by using another data center), depending on the network structure and sample size.

The web application interface acts as a universal cross-platform tool for visualizing the calculation results; an alternative option may be to use a separate desktop application. To work with the complex tool developed at the department of traction rolling stock of Russian Open Academy of Transport of Russian University of Transport, an application was created providing a connection to the database.

Conclusion

The application, through a direct connection to the database, extracts the calculation results and displays it on the display of the user (driver). The prototyped version, implemented at the department of traction rolling stock, carries out only a search by a unique trip identifier in order to show feasibility of the solution proposed in the paper. If a network database is used, then multi-user access to standards in the database server is supported.

To check operation of the complex tool, normalization variant calculations were performed for various sections of the track with different traffic conditions and train parameters, training was conducted on a limited number of model trips.

For the basic calculation, an arbitrary section of the profile with a length of about 50 kilometers was selected, and the train consisted of VL11 locomotive and fifty gondola cars fully and partially loaded. Ten variant calculations were carried out (Table 2), simulating various situations with passage of a train through separate sections in excess of applied temporal speed limits, considering different traffic conditions. In order to reduce memory consumption and speed up calculations, motion curves are not shown in a graphical form.

The calculation results show that train running time is maintained quite accurately and the spread of this parameter is less than a minute. The numbers obtained by one and the other method are quite close, which confirms the equivalence of the solutions. The calculation results are transmitted to the train driver to perform a motivational function. At the end of the trip, the operating rate is adjusted according to the actual traffic conditions and the trip is analyzed for compliance with the optimal traffic plan. In case of a strong deviation of the norm and the factual result, the trip is added to the training set for ANN retraining.

This approach is only the first step in creating a modern unmanned single control system for promising locomotives [8]. At the second stage of training ANN can form the norms and analyze movement on board the locomotive continuously with constant training in reinforcement mode, that is, without the need for a trainer (a powerful stationary computer is not required). At the third stage, it is necessary to proceed to train control based on ANN while retaining the controlling personnel.

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