One-point method for speed strategy optimization based on slope simplification and speed limit prediction

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Abstract. The automatic driving of trains is an inevitable trend of the modern development of railway transportation, and it is also a necessary requirement for energy conservation and emission reduction. A train automatic driving speed planning scheme with only one operation state transition point in the simplified slope section is proposed based on slope simplification principle and speed limit regulation on an interval line, which reduces the control complexity and energy consumption for automatic driving. An improved fitness function of genetic algorithm (GA) is explored to solve an operation state transition point position of the train, then train energy-saving operation strategy is presented. Practical energy costing experiment for freight train (HXD3) with 2,800 tons for a 33.7km line on Bin-Zhou railway line is obtained and compared with the proposed algorithm. Results show that energy consumption is saved by 15.2% for the speed strategy from the proposed method. So operation strategy is simplified greatly because of only one state transition point in a simplified interval which is more suitable for automatic driving. On the other hand, one point operation strategy is also more energy efficient than manual manipulation. Therefore, the proposed method provides a simple and efficient control strategy for train automatic driving.

1. Introduction
Railway transportation is one of the main ways of China's transportation industry. Due to large-scale and passenger-cargo capacity of railway network, locomotives consume a lot of energy. The automatic driving of train can avoid safety hazards caused by drivers due to personal differences and manipulation methods. At the same time, on the premise of ensuring the operational efficiency of the train, reducing the energy consumption during the transportation process is of great significance for the development of green transportation mode in China.

Optimization of train energy-saving operation is an optimization problem. Taking the energy consumption of train operation as the objective function, the appropriate independent variables are selected to solve the energy-saving speed curve that meets the relevant constraints. In the study of this problem, scholars at home and abroad have proposed different optimization methods.

In the literature, Chang et al. [1] used genetic algorithms to optimize the train punctuality, comfort and train energy consumption, and established a train steering optimization model for trains. The
optimal idle control problem is solved. Wong et al. [2] solved the single and multiple idle point positions of subway train operation by genetic algorithm. Marumo et al [3] adopted parallel multi-group genetic algorithm and achieved good results. Keskin [4] proposed hybrid optimization method based on genetic algorithm and annealing simulation algorithm is used to study the optimal working condition switching point in train operation. The hybrid algorithm can achieve better accuracy and lower running time. Liang et al. [5] proposed a genetic algorithm based on penalty function method for multi-objective optimization of train running curve. The penalty function method was added to the fitness function, which improved the convergence speed of genetic algorithm.

In summary, Based on the slope simplification principle and speed limit regulation, a scheme for automatic driving speed strategy of a train is proposed, which only needs one state transition point in the simplified slope section, and a speed limit prediction model is established based on one point method. Improved genetic algorithm is used to solve efficiently multi-objective optimization model for searching the optimal operation transition point and obtaining train energy-saving operation curve. The feasibility of proposed algorithm is also verified by comparing the optimized curve with the actual train operation data.

2. Building an energy-saving manipulation model

The specific line segmentation steps are as follows:

2.1. Combing the same type of slope

According to the size of the slope, the same type of slopes that meet certain rules are combined. Division criteria is as follows:

Total length of the line is \( X \), the planned running time of the train is \( T \), and the ideal cruising speed is defined as:

\[
V_x = \frac{X}{T} \tag{1}
\]

On the slope of the current slope value \( i \), if there is a suitable \( \mu_f \) to satisfy

\[
\mu_f (V_x) = w_o \cdot (V_x) - i \tag{2}
\]

It is said that the slope is a gentle slope. Among them, \( \mu_f (v) \) is the unit of traction and \( w_o (v) \) is the basic resistance.

If satisfied

\[
f (V_x) < w_o (V_x) - i \tag{3}
\]

The slope is said to be a large upslope.

If satisfied

\[
w_o (V_x) < i \tag{4}
\]

The slope is said to be a large downslope.

Express the slope before the merger as:

\[
S_0 = \left[ S_{01}, S_{02}, \ldots, S_{0t}, \ldots, S_{0(n-1)}, S_{0n} \right] \tag{5}
\]

Among them, \( S_{0i} \) indicates the starting position of the \( i \)-th slope before the merger, and there are a total of \( n \) slopes on the line before the merger.

According to the above slope division rule, the merged interval can be expressed as:

\[
S_1 = \left[ S_{11}, S_{12}, \ldots, S_{1t}, \ldots, S_{(n-1)t}, S_{1n} \right] \tag{6}
\]

Among them, \( S_{1i} \) indicates the starting position of the \( k \)-th interval after the merger, and a total of \( m \) intervals on the combined line.
2.2. Segmentation based on one-point slope manipulation strategy

Selection of steering strategy of train during operation is not only related to type of slope in which current position is located, but also to the type of slope in two preceding and following sections. For convenience of description, the train manipulation strategies are divided into three categories: full traction, idle running, and cruise maintenance, and the manipulation strategies on each interval are respectively set.

Start process manipulation strategy (three points) is shown as follow. In initial interval, starting point must be traction state point, so the starting point is regarded as the first strategy conversion point. After traction phase is over, driving strategy is decided by the slope type of the interval and that of next interval. After the type of slope is determined by the mentioned simplified slope model, there are three steering strategy transition points in the first interval.

For initial interval, the switching point position should meet the followed constraint of equation (7):

\[
\begin{align*}
X_{11} &= 0 \\
X_{12} &\leq X_{13} \\
X_{12} &\leq X_{21}
\end{align*}
\]  

(7)

According to position of the selected three policy transition points, starting interval can be divided into three segments to take different manipulation strategies.

Operation strategy in the running interval is determined by the type of slope in this interval and the slope type of the next interval, so only one strategy conversion point method is proposed and decided to simplify control strategy between two adjacent simplified slope intervals. Then control strategy before and after the conversion point is described as followed.

For the \(i\)-th (\(i \neq 1\)) running process interval, switching point position \(X_{if}\) should satisfy the constraint of equation (8):

\[
S_{if} \leq X_{if} \leq S_{f(i+1)}
\]  

(8)

According to position of a selected strategy conversion point, the running process interval can be divided into two sections according to different manipulation strategies.

For the last interval, Since train will stop, inertia operation strategy is considered the best operation for saving energy. Before the inertia operation strategy, operation strategy should be determined by the slope type in this interval, so there is a strategic conversion point in the last interval.

Therefore, the whole running line is divided into \(m\) sections, and there are \(m+2\) transition points in \(m\) sections. Compared with the line proposed by Yan Sanshan in 2018 [6], there are \(2m+1\) conversion points in \(m\) intervals, and calculated strategy conversion point numbers are nearly double. So one point method proposed greatly improves the efficiency of computation. The train manipulation strategy also be simplified so much by the proposed one point method, and it is more efficient for saving energy of freight transport.

3. Manipulation strategy integrated speed limit

According to different speed limit for different terrain, the whole line is divided into different segment \(S_i\). From the starting point, speed limit value is compared segment by segment, the current speed limit of segment \(S_i\) is \(V_i\), and the next speed limit of segment \(S_{i+1}\) is \(V_{i+1}\).

The distance of speed limit \(V_i\) is \(S_i\), and acceleration distance for approaching to speed limit \(V_i\) is \(S_{ia}\), and deceleration distance for approaching to next speed limit \(V_{i+1}\) is \(S_{il}\).

When \(V_i < V_{i+1}\), the speed limit is \(V_i\), otherwise it is judged as \(S_i < S_{ia} + S_{il}\). If \(S_i < S_{ia} + S_{il}\) is established, the speed limit is \(V_i\), and in other cases the speed limit is \(V_{i+1}\).

4. Solution of transformation point of operation strategy based on improved genetic algorithm

In this paper, an improved genetic algorithm (GA) is proposed to solve the position of operation strategy switching point. The fitness function of GA is improved. Running time and energy cost are used as joint constraint factors to accelerate convergence and improve efficiency of GA.
The \(i\)-th energy cost individual of GA is expressed as \(E_i\), and the \(i\)-th time cost individual of GA is expressed as \(T_i\). \(T\) is planned running time, and \(\Delta T_i\) is the difference between actual time and the planned running time.

Fitness function with time and energy as the target can be expressed as:

\[
J_i = \alpha \left(1 - \frac{\Delta T_i}{\sum_i \Delta T_i}\right) + \beta \left(1 - \frac{E_i}{\sum_i E_i}\right)
\]  

(9)

In the above formula, \(\alpha\) is the running time weight, \(\beta\) is the train energy weight. \(\alpha + \beta = 1\). The values of \(\alpha\) and \(\beta\) are determined by the calculation principle. For example, time-saving operation of the train running time or the energy-saving operation focusing on energy consumption can be set by adjusting the weight.

5. Comparison between simulation results and actual results

Based on the slope simplification, speed limit integration and the improved GA, a 33.7 km of some sections of Harbin-Manzhouli railway line is selected to simulate operation and compared with practical train running processing.

5.1. Train parameters

The model of the locomotive selected in this paper is the HXD3 locomotive with 25t axle load. The locomotive weighs 138t, the vehicle is C70 model, a total of 40 knots, empty vehicle weight is 20t with 70t full load.

5.2. Line condition

According to the slope reduction rule and the above-mentioned energy-saving manipulation strategy, the energy-saving manipulation strategies of each section are shown in Table 1. Among them, No.3 means full traction, No.2 means cruise, and No.1 means coast.

| Interval | Interval Length (m) | Slope Type       | Energy-saving Manipulation Strategy |
|----------|---------------------|------------------|-------------------------------------|
| Interval 1 | 3567                | Gentle slope     | 3-2-3                               |
| Interval 2 | 550                 | Large upslope    | 3-2                                 |
| Interval 3 | 250                 | Gentle slope     | 2-1                                 |
| Interval 4 | 500                 | Large downslope  | 1-2                                 |
| Interval 5 | 200                 | Gentle slope     | 2-3                                 |
| Interval 6 | 200                 | Large upslope    | 3-2                                 |
| Interval 7 | 500                 | Gentle slope     | 2-1                                 |
| Interval 8 | 450                 | Large downslope  | 1-2                                 |
| Interval 9 | 1250                | Gentle slope     | 2-1                                 |
| Interval 10 | 1000               | Large upslope    | 1-2                                 |
| Interval 11 | 1100               | Gentle slope     | 2-3                                 |
| Interval 12 | 850                 | Large downslope  | 3-2                                 |
| Interval 13 | 4550               | Gentle slope     | 2-1                                 |
| Interval 14 | 400                 | Large upslope    | 1-2                                 |
| Interval 15 | 700                 | Large downslope  | 2-3                                 |
| Interval 16 | 4000                | Gentle slope     | 3-1                                 |
| Interval 17 | 800                 | Large downslope  | 1-2                                 |
5.3. Genetic algorithms design
For the railway line conditions, there are 20 state transition points, so the chromosome length of GA is 20, the population size of GA is 50, the maximum evolution algebra of GA is 1000, the crossover probability of GA is 0.4, the mutation probability of GA is 0.04, and schedule time for 33.7km is 2800s.

5.4. Results comparison
Based on the slope simplification theory described above and improved genetic algorithm, the running speed curve corresponding to the actual road segment is obtained through simulation, as shown in Figure 1. The position of the state transition point and the corresponding energy-saving operation state in each section are calculated, and the energy-saving operation state is shown in Table 2.

| Interval | Slope Type | State Transition |
|----------|------------|------------------|
| 18       | Gentle     | 2-1              |
| 19       | Large      | 1-2              |
| 20       | Gentle     | 2-1              |

![Figure 1. Comparison of train automatic driving speed planning curve and actual curve.](image)

Table 2. Comparison of simulation results and measured data based on improved genetic algorithm

| Plan           | Energy Consumption (kWh) | Operation Times(s) | Energy-saving Rate(%) |
|----------------|--------------------------|--------------------|-----------------------|
| Actual running | 1517.67                  | 2789.28            | --                    |
| Simulation     | 1287.36                  | 2781.27            | 15.2                  |

It can be seen from Figure 1 that speed strategy curve from proposed algorithm is faster than actual running speed curve from driver for mostly route. So running time calculated by the improved genetic algorithm is 2781s, and practical running time is 2800s, so efficiency of train running is higher if the speed from simulation is used. In terms of energy consumption, 1287.36kWh from proposed algorithm is lower than 1517.67 kWh that of practical running operation, 15.2% energy is saved on the 33.7km distance only, if all routes can be considered to used the speed strategy from proposed algorithm, it will produce huge economic benefits.

6. Conclusion
Aiming to the problem of more dimensions in the train energy cost solution problem, a slope simplification principle is proposed, it integrates the complex type of slope, reduces the solution
dimension, then only one state transition point is need to perform under the simplified slope and speed limit conditions. The model is used to determine the speed constraint of the train during the section operation, avoiding the contradiction between the strategy determined by the section slope and the section speed limit. So the energy cost model is simplified greatly. For solution of the model, an improved GA is proposed by optimizing the fitness function, which modified survival rate of the population, then efficiency and accuracy of the algorithm are improved greatly. Through the comparison with practical train on-line operation experiment, energy consumption is saved by 15.2% and running time is also reduced by speed strategy simulation, which verifies the feasibility and reliability of one point method. The proposed method provides a new idea and reference direction for the automatic driving speed planning of freight trains in the future, and has strong practicability, which provides a theoretical basis for the actual operation of freight train automatic driving.

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