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Algorithm for determining restrictions on train control

Kostiantyn Zhelieznov [1], Artem Akulov [1], Oleksandr Zabolotnyi [1], Eugene Chabaniuk [1], Angela Shvets*[1]

[1]Ukrainian State University of Science and Technologies, Department of Engineering and Design Specialized Department «Microprocessor-Based Control Systems and Safety in the Railway Transport» (EDSD MBCSS), Ukraine, ConstantinZ@i.ua, asakulov@gmail.com, zabolotnyi@i.ua, 457m@ukr.net, angela_shvets@ua.fm

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Abstract

One of the priority areas for ensuring the stable and profitable operation of railway transport and its development and improvement is the transition to resource-saving technologies. Optimization of train control modes is one of the most important measures to address the currently pressing problem of saving fuel and energy resources for train traction. The purpose of this study is to develop an algorithm for determining restrictions on train control while complying with safety requirements and timetables. This algorithm must allow calculations to be performed quickly and without significant loss of accuracy, and the results of the calculations must meet the criteria of optimality, safety, and compliance with the train schedule. The information base for the development of the algorithm was the existing mathematical and algorithmic methods for solving isoperimetric problems of finding an optimal solution in the presence of resource restrictions. The proposed calculation method consists of using simplified calculations of the state of the train as a controlled system, without using differential equations of motion, which allows solving problems of finding optimal control almost in real-time. The results of these studies were used to create simulators for training train drivers.

Introduction

An important problem in the further development of railways is the energy efficiency of various modes of train movement. In modern conditions of a market economy, for all energy consumers, including railway transport, the most significant and determining factor in energy use is the cost of energy. The successful operation of railways in the electricity market is associated with the further development of information technologies for the management of railway transport, combining electric traction systems and the organization of the transportation process with optimal train movement modes [1-3].

It is well known that one of the ways to reduce the cost of transportation by rail is to reduce energy costs for running trains. The least expensive way to achieve this goal is to introduce training systems for training in energy-optimal and safe train control modes. There are many methods designed to calculate such modes. This paper discusses algorithms for determining restrictions on train control to construct an energy-optimal train trajectory [4-6].

Material and Method

The method of energy-optimal traction calculation, taking into account the track plan and profile, train length, characteristics of cars, traction and braking characteristics of the locomotive, and speed limits is presented in the work [7]. This technique allows for performing calculations quickly and without significant loss of accuracy, and the results of the calculations meet the criteria of optimality, safety, and compliance with the train schedule.

To implement this method, a grid is constructed in *Speed-Way* coordinates. The possibility of transition between nodes of adjacent grid sections (Figure 1) should be determined at the first stage of solving the problem of obtaining an energy-optimal train trajectory [7].

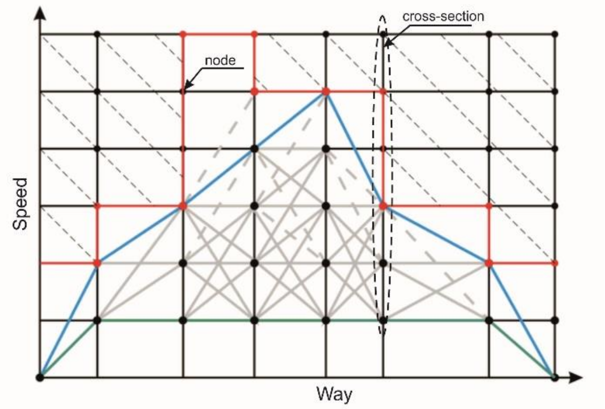


Figure 1. Possible options for the train's movement trajectory

Practically speaking, it is necessary to obtain one train trajectory that ensures minimal energy consumption for a given travel time. In the process of constructing the optimal train trajectory, it is essential to determine the possibility of transition between grid nodes of adjacent sections. Until now, this has been done by integrating the train motion equation using one of the numerical integration methods. To speed up this process, it is proposed to determine the work that a locomotive must perform in order for a train to overcome the distance between adjacent sections of the grid and change its speed from the speed at the initial node to the speed at the final transition node.

$$A_{\mathrm{L}} = \Delta E_{\mathrm{k}} + \Delta E_{\mathrm{p}} + A_{\mathrm{wo}}. \tag{1}$$

Here: ΔE_{K} – change of the kinetic energy of the train; ΔE_{P} – change of the potential energy of the train; A_{wo} – the work of the forces of the main resistance to the movement of the train. The first two can be accurately calculated:

$$\Delta E_{\mathrm{к}} = M_{\mathrm{t}} \frac{v_{\mathrm{f}}^2 - v_{\mathrm{i}}^2}{2}, \tag{2}$$

$$\Delta E_{\mathrm{P}} = M_{\mathrm{t}} \cdot g \cdot \Delta h. \tag{3}$$

Here: M_{t} – the mass of the train; v_{f}, v_{i} – speed in the initial and final nodes of the grid; Δh – the difference in the heights of the center of the train's mass as it moves between the sections of the grid.

To accurately determine the work of the main resistance forces on train movement, it is necessary to know the speed of the train as a function of the distance travelled between the nodes of adjacent grid sections.

$$A_{\mathrm{wo}} = M_{\mathrm{t}} \int_0^S w_o\left(v\left(x\right)\right) dx. \tag{4}$$

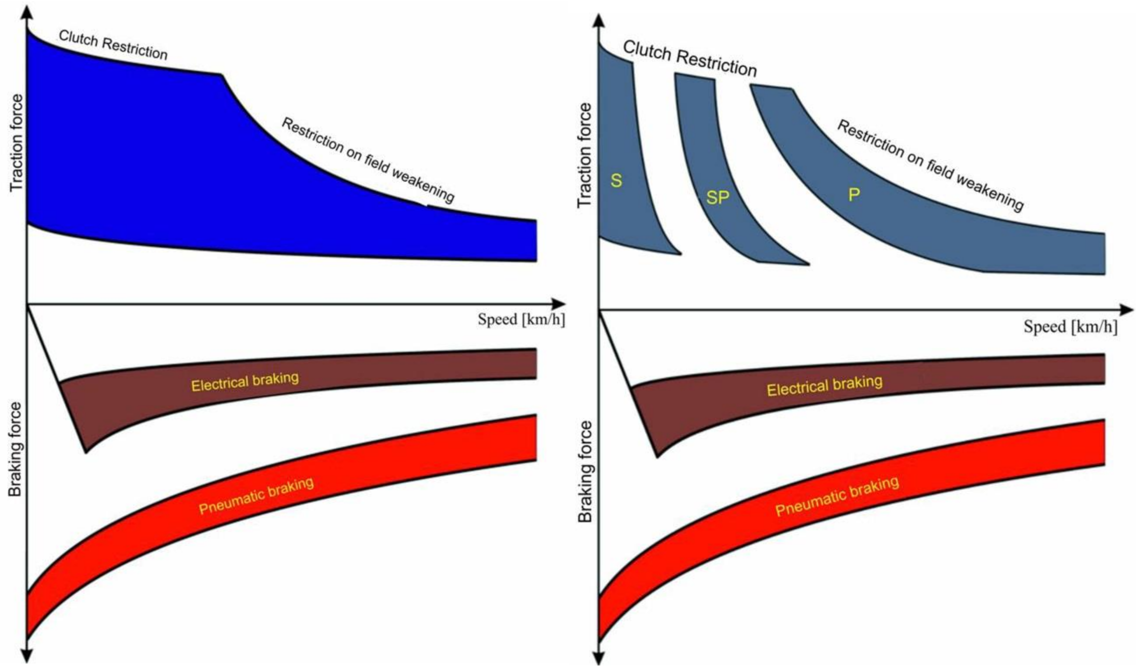
Here: S – distance between adjacent sections of the grid; w_{o} – the main specific train resistance force.

Results

The possibility of transition between grid nodes of adjacent sections means its feasibility. Each locomotive has limited train control resources, so control feasibility means the use of control that does not exceed the resources of the locomotive. First, let's look at the restrictions on train control. By controlling the movement of the train, the driver's use of traction mode and braking mode, that is, an artificial and purposeful change in the phase state of the train, is meant. The running idle mode (coasting) also changes the phase state of the train but is neither artificial nor purposeful because, in this case, a change in phase state occurs without the intervention of the driver due to natural causes. So, only two modes of train movement control are possible – traction mode and braking mode (Figure 2, a).

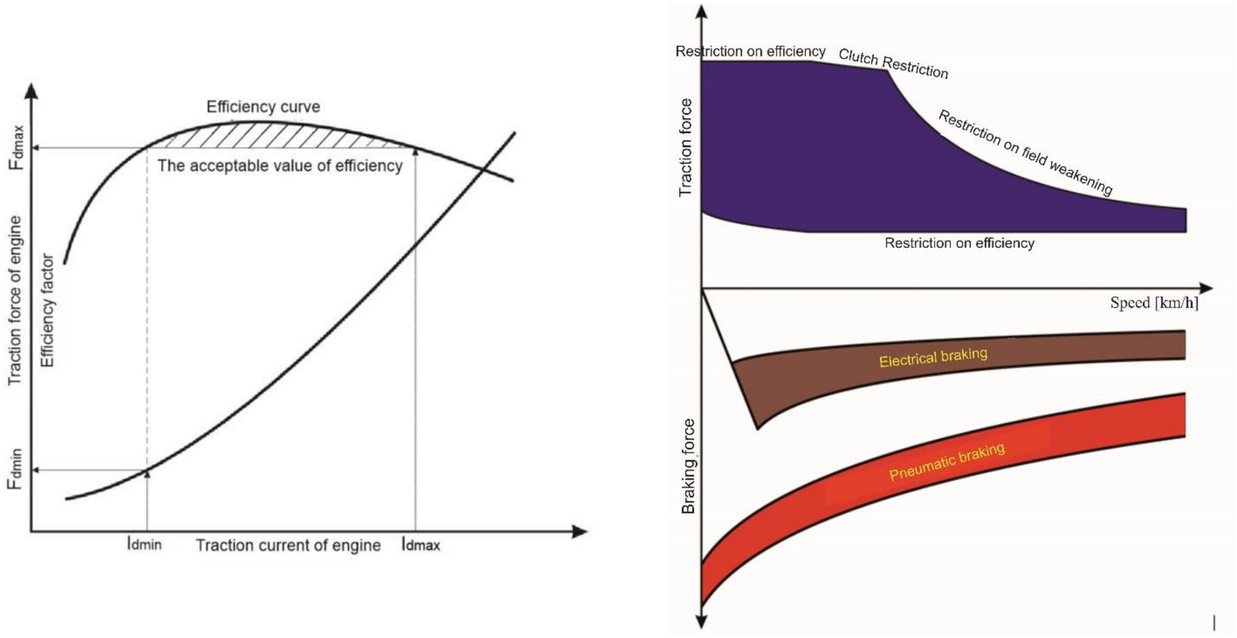
The main braking mode is the train's pneumatic braking mode, although some locomotives have an electric brake (rheostatic or regenerative). Thus, it is possible to construct train control restriction zones in *Force-Speed* coordinates. The traction force limitation zone shown in Figure 2 (a) is typical for AC electric locomotives and diesel locomotives. For DC locomotives, the traction force limitation zone is divided into parts in accordance with the connection schemes of the traction motors (Figure 2, b).

Admissible control in the traction mode can be limited from above, for example, by constraints on coupling and weakening of the field (Figure 3).



a *b*

Figure 2. Train control restriction zones: a –for AC electric locomotives and diesel locomotives; b –for DC locomotives S – series, SP – series-parallel and P – parallel engines connection



a *b*

Figure 3. Acceptable train control: a – qualitative scheme of electromechanical characteristics of the locomotive engine; b – control limitation zone in traction mode

It is possible to construct a curve limiting the traction force from below based on the minimum traction current at which the efficiency has not too small value. And it is possible, using electromechanical characteristics of the locomotive engine (Figure 3, a), to allocate some acceptable level of engine efficiency and on the curve of the dependence of the efficiency on the engine traction current to determine the range of traction current ($I_{\text{dmin}} \div I_{\text{dmax}}$), and to determine, according to the dependence of the engine traction force from current, the range of the engine traction force ($F_{\text{dmin}} \div F_{\text{dmax}}$) and, then, the range of the traction force for the entire locomotive. Then, the control limit zone in the traction mode will look as shown in Figure 3 (b). In this case, the traction zone is narrowing.

It should be noted that while the control of the locomotive traction in the zone with big values of the engine efficiency reduces the losses of energy, it does not guarantee a reduction of power consumption for the traction of the train throughout the track section, because in this case, it will be necessary to use for the acceleration of the train either longer or more frequent traction modes.

When driving trains equipped with pneumatic braking means to the required extent, to regulate the speed of the train, almost always (except for stopping braking and steep descents), a braking stage is used with the discharge of the brake line in the summer for loaded trains at 0.6-0.7 ATM, and for empty trains at 0.5- 0.6 ATM. Using these ranges of brake system discharge, it is possible to calculate the curves that limit the zone of possible braking forces. In Figures 3 (b) and 4, this area is shown in red. Similar brake force zones can be constructed for other ranges of discharge of the brake system.

Electric braking is mainly used to stabilize or limit the growth of the train's speed on long descents. The use of pneumatic braking in such situations, especially for loaded freight trains, leads to a significant reduction in speed due to the fact that the processes occurring in the braking system of the train are rather slow. Consequently, the use of pneumatic braking to stabilize the speed of the train leads to a useless and excessive loss of its kinetic energy. The use of electric braking of the locomotive (especially regenerative) allows to achieve a smooth reduction or stabilization of the speed and can reduce power consumption. Therefore, it should be used in those cases where there is no need to significantly reduce the speed of the train. The zone of possible braking forces in Figures 3 (b) and 4 is shown in brown.

Next to consider is the choice of the train control mode during navigation between nodes of adjacent grid sections. Earlier, it was shown how to obtain the value A_L of the locomotive work or the brake system of the train for the transition between the grid nodes. Obviously, this work is connected with the traction and braking forces:

$$A_\mathrm{L} = \begin{cases} \int_0^S F_\mathrm{t}(x)\,dx, \text{ traction} \\ \int_0^S F_\mathrm{b}(x)\,dx, \text{ braking.} \end{cases} \tag{5}$$

From this equation, it is possible to determine the traction or braking force as a function of the track:

$$F(x) = \frac{dA_\mathrm{L}}{dx}, \tag{6}$$

or the average value of the force on the path segment $0 \div S$:

$$F_\mathrm{av} = \frac{A_\mathrm{L}}{S}. \tag{7}$$

Regarding the running mode, here, expression (1) should take the following form:

$$\Delta E_\mathrm{k} + \Delta E_\mathrm{p} + A_\mathrm{wo} = 0. \tag{8}$$

So, the sum of the changes of the kinetic and potential energies should be compensated by the work of the forces of the main resistance on the movement of the train. Nevertheless, this condition practically always cannot be fulfilled. Therefore, in order to implement the idle running mode, it is necessary to introduce a certain threshold on force $\pm F_\mathrm{o}$. And, if the force obtained from the expression (3) does not exceed the threshold, the idle running mode can be used. In this case, the deviation of the final speed from the speed in the final grid node should not exceed $\pm\delta v$.

When performing a transition between nodes of adjacent grid sections with equal speed, the v_i and v_f ratio between speeds is equal to:

$$v_\mathrm{f}^2 = v_\mathrm{i}^2 + 2aS. \tag{8}$$

If the transition is possible in the idle running mode, the acceleration is equal to:

$$a = \frac{W_\mathrm{i} + W_\mathrm{o}}{M_\mathrm{t}}. \tag{9}$$

Where: W_i – resistance force to train movement from the slope of the track or downhill, W_o – the actual resistance force. Taking this into consideration:

$$v_\mathrm{f}^2 = v_\mathrm{i}^2 + 2S\frac{W_\mathrm{i} + W_\mathrm{o}}{M_\mathrm{t}}. \tag{10}$$

Now, if, supposedly, in addition to the two mentioned forces, another force acts on the train F_o, then the final speed should change:

$$v_\mathrm{f}^{*2} = v_\mathrm{i}^2 + 2S\frac{W_\mathrm{i} + W_\mathrm{o} + F_\mathrm{o}}{M_\mathrm{t}}, \quad v_\mathrm{f}^* = v_\mathrm{f} + \delta v, \tag{11}$$

After some transformations, the following result is obtained:

$$F_\mathrm{o} = \frac{\delta v \cdot \left(2v_\mathrm{f} + \delta v\right)}{2S} M_\mathrm{t}. \tag{12}$$

The deviation of the final speed from the speed at the endpoint can be either increasing or decreasing. Hence, the force F_o can be both positive and negative:

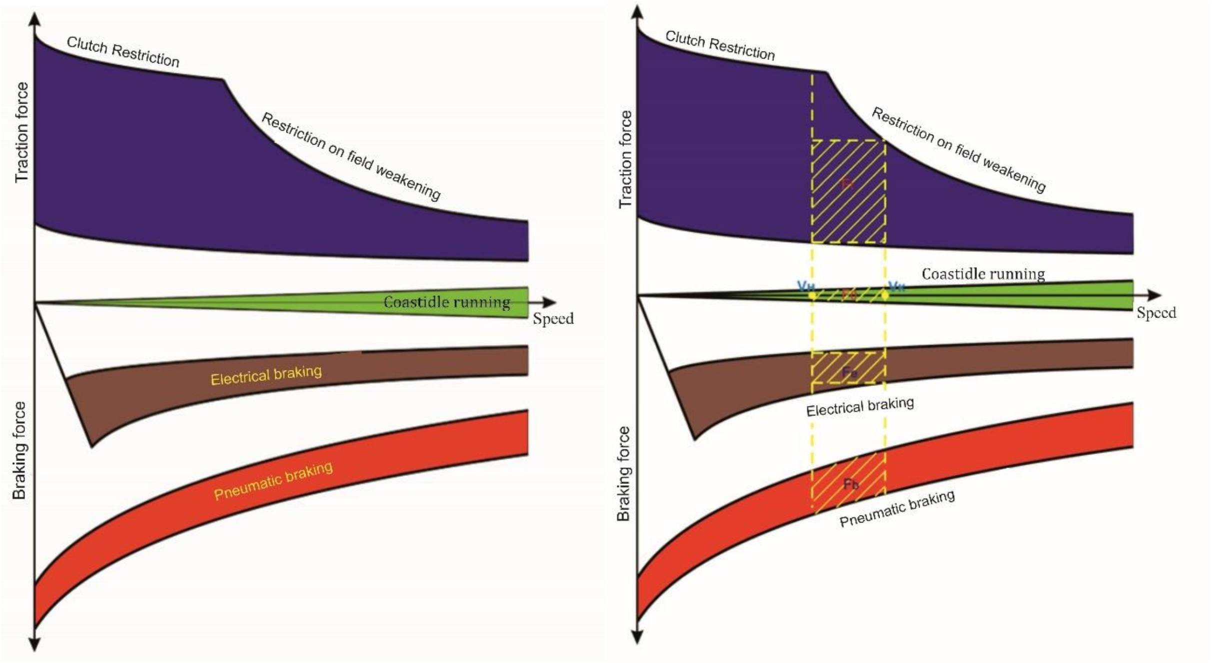
$$F_\mathrm{o}^+ = \frac{\delta v \cdot \left(2v_\mathrm{f} + \delta v\right)}{2S} M_\mathrm{t}, \tag{13}$$

$$F_\mathrm{o}^- = \frac{-\delta v \cdot \left(2v_\mathrm{f} - \delta v\right)}{2S} M_\mathrm{t}. \tag{14}$$

Thus, if, as a result of the transition between the two nodes, an average force is obtained $F_\mathrm{av} \le \left|F_\mathrm{o}\right|$, then the deviation of the final speed (v_f^*) of the speed in the final grid node (v_f) does not exceed the value δv , i.e.:

$$\left|v_\mathrm{f}^* - v_\mathrm{f}\right| \le \delta v. \tag{15}$$

Now, the control restriction zones look like this (Figure 4, a).



a *b*

Figure 4. Train control constrains zones: a – with coasting mode; b – the entry of an average force into one of the zones of admissible controls

Having determined the average force F_{av} along a segment of the path, it is possible to check in which zone (traction, run-out, or braking), with a known change in speed ($v_i \div v_f$), it falls into (Figure 4, a) and, thus, determine the feasibility of the transition between grid nodes and the train control mode during this transition. If the average force does not fall into any of the allowable control zones, such a transition is considered impossible.

If the value of F_{av} falls within the zone of pneumatic braking, then, in this case, the control is reduced to the application of the braking stage, for which the range of pneumatic braking forces is calculated. If the value of F_{av} falls into the zone of electrically controlled braking, then it is necessary to additionally check the possibility of its implementation throughout the entire speed range ($v_i \div v_f$). If the speed falls into the run-out zone, then the idle mode of the locomotive should be applied. If the F_{av} value falls within the traction zone, the possibility of realizing the traction force in the speed range should also be checked ($v_i \div v_f$). In Figure 4 (b), zones of implemented control are crosshatched. The issue of time spent on transition between nodes of adjacent grid sections is discussed in detail in the study [7].

Conclusion

The proposed algorithm for determining restrictions on train control consists of the use of simplified methods for calculating the state of the train as a controlled system without using differential equations of motion, which makes it possible to significantly reduce the time needed for calculations. This, in turn, will make it possible to solve problems of finding optimal control almost in real-time, taking into account changing conditions while the train is moving. The practical significance of the results obtained lies in the use of a calculation method that does not require significant time to complete and can be used as a subsystem of the onboard train control system, capable of performing calculations taking into account changes in the current train situation. The results formed the basis of the software and hardware complex “Train Driver Simulator”.

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