Energy efficiency emergence of high-speed train operation and systematic solutions for energy efficiency improvement

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Abstract

Different from the concept of energy consumption, the energy efficiency reflects the efficiency of using energy resource and the service-oriented business philosophy of railway transportation enterprises. The energy efficiency of high-speed train operation is mainly embodied in the operation stage of railway transportation system, but involves a number of factors during the whole life cycle of railway transportation system. Based on the above understanding, the principle of making gradual and orderly progress is followed to broaden our research vision in space and time so that the global energy efficiency of high-speed train operation can be better studied. Firstly, we describe in detail the definition of the operational energy efficiency of high-speed train. Then the energy efficiency model of high-speed train operation is established to reveal the energy efficiency emergence mechanism of high-speed train operation. The simulation is carried out to analyze the complex influence of train light-weighting, control scheme, load ratio, and different inter-station distance on the operational energy efficiency of high-speed train moving through a block section. The proportion of the braking energy consumption of high-speed train with the non-regenerative braking mode is calculated in real time so that the maximum amount of available regenerative braking energy can be known for the better design of the regenerative energy recycling system in the future. This study can help to get the systematic solutions to further improve the operational energy efficiency of all in-service high-speed trains.

Keywords High-speed train · Energy efficiency · Service orientation · Emergence · Train control · Transportation organization

1 Introduction

How to reduce energy consumption and improve efficiency of high-speed railway transportation systems has long been one of hot research topics internationally. Many scientists, scholars, and engineers made great efforts and obtained a lot of theoretical and applied achievements, which substantially promote the rapid development of railway transportation.

In the 1950s, energy-saving train operation was first studied [1], the sequential space–time optimized combination of traction, coasting, and braking conditions under the constraints of railroad conditions, train performance,

wheel–rail interaction, and air drag, etc. was focused on to get the expected energy-saving speed profile between two successive stations for train control [2, 3].

The recycle of regenerative energy during train braking is another important technology to reduce energy consumption, and can be divided into two categories [4]: the direct use of regenerative energy [5, 6] and the indirect use of regenerative energy [7–11]. The former has a high requirement on train timetable, only the strict space–time match of accelerating and braking trains can ensure the high efficiency of directly using the regenerative energy. It would be very difficult to have train timetable optimized for the good match of

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accelerating and braking trains if a serious imbalance exists in the space–time distributions of passenger and freight flows. Aiming to solve this defect, the latter came into existence, but such energy storage devices as super-capacitors, chargeable batteries, and flywheels should be equipped for the flexible use of regenerative energy, more funds have to be invested to the infrastructure construction and later maintenance.

However, all in-service trains are just a group consisted of many mobile individuals in railway transportation system. The tactical (local) optimization of train behavior should be organically integrated with the global optimization of the whole high-speed railway transportation system's behavior, as a result, more attentions were paid to the timetable optimization, the train scheduling optimization, and their combination with energy-saving train control for the reduction of passenger travel time, time delay, and energy consumption [12–15]. It should be pointed out that timetable or scheduling is just one part of transportation organization, other aspects of transportation organization such as the forecasting of passenger and freight flows, train plan, transportation task organization, and train organization, etc. also contribute to the reduction of passenger travel time, time delay, and energy consumption. The further reduction of energy consumption and the further improvement of transportation efficiency require a global perspective to study problems so that the systematic solutions can be obtained.

A very important fact is that the reduction of energy consumption does not mean the energy-saving operation of railway transportation system. For example, when the transportation tasks are drastically reduced, the total energy consumption is bound to decrease even if no energy-saving measure is taken. Similarly, the increase of energy consumption, in a sense, does not mean that energy conservation is not well done. For example, when the transportation tasks are drastically added, the total energy consumption is bound to increase even if some energy-saving measures are taken and good results are achieved. It is impossible for public transportation not to consume energy, let alone stop the daily public traffic to save energy. So energy consumption is not a good indicator in evaluating and optimizing the behavior of railway transportation system. For railway transportation system, the study of energy efficiency improvement, i.e. energy saving and efficiency increase, should be organically integrated with the space–time distributions, flow directions, and flow volumes of transportation tasks. Unfortunately, in some papers, energy efficiency was regarded/understood as energy consumption to be studied, although a lot of great achievements have been recognized worldwide.

Based on the above analysis, energy efficiency can be defined as follows:

$$e = \frac{\sum_{i=1}^m \sum_{j=1, j < k}^n N_{i,j,k} * S_{i,j,k}}{E} \quad (1)$$

where e denotes the operational energy efficiency of all in-service trains or railway transportation systems, $N_{i,j,k}$ denotes the number of passengers and the weight of freights delivered by the i th train from the j th station to the k th station, $S_{i,j,k}$ denotes the distance of the i th train traveling from the j th station to the k th station, E denotes the total energy consumption of completing the given transportation tasks, m denotes the numbers of all in-service trains, n denotes the number of stations on the route of the i th train.

Parameter e would be the operational energy efficiency of all in-service trains if E denotes the total energy consumption of all in-service trains. Similarly, parameter e would be the operational energy efficiency of railway transportation system if E denotes the total energy consumption of railway transportation system. Clearly, in comparison with the concept of energy consumption, the definition of energy efficiency reflects the service-oriented business philosophy of railway transportation enterprise to a certain extent. Only under the guidance of this philosophy can we study to find the inherent emergence laws of the operational energy efficiency of high-speed train.

The reciprocal of energy efficiency is called unit turnover energy consumption, i.e. the energy consumed per passenger/ton kilometer [16, 17]. However, there are some differences between train unit turnover energy consumption and the unit turnover energy consumption of railway transportation system. The latter traditionally uses the macroscopic statistic data to calculate the global energy efficiency, which does not involve the details of train behavior during its own operation. In contrast, the former not only involves the total energy consumption of train operation, but also is closely related to the delivered passenger numbers or freight weight and the corresponding traveling distance. The increase of energy efficiency is inseparable from the use of advanced train control technology and the improvement of the transportation organization level. Thereby, we can firstly focus on the micro-behavior optimization of high-speed train under control, then turn to the entire railway transportation system to refine the measures of increasing energy efficiency from the operating process of entire transportation organization, including organization of passenger and freight flows, train plan, train formation and breakup, and compilation of train diagram, etc. In the current study, what need to be improved are as follows:

1. The energy consumption, rather than energy efficiency, was usually used to evaluate the effect of energy-saving train operation, which may be difficult

to obtain the objective conclusions, especially in some cases such as the rapid increase or sharp decrease of transportation tasks.

2. Due to the lack of deep understanding of the operational laws of railway transportation system in its whole life cycle, we have to focus on the microscopic energy consumption/efficiency problem of railway transportation system within a limited time and space in its whole life cycle, especially in the operation stage of railway transportation system. As a result, the complex space–time coupling relationships of various parameters or factors, which have influence on the energy consumption of train operation, are often ignored inadvertently. Although the significant energy-saving effects have been obtained, there is still a lot of room to improve the global energy efficiency of railway transportation system by adopting the systematic energy-efficient measures.
3. Train control and transportation organization are not closely connected, although there are many significant achievements in the above two aspects, e.g. the combination of energy-saving train control and timetable optimization, but it is necessary to unify them organically on the whole system level.

As shown in (1), energy efficiency is composed of the numerator and denominator. The energy efficiency improvement of train operation not only relies on the reduction of energy consumption, but also depends on the increase of passenger numbers and cargo weight, as well as the distance travelled by train(s). In order to adapt to the high integration of train control and transportation organization, all parameters and factors that affect the improvement of energy efficiency should be considered together, especially the complex space–time coupling relationship among them, so that the effectively

comprehensive measures of energy efficiency improvement can be found.

As known to all, railway transportation system is a huge complex system. Only the comprehensive and profound understanding of its energy efficiency emergence mechanism can help us to find the systematic solutions for energy efficiency increase. An appropriate entry point is important to simplify the problems and improve research efficiency. Where to start the study of the energy efficiency improvement of railway transportation system has to be also seriously considered. Below are the reasons of choosing the energy efficiency of high-speed train operation as the study subject:

In (1), energy consumption play an important role as the denominator of energy efficiency. The total energy consumption of railway transportation system can be divided into three parts: the energy consumption of all in-service trains, the energy consumption of all inter-station infrastructures. The main difference between the energy efficiency of all in-service trains and that of railway transportation system concentrates on their different energy consumption. As shown in Fig. 1, the energy consumption of all in-service trains can be further decomposed into the energy consumption of train operation (movement) and the energy consumption of train environment system. Correspondingly, the energy consumption of all stations can be further divided into two parts: one is for train operation (movement), another is for station environment system.

When $E = E_{\text{RailwayTransportationSystem}}$, parameter e in (1) denotes the operational energy efficiency of railway transportation system. Similarly, parameter e in (1) denotes the operational energy efficiency of all in-service trains when $E = E_{\text{TrainOperation}}$.

It should go without saying that besides seasonal factors, the energy-saving controls of train and station

Fig. 1 The main components of the total energy consumption of railway transportation system

environment systems are closely related to the dynamic density of passenger flows, the quantity and storage-at-station time of freights, and the average traveling time of passengers and freights. Every train transports passengers and freights from a station to another station, as the roots of railway transportation and the most indispensable ingredient, playing an important even decisive role in systematic energy conservation. Although with the increasing expansion of the railway network and the continuous progress of technology, transportation organization has been gradually developed and become more and more important, train operation are also getting increasingly integrated with it. Viewed from another perspective, transportation organization based on all stations are responsible to coordinate the operation of all in-service trains and provide them services for energy saving and efficiency improvement. All passengers and freights would only stay at stations and yards if all trains stop running. Therefore, according to the historical development trajectory of railway transportation systems, on the research roadmap energy-efficient train operation should be in advance considered along with transportation organization in studying the energy efficiency emergence mechanism of railway transportation system, at least before studying the energy-saving control of environment system.

On the other hand, there are still something in common and close relationship between the energy efficiency of all in-service trains and railway transportation system, i.e. the numerators in the equation of calculating their energy efficiency are distance times passenger numbers or cargo weight [see (1)], no matter which energy efficiency is considered, the systematic research around the performance optimization and scientific application of railway infrastructures must be based on the space–time distributions of passenger and freight flows. As revealed in (1), transportation organization needs to be considered in studying the operational energy efficiency improvement of all in-service trains. As for all those auxiliary infrastructure assisting train operation for safety, efficiency and smoothness, and improving the quality of transportation service, their energy consumption cannot be ignored, but as mentioned above, they depend on, derive from, and serve train operation for passenger and freight delivery from a station to another. In a sense, the operational energy efficiency improvement of railway transportation system would be readily and easily solved if the operational energy efficiency of all in-service trains can be firstly improved, in other words, the key of improving the operational energy efficiency of railway transportation system is to raise the operational energy efficiency of all in-service trains.

Additionally, there are many factors such as energy-saving stop and inter-station distance, etc., which have effects on the operational energy efficiency of all in-service trains,

and should be firstly considered in the planning, design, and construction stages of railway transportation system, not just in the operation stage. In the study of increasing energy efficiency, the research horizons need to be gradually broadened in space and time to understand the energy efficiency emergence mechanism of railway transportation system during its whole life cycle, so that the systematic solution can be obtained for energy efficiency improvement.

In view of the complexity of energy efficiency improvement, we take the calculation of train behavior as the starting point, and the mathematical model of high-speed train adjusting its own behavior is built to analyze the energy efficiency emergence mechanism of high-speed train operation, including the complex influence of other factors during the whole life cycle of railway transportation system, especially in the planning, design, and construction stages on the energy efficiency of high-speed train operation. Then, in simulation we further discuss the effects of train light-weighting, load ratio, and the schemes of train control on the energy efficiency improvement of train operation. At the same time, we assume that only the non-regenerative braking mode can be adopted by the train and the ratio of train braking energy consumption in the total energy consumption of train operation is quantitatively analyzed, so that the maximum amount of available regenerative braking energy can be known for the better design of the regenerative energy recycling system in the future.

2 Energy efficiency emergence of high-speed train operation

The most primitive and simplest transportation behavior of high-speed train is to transport passengers or freights from a station to next station. The energy efficiency of high-speed train moving between two successive stations is first studied, then we broaden our research vision in space and time until the global energy efficiency emergence of all in-service high-speed trains in the whole life cycle of railway transportation system can be understood.

2.1 Energy efficiency analysis of high-speed train operation

To make maximum possible efforts to deliver the passenger and freight transportation tasks with different space–time distributions, different flow directions, and different flow volumes to their respective destinations in safety, rapidity, smoothness, and comfort, is not only the concrete embodiment of railway transportation enterprises serving society, but also the basic way of the railway

transportation enterprises to create social value. So, the energy efficiency optimization of high-speed train operation involves the following main aspects:

1. The optimization of railway transportation organization, which covers the forecasting and organization of passenger and freight flows, the optimization of train routes, the organization of vehicle flows, the compiling of train plan and diagram, and train organization, etc.;
2. The performance optimization of railway infrastructures for energy-efficient train operation;
3. Application of advanced energy-saving technologies.

The optimization of railway transportation organization should be based on the space–time distributions, flow directions, and flow volumes of passengers and freights. The performance optimization of railway infrastructure can provide a good condition for energy consumption reduction and energy efficiency improvement, which should be separated from the application of advanced energy-saving technologies during the operation stage. The optimization of train routes reflects the transportation demands of passengers' arriving at the destinations as soon as possible and the intrinsic motivation of railway transportation enterprises improving the energy efficiency for energy consumption and cost reductions. Mlinarić and Ponikvar [18] pointed out that railway infrastructure, traffic management, and dynamic train movement have an important impact on the energy consumption of train operation. In other study results, the energy-efficient train control and timetabling are regarded as the effective measures to improve the global energy efficiency and reduce the total energy consumption, and the significant effects have been obtained [19]. It must be particularly pointed out that railway transportation organization has wider implications than timetabling and train organization, and includes the transportation organization planning, the organizations of passenger and freight flows, the compiling of train plan and diagram, and the match of neighbor transportation organization links, etc., which all need to be considered for energy efficiency improvement. As known to all, high-speed train is used to meet the market demand of rapid railway transportation. For the given transportation tasks whose space–time distributions, flow directions, flow volumes are fixed, the transportation organization can be optimized to complete the given transportation tasks by the in-service trains fewer than before, as a result, the energy efficiency of all in-service trains is improved, although the energy consumption of a single high-speed train may increase with its load ratio. It is why the energy efficiency of high-speed train is defined as the form shown in (1) and energy-efficient train

operation should be organically integrated with transportation organization.

The speed of freight and passenger trains is also one of the important factors that affect its own operational energy consumption [20]. More energy consumption would be consumed if the train moves faster than before because the resistance force of train operation increases with its speed. Daly et al. [21] pointed out that if without considering the market transportation demand for rapidity, the model of energy-efficient train operation would be established in the most energy-saving, cheapest, and slowest mode. However, we cannot ignore the market demand for rapid railway transportation and have all train move slowly just for the low cost. No railway transportation enterprise can disregard the demands from transportation market. Also we cannot have all trains stop and always stay at their original locations for energy consumption reduction and energy efficiency improvement even if energy efficiency is understood as the reduction of energy consumption. In the process of predesigning the expected optimal inter-station speed profiles, the permitted maximum speed and the inter-station distance should be considered as two main constraints so that the excellent performance of high-speed train can be made full use of and the train can move on schedule.

2.2 Energy efficiency model of high-speed train operation

In the operation stage of railway system, the key of energy consumption reduction and energy efficiency improvement, besides the optimization of railway infrastructure, mainly lies in how to use the trains and have them move in safety and high efficiency in the railway transportation network. Clearly, the advanced train control technology and highly efficient transportation organization management are two aspects we cannot neglect.

On the other hand, any one block section between two successive stations can be regarded as an indivisible "atom". The energy-saving train operation under control and carrying more passengers or freights within density/weight limits are a common problem faced by any train traveling in every "atomic" block section. If every train can energy-efficiently move in every "atomic" block section through infrastructure optimization, train control, and transportation organization, the global energy efficiency of all in-service trains would be greatly improved.

Figure 2 describes an expected optimal inter-station speed profile.

The operational energy efficiency e_{train} of the high-speed train in the atomic block section can be calculated below.

Fig. 2 An expected optimal inter-station speed profile

$$e_{\text{train}} = \frac{N * L}{F * L_1 + B * L_3 - E_{\text{Regenerativebraking}}} \quad (2)$$

where N denotes the number of the delivered passengers or the weight of freights, F is the average traction force under the traction condition, B is the average complementary braking force when the regenerative braking force is not enough under the braking conditions, $E_{\text{Regenerativebraking}}$ denotes the regenerative electric energy, L_1 denotes the distance the train moves under its traction force, L_2 denotes the distance of the train moving under the coasting condition, L_3 denotes the distance of the train traveling under the braking condition. Let L be the distance between two successive stations, we have

$$L = L_1 + L_2 + L_3 \quad (3)$$

Thus, some intrinsic laws of improving energy efficiency can be drawn below:

Law 1 The starting and accelerating process of the high-speed train undergoes the traction accelerating stage until it begins to cruise at a maximum constant velocity. In the stage of train coasting, only the basic and additional resistance forces have the train to slow down until it enters into the braking stage for stop, no electrical energy consumption is consumed for train coasting. The space–time boundary points of any two adjacent stages can be reasonably located to reduce the energy consumption of high-speed train to some extent. Especially, increasing the coasting distance of the train can reduce energy consumption and improve energy efficiency [see (2)].

Law 2 The purpose of train coasting is to utilize its own kinetic energy for energy consumption reduction. With the increase of train coasting time, the kinetic energy of train operation and the available regenerative energy would be less and less.

Law 3 During the braking stage, energy would be consumed to reduce the kinetic energy of train operation for stop if the non-regenerative braking mode is taken, otherwise, the coasting would have no engineering value in energy-saving train operation. Under the regenerative braking mode, the part of train kinetic energy can be converted to the regenerative electric energy. The recycle, store, manage, utilization, and the increase of the utilization rate of regenerative electric energy can reduce energy consumption for the further improvement of energy efficiency [see (2)].

Assuming that N_0 be the carrying capacity of the high-speed train. Then N can be expressed below:

$$N = N_0 * \eta \quad (4)$$

where η denotes the load ratio of the train.

By (2) and (4), we can get

$$e_{\text{train}} = \frac{N_0 * \eta * L}{F * L_1 + B * L_3 - E_{\text{RegenerativeBraking}}} \quad (5)$$

Let m_p be the average weight of passengers, when the load ratio goes up by $\Delta\eta$, the increment Δm of train gross mass can be express below:

$$\Delta m = \begin{cases} m_p * N_0 * \Delta\eta & \text{for passenger train} \\ N_0 * \Delta\eta & \text{for freight train} \end{cases} \quad (6)$$

The increment Δm of gross train mass has an effect on the traction and braking forces of train operation with the same acceleration and deceleration. The gross weight of the train increases with the load ratio η , thereby leading to the increase of the resistance force acting on the train. As a result, the greater traction force has to be taken by the train to move forward, and more energy consumption has to be consumed in its traction condition. Although the increase of the load ratio η can lead to the rise of energy consumption, the denominator in (2), the negative effect is limited and small enough in comparison with the effect of numerator increase because the increment Δm of gross train mass is generally far less than the previous gross train mass.

Suppose that each train is numbered uniquely and no repeatedly, Eq. (7), as shown below, can be used to calculate the operational energy efficiency of all in-service high-speed trains in railway transportation system.

$$e = \frac{\sum_{k=1}^{n_l} \sum_{p=1}^{n_t^k} \sum_{q=1}^{n_b^k} N_0^{p,q} * \eta^{p,q} * L^{p,q}}{\sum_{k=1}^{n_l} \sum_{p=1}^{n_t^k} \sum_{q=1}^{n_b^k} (F^{p,q} * S_1^{p,q} + B^{p,q} * S_2^{p,q} - E_{\text{RegenerativeBraking}}^{p,q})} \quad (7)$$

where p denotes the p th train, q denotes the q th atomic block section, n_b^k denotes the number of all atomic block

sections in the k th line where the p^{th} train moves, n_t^k denotes the number of trains moving in the k th line, n_l denotes the number of the rail lines in the whole railway transportation system.

Law 4 For the given transportation tasks, the space–time distributions, flow directions, and flow volumes of passengers and freights have been known. The increase of the load ratio η of each train in each atomic block section can not only improve the energy efficiency of train operation, but also have the given transportation tasks completed by fewer trains than before. Undoubtedly, it will reduce the energy consumption of railway transportation system, and improve the global energy efficiency of all in-service high-speed trains.

Law 5 The load ratio η is closely related to the transportation organization under the constraints of railway network topology and transportation tasks. It involves the route optimization, the organization of passenger and freight flows, the choice of vehicle type, the organization of vehicle flows, the establishment of train plan, the operation of train formation and breakup [22], the compilation of train diagram, etc. Clearly, the operational energy efficiency improvement of all in-service trains is a complex and dynamic process integrated with the forecast of transportation tasks, the planning of transportation organization, and the actual transportation organizations.

The profits of railway transportation enterprises should be made by providing the publicly-satisfactory and high-quality services. All railway transportation enterprises have the duty to try best to satisfy the transportation needs from the development of society and economy. If the load ratio is overemphasized and the guiding philosophy of serving society is ignored, the measures taken for energy efficiency improvement would be meaningless, e.g. the unreasonably high prices are used to increase revenue.

2.3 Energy efficiency improvement of high-speed train operation in the life cycle of railway transportation system

In fact, the energy efficiency of railway transportation system reflects the complex action of various factors within its life cycle, not only during the operation stage.

2.3.1 In the stage of planning, design and construction

For energy-saving slopes, we can draw the following laws by (2):

Law 6 The reasonable use of the additional traction or resistance force resulted from the slopes can enlarge the range of train acceleration/deceleration value, enhance the control ability of the train adjusting its own behavior.

Moreover, by the reasonable use of the slopes, high-speed train can move at the same acceleration or deceleration with the traction or braking force less than the straight lines, so the energy efficiency of train operation can be improved and the energy consumption can be reduced.

As shown in Fig. 3, the terrain needs to be considered in the planning and design of energy-saving slope so that the construction cost can be reduced. Generally speaking, for the straight and level lines between any two adjacent stations, the energy-saving slope cannot be just artificially designed for energy-saving train operation regardless of cost.

When the straight and level distance l between two adjacent stations is given, the value of $l_1 + l_2 + l_3$ mainly depends on the size of parameters h_1 , h_2 , α , and β . Although the slope can have high-speed train travel in energy saving, it can also lengthen the inter-station distance, which means the high-speed train would have to spend more energy to finish the journey longer than no slope if the positive effect of the energy-saving slope is not fully used by the train or the energy-saving slope is unreasonably designed. Therefore, the permitted maximum operation speed, dynamics performance, and kinematics characteristic of high-speed train need to be considered in combination with the inter-station distance and line condition to give a reasonable design scheme of the energy-saving slope when the terrain is fit for energy-saving slope design. At the same time, the expected optimal inter-station speed profiles of high-speed train and the conventional/emergent braking curves with target distance need to be reasonably calibrated for safe and energy-efficient train operation on schedule. Thus, according to the train timetable based on the expected optimal inter-station speed profiles, the high-speed train can not only use the downhill slope to raise its own speed, but also use its own speed to successfully cross the uphill slope to stop at the next station, so that under the assistance of the conventional/emergent braking curves with target distance, the safe, punctual, and energy-efficient train operation can be realized by the reasonable use of the energy-saving slope.

Fig. 3 Diagram of energy-saving slope

2.3.2 In the stage of producing and manufacturing

(1) Technologies of train light-weighting

For a given expected inter-station speed profile, when gross train mass is reduced, the absolute value of traction force F or braking force B would be correspondingly reduced for the same acceleration or deceleration that can be calculated by using the given target speed profile. Therefore, train light-weighting can contribute to the increase of energy efficiency, which can be seen from (2).

Law 7 The technologies of train light-weighting can also enlarge the range of train acceleration/deceleration value, enhance the ability of the train controlling its own behavior, so that the train can move at the same acceleration/deceleration with a smaller traction or braking force, which leads to energy consumption reduction and energy efficiency improvement of train operation.

(2) Technologies of train resistance reduction

Law 8 With the increase of train speed, air drag gradually becomes the main contradiction that has to be overcome by high-speed train during its accelerating and cruising. The technologies of reducing train resistance force, especially the resistance reduction technology of train reshaping or performance modification, can have the train to move at the same acceleration/deceleration with relatively smaller traction/braking force, thus the operational energy consumption of high-speed train can be reduced and the energy efficiency can be raised.

2.3.3 In the stage of system operation and maintenance

Besides the energy-efficient measures mentioned above, from (1) and (2) other laws can be also refined below:

Law 9 The advanced equipment, devices and train control technology for energy conservation, the technological renovation of transportation infrastructures, the upgrades of train control system, and the optimization of transportation organization, can be used to improve train performance and eliminate transportation bottlenecks for transportation level increase, with a result of energy consumption reduction and energy efficiency improvement.

Law 10 Maintenance can help maintain the good working condition of railway transportation system for energy efficiency improvement. Otherwise, the decrease of transportation capability and level will lead to the reduction of energy efficiency, because the given transportation tasks with different space–time distribution, different flow directions, and different flow volumes cannot be high-efficiently completed.

2.4 Systematic measures for energy efficiency emergence

In the stage of system operation and maintenance, the global energy efficiency improvement of high-speed train operation needs to be studied under integrating train control and transportation organization until the systematic solutions of the global energy efficiency improvement are achieved. On the one hand, the local space–time energy efficiency model needs to be extended or expanded to the whole life cycle of railway transportation system for the global energy efficiency improvement. On the other hand, we need to uphold the service-oriented business philosophy to realize the space–time integration of train behavior adjustment and transportation organization for energy efficiency emergence.

Figure 4 describes the system mechanism of the energy efficiency emergence of high-speed train operation in the whole life cycle of railway transportation system.

The systematic solutions of global energy efficiency improvement ultimately need to be cooperatively implemented by all functional individuals in all stages of its whole life cycle. Moreover, the concrete measures of energy efficiency improvement taken by all functional individuals in all stages are local in space and time, need to center the global energy efficiency optimization under the direction of the service-oriented business philosophy to build a synergy mechanism for global energy efficiency emergence. In a sense, the definitions of energy efficiency and the energy efficiency emergence have largely revealed the systematic approaches of improving the operational energy efficiency of high-speed train.

3 Simulation and discussions on systematic solutions

Here, several key technologies, such as train light-weighting, load ratio increase, train control, and their integration are simulated for energy efficiency improvement. Train light-weighting is completed in the stage of manufacturing, the size of load ratio comprehensively reflects the level of transportation organization which covers the planning of transportation organization and the actual transportation organization, and train control with the expected inter-station speed profile involves the off-line sequential optimized space–time combination of traction, coasting, and braking stages.

In order to reduce complexity, we choose the atomic block section to simulate the operational energy efficiency of high-speed train. The initialization conditions are as follows: The CRH380CL high-speed train is composed of 8 motor cars and 8 trailers and weighs 380 tons with power

Fig. 4 Systematic solutions for energy efficiency improvement of high-speed train

of 9200 kW. The maximum traction force is 520 kN, the maximum braking force is 520 kN [23], and assuming that only the non-regenerative braking mode can be taken by the train so that the maximum space available for the regenerative energy converted from train kinetic energy can be calculated to better design the regenerative energy recycling system. The capacity of the CRH380CL high-speed train is 1015 passengers. The maximum velocity of high-speed train is 350 km/h. The number of passengers actually delivered is 980 and the average weight of passengers is set to be 60 kg. The high-speed train moves on a straight line without slope between two successive stations 60 km apart. And the unit basic resistance force is calculated by $w_0 = 0.7750 + 0.006364013v + 0.000115135v^2$ [24] where the velocity of high-speed train is in km/h, the unit basic resistance force w_0 is in N/kN.

From Figs. 5 and 6, we can see that in comparison with “3% or 4% train weight loss + energy-saving train operation”, “the increase of the load ratio by 10% + energy-saving train operation” has the high-speed train consume more energy. However, Fig. 7 shows that the energy efficiency of the latter scheme can be improved more than the former, which indicates that the energy efficiency is different from the energy consumption in concept although they are closely related to each other. Figure 8 describes the percentage of the braking energy consumption in the total operational energy consumption of high-speed train under energy-saving/rapid train control and other energy-efficient measures, varying from 15.84% to 22.43%, which

Fig. 5 Energy consumption of high-speed train operation under different schemes of energy efficiency improvement

reflects that the braking energy consumption of high-speed train operation accounts for a large proportion.

No matter what braking mode, non-regenerative braking or regenerative braking, is taken by the train, the same inter-station speed profile should be followed to stop at next station safely, efficiently, and punctually. For the same train with the same inter-station speed profile, whether non-regenerative braking mode or regenerative braking mode is taken, the regenerative braking force should be equal to the non-regenerative braking force, and the works respectively done by them should also be equal to each other. The main difference is that energy needs to be

Fig. 6 The increase or decrease ratio of energy consumption of different schemes in comparison with energy-saving train operation

Fig. 7 The percentage improvement of energy efficiency of different schemes in comparison with energy-saving train operation

Fig. 8 Percentage of train non-regenerative braking energy consumption in the total energy consumption of high-speed train operation

consumed by the non-regenerative braking force to do work for decreasing train kinetic energy, the work done by the regenerative braking force can be converted from train kinetic energy, no energy consumption for regenerative braking, at the same time, the regenerative electric energy can be sent back to the traction power system, or directly consumed by the electrical resistance, or directly used by other accelerating high-speed train, or recycled by the energy storage device such as super-capacitors, chargeable batteries, flywheels, etc. for future use. For this reason, the corresponding technological measures should be taken to intensify the recycle, management, and utilization of the regenerative electric energy to reduce energy consumption and improve energy efficiency.

Comparatively analyzing Figs. 4, 5, 6 and 7, we can see that the systematic optimization measures, such as energy-saving train operation, train light-weighting, and load ratio increase, have great effects on the energy efficiency improvement of high-speed train operation. In particular, the increase of the load ratio can not only raise the operational energy efficiency of a single train, but also can reduce the global energy consumption of railway transportation system because the given transportation tasks can be accomplished by fewer trains (vehicles) through increasing the load ratio. Another important thing is that, the non-regenerative braking energy consumption can increase with the reduction of station spacing, under which the train has to brake at a higher speed with a result of the reduction of train coasting time. Conversely, the non-regenerative braking energy consumption would decline if the distance between two successive stations increases, because the train can coast a longer time at a higher speed for energy saving. That is to say, the shorter the distance between two successive stop stations, the higher the non-regenerative braking energy consumption (see Fig. 9), and the lower the energy efficiency of high-speed train (see Fig. 10). So, for high-speed train, the length of inter-station distance plays a decisive role in determining whether the coasting operation or the regenerative braking mode is taken for energy saving.

As known to all, the increase of the load ratio adds an extra weight to the high-speed train, so that the train has to consume more energy to overcome the additional resistance force generated by the extra weight. On the other hand, the given transportation tasks can be accomplished by the fewer trains than before, which will have all trains move energy-efficiently. That is to say, the amount of global energy consumption can be reduced by the improvement of energy efficiency. It indicates that the concept of “energy efficiency” fully reflects the efficiency of using energy resource.

Figure 10 still indicates that, for a given route, reducing the number of train stops can have the train move a

Fig. 9 Percentage of train non-regenerative braking energy consumption in the total energy consumption of high-speed train operation under different inter-station distance

Fig. 10 The operational energy efficiency of high-speed train under different inter-station distance

greater distance between two successive stops, thus the kinetic energy of high-speed train can be more fully utilized through longer coasting. It reveals the importance of the highly efficient train operation scheme completed in the stage of transportation planning to energy efficiency improvement and energy consumption reduction.

4 Conclusions and future developments

Energy efficiency is a better index than energy consumption to evaluate the behavior and performance of railway transportation system, and the energy-saving operation of high-speed train can be well realized by the improvement of its energy efficiency. In this paper, following the development trend of the high integration of train control and transportation organization, we first build the energy efficiency model of high-speed train operation to refine the intrinsic laws. Finally, the simulation is carried out to analyze the comprehensive effect of train light-weighting, train control, and load ratio on the operational energy

efficiency of high-speed train. The percentage of the non-regenerative braking energy consumption in the total energy consumption of high-speed train operation is also given, so that the maximum space of regenerative energy recycle and utilization can be calculated. In the future, our research group will mainly focus on the following aspects:

1. The optimization of railway transportation organization for the operational energy efficiency improvement of all in-service high-speed trains.

The increasing of the load ratio, especially in transportation off-season, can help improve the operational energy efficiency of high-speed train(s). However, the increase of load ratio depends on the space–time optimization of railway transportation organization during its whole life cycle.

2. The energy consumption of station infrastructure for train operation, as well as the energy consumption of station and train environment systems are not considered in this paper. But they are important aspects that

cannot be ignored in improving the energy efficiency of high-speed railway transportation system [25]. The further research of these aspects needs to be strengthened.

3. The integration of energy efficiency improvement and rapid movement of high-speed train.

As far as the micro-behavior of high-speed train between two successive stations is concerned, the rapidity of train operation increases with the energy consumption because the time extension of train cruising is always accompanied by the reduction of train coasting distance. But, at the macro-level, the optimization of train routes, the reduction of stops and dwell time, and the permitted maximum speed of train operation, as the necessary constraints of improving the global energy efficiency, can increase or ensure the rapidity of train operation.

4. The recycle, storage, management, and utilization of regenerative energy and its integration with the coasting operation of high-speed train.

The kinetic energy of train operation can be utilized through train coasting or regenerative braking, but the kinetic energy of the train decreases with the extension of its coasting time, as a result, the available regenerative energy will be less and less correspondingly. The inter-station distance needs to be comprehensively considered in the integration of train coasting and regenerative braking for energy efficiency improvement.

5. In future, the multi-agent system and virtual reality technology can be used to establish an energy efficiency simulation platform to obtain the systematic solutions of global energy efficiency improvement. In the process of establishing the energy efficiency simulation platform, the huge potential hidden in large sets of data can be fully exploited by using the advanced intelligent data-driven approaches to improve energy efficiency, reliability, and feasibility of high-speed railway transportation systems [26].

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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