Guidance and evaluation system for smooth operation of heavy-haul trains

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Abstract

The operation rules and methods for heavy-haul trains were studied and summarized according to the characteristics of the Daqin Railway, such as a large traffic volume, a high density and high-speed and difficult-to-operate heavy-haul trains. Combined with traction calculation and operation experience, these can be quantificationally decomposed into an evaluation standard for the smooth modularized operation of heavy-haul trains that can be recognized by computers. A train operation guidance system was designed to collect locomotive drivers’ operation data, display the actual operation and standard curves in real time and give voice prompts and violation-operation alarms for safety-critical operation. In addition, software for operation analysis and evaluation was developed according to the quantified smooth operation standard. The smooth operation of heavy-haul trains was evaluated and statistically analysed through a comparative analysis of the actual operation records. Moreover, a train impact force detection device capable of monitoring the three-dimensional impact force of heavy-haul trains in real time was developed. Meanwhile, the evaluation standard for smooth operation was verified and optimized by real-time monitoring of the impact force of heavy-haul trains. Finally, on the basis of the above studies, a complete closed-loop management scheme for the smooth operation of heavy-haul trains was constructed, and the objectives of optimizing train operation strategy, standardizing drivers’ operations and ensuring the smooth operation of trains were realized through application.

Keywords: heavy-haul trains; smooth operation; traction calculation; synchronous operation; simplified line model
1. Introduction

Heavy-haul freight trains have become a development direction for railway freight transport worldwide because of their high efficiency, low emission, low cost and large transportation capacity. Since the 1960s, the United States, Australia, South Africa, Canada, Russia, Brazil and other countries have successively researched long marshalling, large axle loads and technical equipment for heavy-haul freight trains and have achieved economic benefits [1]. In recent years, countries transporting heavy-haul freights have been conducting extensive research on the intelligent control technology of heavy-haul trains.

Since the 1980s, China has been committed to the development of the heavy-haul railway. Through the exploration of experimental heavy-haul transportation—the Daqin Railway heavy-haul line—new breakthroughs are being continuously made in heavy-haul technology in China. The Daqin Railway starts from Hanjialing Station in Datong City, Shanxi Province, in the west and ends at Liucun South Station in Qinhuangdao City, Hebei Province, in the east, with a total length of 653 km. It is the first electrified double-track freight line in China, and it is mainly used for coal transportation. After three capacity expansions and reconstructions, and with the application of a large amount of advanced rolling-stock equipment and dispatching and train-control technology, the railway now has a normalized operation capacity of 450 million tons of annual traffic volume. The daily operation of 65 pairs of 20 000-ton heavy-haul combined trains, with a tracking interval of 12 minutes, has set a world record for heavy-haul railway transportation. After three capacity expansions and reconstructions, and with the application of a large amount of advanced rolling-stock equipment and dispatching and train-control technology, the railway now has a normalized operation capacity of 450 million tons of annual traffic volume. The daily operation of 65 pairs of 20 000-ton heavy-haul combined trains, with a tracking interval of 12 minutes, has set a world record for heavy-haul railway transportation. However, the operation of heavy-haul trains with a high density and large capacity requires drivers to have considerable train-operation abilities. Therefore, managing drivers’ operation scientifically and normatively to ensure the smooth operation of heavy-haul trains is a complex system problem.

2. Operation characteristics of heavy-haul trains

Heavy-haul trains travel the Daqin line from west to east mainly on the down ramp; the maximum gradient per mile of down ramp is 12‰, while that of up ramp is 4‰. The railway includes two long and large continuous down ramps with a total length of 109 km. The 20 000-ton heavy-haul combined train running on the line comprises HXD1, HXD2 AC drive electric locomotives, and C80 series freight vehicles, and the marshalling mode is HXD1(HXD2) + C80(105 vehicles) + HXD1 + C80(105 vehicles) + controllable EOT. The total length of the train is 2.7 km, and wireless-multi-traction synchronous control is adopted. The line also adopts a four-display automatic block-signalling system. Operating a heavy-haul combined train on this complex line is considerably more difficult than operating an ordinary freight train. The former mainly has an increasing risk of decoupling, disconnection and derailment caused by the longitudinal power of heavy-haul trains, the coordination difficulties of air-electric combined braking (determined by the characteristics of combined trains), the complexity of prediction for reducing the operation impact force of undulating ramps and the difficulty in tracking and controlling heavy-haul trains under high-density operation [2–4]. In addition, owing to changes in traffic volume and improvements in locomotive operation efficiency, transportation organization and train marshalling modes need to be continuously adjusted. Therefore, the optimization of train operation methods and the accuracy of driver operation will impact the scientific and standardized management of the smooth operation of heavy-haul trains.

3. Closed-loop management model for the smooth operation of heavy-haul trains

3.1 Factors affecting the smooth operation of heavy-haul trains

According to the basic equipment of the Daqin Railway and the operation practices of heavy-haul trains [2, 3, 5–7], the main factors affecting the smooth operation of heavy-haul trains include train marshalling, transportation efficiency, the vehicle characteristics of locomotives, line complexity and differences in driver operation, as shown in Fig. 1.

Considering the smooth operation of the 20 000-ton combined trains on the Daqin line, the current marshalling mode, locomotive configuration and synchronous operation of the front and rear locomotives are not the best modes [7–10]. However, owing to the limitations of transportation organization, locomotive operation efficiency, technical equipment conditions and other factors, under the existing objective conditions of transportation, one of the main ways of reducing train impact force and improving stability is to optimize
3.2 Closed-loop management design for the smooth operation of heavy-haul trains

The closed-loop management for the smooth operation of heavy-haul trains is realized by establishing a smooth operation guidance and evaluation system that fulfills the requirements of field management and aims to optimize and assist in driver operation. The ultimate goal is to manage heavy-haul train operation in a scientific and standardized manner and ensure the smooth operation of such trains.

The design of the abovementioned guidance and evaluation system for the smooth operation of heavy-haul trains can be divided into four steps, as shown in Fig. 2.

(i) The operation rules of heavy-haul trains are summarized, organized and quantified, and supplemented by the conclusions of traction calculations and a longitudinal dynamics test. In this way, the modular operation standards of heavy-haul trains are established.

(ii) The key parameters of train operation are collected, and modular operation standards are used for a synchronous comparative analysis performed to guide driver operation.

(iii) On the basis of these modular operation standards, all types of indexes and key manipulations in the entire process of the driver’s manipulation record are analysed, and the operation results are evaluated.

(iv) The operation impact force data of the key points of the train are collected, and the operation results are evaluated in combination with the train operation records to provide the basis for optimizing the modular operation standards.

3.3 Principles of the guidance and evaluation system for the smooth operation of heavy-haul trains

The block diagram of the principle of the guidance and evaluation system for the smooth operation of heavy-haul train as shown in Fig. 3.

3.3.1 Line-modelling design. The line-modelling design aims to classify the lines’ features and highlight the main features of each section to simplify the line input conditions in the computer modular-operation analysis, reduce calculation difficulty and make the system portable for different line applications. According to the different control ranges, the line model can be divided into three types: real-time control-section model, predictive control-section model and whole-process control model. In the design process, factors
such as ramp fluctuation, ramp slope change and multi-feature superposition (ramp, curve, bridge and tunnel) are simplified to highlight the main features of the model and reduce the influence of secondary factors, thereby avoiding the longitudinal impact force of a train caused by frequent operation fluctuation.

**Real-time control-section model.** On the basis of the head-end locomotive of the train, the section where the train is located and the part 3 km ahead of it are divided into real-time control sections. The basic line characteristics of this section, such as an undulating slope and trough, are identified. The section is classified, its operation guidance is qualitatively listed and the train operation conditions of the front end of this section are predicted.

**Predictive control-section model.** The section 10 km ahead of the locomotive at the head of the train is divided into predictive control sections. The basis for classification adopted by this model is that the section has evident characteristics and requires a change in train operation. If there are up and down ramps with continuous and large slopes, undulating ramps, in and out signals and phase separation of difficult sections, advanced confirmation will be required.

**Whole-process control model.** The whole-process control model is mainly used to identify some specific characteristics of the line, such as the test positions of the train and cyclic braking sections, sections where bad weather may cause driving difficulties and overall line conditions (such as speed-limit change location, marshalling departure, decomposition and destination).

3.3.2 **Modular operation analysis.** The operation of heavy-haul trains can be divided into different control modules according to the train’s characteristics. The timing and logic of the driver’s operation in the critical section are constrained through the modular design, whereas in the non-critical section, the driver can make judgment calls to reduce the difficulty of operation. In the train smooth-operation analysis, the operation modules are classified, and modular operation standards are designed. Modular operation analysis takes marshalling information and train speed as input conditions. Through the quantification of operation rules, train traction calculations, test simulation and other methods, the operation parameter data, operation logic relationship and time sequence of the module are obtained and then combined with a comprehensive comparison and selection calculation of the actual operation experience of excellent drivers. Finally, a smooth operation standard that can be recognized by computers is formed after a field test verification.

3.3.3 **Operation guidance, evaluation and verification.** The guidance and evaluation system for the smooth operation of heavy-haul trains is based on the abovementioned modular operation standards. Analysis and tolerance calculation were conducted by collecting the key parameters of train operation and comparing the actual and standard operations. Consequently, the on-board guidance of driver operation and the operation evaluation in the whole process were achieved. Combining the monitoring of the online acceleration at the key positions of the train with the train operation conditions at the same time, the causes of the train impact force can be analysed to provide the basis for optimizing the operation.

At the same time, in the case of bad weather (e.g. rain, snow) under the traction/electric-brake,
the locomotive may slip and slide, and then the driver needs to properly sand to the rail or even stop the train. These manipulations are identified by velocity data acquisition and are determined by the system that the driver is not misbehaving.

4. Modular operation design of heavy-haul trains

The modular operation of heavy-haul trains is the basis of the guidance and evaluation system for their smooth operation. The proposed system performs modular classification according to 10 types of operation in terms of starting, stopping, passing phase separation, working condition conversion, traction/regenerative braking, electric-air combined braking, cyclic braking, signal change, network voltage fluctuation and safety forbidden items. Simultaneously, the rules and regulations of the China Railway Group and Taiyuan Bureau Group pertaining to heavy-haul train operation are summarized and sorted. Accordingly, the modular operation method for heavy-haul trains on the Daqin line is studied and formulated through train traction calculation in the key sections and a large number of driver operation records, which are combined with the operation experience of HXD1 and HXD2 electric locomotives, the marshalling mode of heavy-haul trains and the line model data of the Daqin line. Moreover, each operation requirement is decomposed according to relevant parameters and quantified as a smooth-operation analysis standard recognizable by computers.

4.1 Rules to be followed by the modular operation design of heavy-haul trains [4]

When the train is started, the traction force of the train should be gradually increased. Directly setting the traction force to 30% (200 kN) or above is strictly prohibited, and the train can only run up to speed after the entire train is started.

(i) On undulating ramps, the train should be operated using an inert or small traction (power-braking) force to pass through the grade-change point according to the longitudinal section of the line, thereby maintaining the stable working condition of the locomotive and reducing the impact force of the train.

(ii) For the passing of the neutral section, the handle should return to zero 300 to 500 metres before the ‘power off’ sign. After the main control locomotive passes the neutral section owing to inertial force, the given value of the traction force (power braking) should be mastered according to the speed.

(iii) The side-line parking should be foreseen in advance, and fast working condition conversion is prohibited. The speed should be controlled as soon as possible by small power-braking, thus avoiding the fast supply of or sudden increase in the power-braking force.

(iv) After air-brake speed regulation, the driver should stop for release when there is no release condition. Under normal conditions, large pressure reductions or emergency brake stops should be avoided.

(v) As the train parks at a station, the power brake should be used in advance to control the speed. There should be an initial brake-pressure reduction of 50 kPa for smooth parking, and the additional pressure reduction should exceed 100 kPa after parking.

4.2 Main calculation formula for traction for modular operation of heavy-haul trains [11]

(i) Basic resistance per unit operation of HXD1 and HXD2 locomotives:

\[ \omega_0’ = A + Bv + Cv^2. \]  

In formula (1), A = 1.2, B = 0.0065, C = 0.000279 and v is the speed.

(ii) Basic resistance per unit operation of freight car:

\[ \omega_{02}’ = A + Bv + Cv^2. \]  

In formula (2), A = 0.92, B = 0.0048, C = 0.000125 and v is the speed.

Formulas (1) and (2) are mainly used to draw the standard curve of the train traction.

(iii) Adding gradient per mile:

\[ i_j = \frac{1}{L_i} \left[ \sum (i_i \cdot l_{ii}) + 600 \sum \frac{l_{ri}}{R_i} + \sum (\omega_{sii} \cdot l_{i}) \right]. \]  

where L is the length of the train in metres (m); i is the gradient per mile of the i-th ramp covered by the train; l is the length of the i-th
ramp covered by the train (excluding the calculated length of the uncovered part) in metres (m); \( R_i \) is the radius of the \( i \)th curve covered by the train in metres (m); \( l_i \) is the calculated length of the \( i \)th curve covered by the train (excluding the length of the uncovered part) in metres (m); \( \omega_{aj} \) is the unit tunnel additional resistance of the \( i \)th tunnel covered by the train in N/kN; and \( l_i \) is the length of the \( i \)th tunnel covered by the train (excluding the length of the uncovered part) in metres (m). Formula (3) is mainly used for the formulation of operation guidance suggestions in the design of the line model.

(iv) Train braking distance:

\[
S_k = S_k + S_e = \frac{v_0 \cdot t_k}{3.6} + 4.17 \times \frac{\left( v^2_i - v_2^2 \right)}{1000\beta_c \cdot \phi_h \cdot \phi_n + \omega_0 + i_j}, \tag{4}
\]

where \( S_k \) is the idle distance of braking; \( S_e \) is the effective distance of braking; \( v_0 \) is the idle initial speed of braking; \( t_k \) is the idle time of braking; \( v_1 \) is the effective initial speed of braking; \( v_2 \) is the final brake speed; \( \beta_c \) is the common braking coefficient; \( \phi_h \) is the converted braking force of the train; \( \phi_n \) is the converted friction coefficient; \( \omega_0 \) is the basic resistance per unit operation of the train; \( i_j \) is the adding gradient per mile. Formula (4) is mainly used for the selection of braking time in the operation of cyclic braking and parking modules.

4.3 Example of cyclic-braking module design for a long and steep downhill

The logical sequence of the single-brake operation during cyclic breaking is as follows: increasing the train speed on down ramp \( \rightarrow \) applying regenerative braking to suppress speed rise \( \rightarrow \) applying air braking to reduce speed \( \rightarrow \) adjusting regenerative braking to decelerate \( \rightarrow \) releasing air braking while maintaining regenerative braking \( \rightarrow \) increasing the speed regulation of regenerative braking.

The starting time of pneumatic braking verified by test includes the train pipe pressure satisfying the constant pressure 600 Kpa, the whole train of couplers being in a compressed state, the train continuing to accelerate, etc. For example, when HXD1 locomotive traction unit 10 000 ton train has applied 400 kN electric braking force and the train is on a 10% continuous downhill ramp with a speed limit of 80 km/h, but its speed still rises to 70 km/h, initial braking decompression (50 Kpa) can achieve better results with consideration of train stability, safety and running efficiency. This is basically consistent with the result of traction calculation. The choice of train pipe press release time is more concerned with safety. According to the longitudinal dynamic analysis, when the train coupler is released from the press state to the pull state, there will be a greater impact force in the middle and rear of the combined train [12, 13]; therefore, reasonable selection of the release speed and regenerative braking force during release are the key to reducing the longitudinal impact force of the train [14]. Six fault-separation tests on a 20 000-ton heavy-haul combined train on the Daqin line are considered as an example. For the 50 kPa decompression in the cyclic braking test at positions k141–k179 in a long and steep downhill (average gradient 8.2‰), the relationship between the six release speeds and the change range in the coupler force and the relationship between the slave-control locomotive electric-braking force and the change range of the coupler force during release, when the first brake is released at the k144 position, are shown in Fig. 4 [15]. Among them, the point (1655/-318) in the Fig. 4 is invalid data with large discrete deviation.

The test data show that the speed of the release point of air braking is inversely proportional to the change range of the coupler force on the long and steep downhill. When the braking is released, the electric braking force applied by the slave locomotive is directly proportional to the change range of the coupler force. Therefore, according to experience and the test data, the operation standard is based on a release speed of 35–45 km/h and a regenerative braking force of 50% (230 kN) during release.

5. Design of heavy-haul train operation guidance

The on-board guidance system for heavy-haul trains has two parts: a locomotive-operation state acquisition device and an operation guidance display. The acquisition device collects real-time operation data and comprehensive train information during train operation through the locomotive network and the expansion communication port of the TAX equipment of the train-operation monitoring device. Such
information mainly includes 13 data items: locomotive number, train number, marshalling information, kilometre mark, speed, speed limit, annunciator status, traction/regenerative braking force, train pipe pressure, brake cylinder pressure, tail air pressure, catenary voltage and main circuit-breaker status. The operation guidance display compares and shows the standard design curve and real-time operation curve of three key operation parameters in real time, i.e. locomotive speed, traction/regenerative braking force and train pipe pressure, through the built-in line model data and the modular operation of the standard and acquired data.

Under normal operation conditions, the driver operates according to the standard curve. When the operation conditions are affected, and the signal suddenly changes to a red light, the system will call the standard parking-control module to guide the driver to stop before the signal according to the signal change conditions. After the departure conditions are met, the standard starting-control module is called until the standard control curve is restored. In addition, the on-board system will give voice prompt in advance at key control points and alarm prompts for serious control errors to guide the driver’s operation.

The system also has a built-in processing mechanism that will correct the operation guidance in a timely manner with changes in signal, speed limit, locomotive fault and other factors affecting the train’s operation. The functions of this mechanism include operation data download and standard-operation database update. The structure and display interface of the on-board guidance system are shown in Figs 5 and 6, respectively.
6. Design analysis and evaluation of heavy-haul train operation

The ground analysis and evaluation system is used to analyse the data of the driver’s entire process after the operation. This system adopts network and computer technology to compare and analyse the actual operation of the driver with the standard operation database, automatically identify the violation items in the actual operation, provide operation suggestions and generate a comprehensive score according to the corresponding weight and quantitatively evaluate the operation safety and stability of each heavy-haul train driver’s operation. The characteristics and distribution of past illegal operation can be tallied by the system according to conditions such as locomotive, driver, section and operation to determine the weak link in the operation management of the heavy-haul train. An open-structure design is adopted in the analysis and evaluation system, in which the operation specifications and standards, basic data and information can be updated to adapt to changes in field application. The software structure is shown in Fig. 7, and an example of the operation interface is shown in Fig. 8.

7. Design verification of handling stability of heavy-haul trains

A train-stability recording device is designed according to the guidance and evaluation system for the smooth operation of heavy-duty trains. The transversal, longitudinal and vertical accelerations of the train monitoring points are collected and recorded in real time by three-dimensional acceleration sensors, and the stability of train
8. Conclusions

A complete management system for the smooth operation of heavy-haul trains is established. Line model analysis and modular operation analysis methods are proposed and fully applied to train operation guidance and operation evaluation. At present, the modular operation standard and driver-operation evaluation and guidance system for heavy-haul trains have been widely applied on the Daqin Railway, thereby ending the illegal operation of drivers. These systems have also played a significant role in ensuring the safe and stable operation of heavy-haul trains and standardizing driver operation. The proposed system is based on a 20 000-ton combined train of the ‘1 + 1’ marshalling mode of the Daqin Railway. After continuous improvement, it is now applicable to various marshalling modes, such as those for 10 000-ton unit trains and 20 000-ton, 30 000-ton and 15 000-ton combined trains. The research results can be
extended to other heavy-haul railway transportation lines, such as the Wari and Haoji heavy-haul railways.

In the modular-operation algorithm design process, owing to changes in train marshalling, external interference and modelling error, the exact model of the actual control process is very difficult to obtain, and various faults of a train will also lead to uncertainty in the model. Therefore, it is necessary to further study the problem of improving the model and algorithm to manage the control robustness of uncertain objects, especially those with large variation ranges of uncertain factors and small system-stability margins.

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Reference
1. Han JG, Wang SC, Wang X, et al. The present situation of world typical heavy-haul railway transportation and its enlightenment to China. Transportation Enterprise Management 2017; 32:104–106.
2. Yan JM, Zhai WM, Chen Q. Dynamics of Heavy-haul Train System. Beijing: China Railway Press, 2003.
3. Geng ZX, Li XF, Zhang B. Simulation Study of Heavy Haul Train Operation on Datong-Qinhuangdao Railway. China Railway Science 2008; 29:88–93.
4. Taiyuan Railway Bureau. Guidance on Heavy-haul Train Operation of Daqin Railway. Taiyuan: Taiyuan Railway Bureau, 2015.
5. Xu Q, Wang YM, Ni CS. Test Study on the Longitudinal Impulse Distribution of Heavy Haul Train. China Railway Science 2013; 34:77–83.
6. Wei W, Wang Q. Influence of train brake on longitudinal impulse of a heavy haul train passing through a ramp. Journal of Vibration and Shock 2014; 33:143–148.
7. Yao XP. Study on the Longitudinal Force of Cyclic Braking of 20kt Trains whose Configuration is Locomotive+10kt+Locomotive. Railway Locomotive & Car 2013; 33:44–48+60.
8. Bohlin M, Gestrelius S, Dahms F, et al. Optimization methods for multistage freight train formation. Transportation Science 2015; 50:1–18.
9. Li W. The key Technology Research and Application of Locomotive Wireless Remote Multi-traction Synchronous Control for Heavy-haul Train. Ph.D Thesis, Central South University, 2012.
10. Li W, Chen TF, Li H, et al. Research on wireless transmission synchronization of the coupling control system for heavy-haul combined train and distribute power locomotive. China Railway Science 2011, 32: 102–106.
11. TB/T 1407.1-2018. Railway train traction calculation part 1 : Trains with Locomotives. Beijing: National Railway Administration of People’s Republic of China, 2018.
12. Locomotive & Vehicle Research Institute of China Academy of Railway Sciences. Test Report on the Application of Locomotive Wireless Remote Multi-traction Synchronous Control on Daqin Line. Beijing: China Academy of Railway Sciences, 2006.
13. Afshari A, Specchia S, Shabana AA. Caldwell N. A train air brake force model: Car control unit and numerical results. Proc Inst Mech Eng Part F J Rail Rapid Transit 2013; 227: 38–55.
14. Ge XC, Wang QY, Sun PF, et al. Study on Optimized Handling for Energy-saving and Smooth Operation of Freight Train. Railway Locomotive & Car 2017; 37:47–52.
15. China Academy of Railway Sciences. Test Report on Fault Separation of 20000 Ton Heavy-haul Combined Train on Daqin Line. Beijing: China Academy of Railway Sciences, 2019.