

Energy Consumption and Running Time Estimation for Train Section Speed Limit Based on Python Simulation

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Abstract

Speed-limited operation is a common scenario in high-speed rail line maintenance and emergency response to unexpected conditions. Under such constraints, fluctuations in train energy consumption and deviations in travel time directly affect the balance between energy efficiency and punctual operations, significantly influencing the quality and efficiency of railway transportation. To investigate the patterns of energy consumption and travel time under various speed-limiting scenarios and achieve optimal coordination between energy efficiency and on-time performance, this study establishes a simulation model for calculating high-speed train energy consumption and travel duration using Python as the platform and PyCharm as the development environment. This research clarifies the matching patterns between energy consumption and punctuality under multiple operating conditions, providing data support and theoretical reference for optimizing energy-efficient and punctual operations and refining operational planning under speed restrictions.

Keywords

High-Speed Train; Speed-Limited Condition; Energy Consumption Characteristics; On-Time Rate; Python simulation

Introduction

The birth and development of China's high-speed rail were rooted in long-term technological exploration and crucial strategic decisions. As early as the beginning of the 20th century, pioneers in China proposed the concept of high-speed railways. However, systematic research and practice began in the 1980s. At that time, in the face of the severe reality of mixed passenger and freight transportation, slow speed, and tight transportation capacity, traditional railways had become a bottleneck restricting social and economic development [1]. Therefore, the state organized forces to conduct comprehensive technical research and exploration, and examined advanced foreign systems, officially initiating the early exploration of high-speed

railways.

To fundamentally alleviate the problems of insufficient railway transportation capacity, low operating speed, and prominent contradictions in mixed passenger and freight transportation, and to enable the railway system to better adapt to the rapid social and economic development after the reform and opening up, China began to actively plan and continuously promote research, development, and construction of high-speed railways since the 1980s [2]. China's high-speed rail has thus experienced a glorious innovation journey from nothing to something, from exploration to breakthrough, from importing and manufacturing to independent creation. In 2008, China built the first high-speed railway with complete independent intellectual property rights and a technical level reaching international standards, the Beijing-Tianjin Intercity High-Speed Railway, with a maximum operating speed of 394.3 kilometers per hour, marking China's official entry into the era of high-speed rail. By the end of 2015, China's total high-speed railway operating mileage had ranked first in the world; by 2017, the "Four Vertical and Four Horizontal" high-speed railway network was fully completed, and the even more ambitious "Eight Vertical and Eight Horizontal" main network construction was initiated. By the end of 2018, the national high-speed railway operating mileage had reached 29,000 kilometers, exceeding two-thirds of the world's total high-speed rail mileage; by 2021, the operating mileage had further exceeded 40,000 kilometers; and by the end of 2023, this figure had exceeded 45,000 kilometers, with cumulative passenger transportation exceeding 2.1 billion trips. China's high-speed rail has continued to maintain its world-leading position [3].

During the daily operation of high-speed railways, adverse weather conditions, geological disasters, and equipment failures are the main causes of temporary speed restrictions on the lines. Such incidents are highly uncertain and unpredictable, often forcing trains to temporarily reduce their speed to ensure absolute safety. However, this directly impacts the core performance indicators of high-speed rail transportation - the punctuality rate of trains. Speed restrictions, as a necessary passive safety response mechanism, the resulting chain effects of time-space compression and disruption of the operation schedule are not negligible. In mild cases, it will cause single train delays, affecting passengers' travel experience and schedules; in severe cases, it will lead to the interruption of the travel plans of a large number of transfer passengers, greatly weakening the reliability and accessibility of railway services, and even triggering a chain-like chaos and paralysis of the entire network operation order. Therefore, in the face of speed restriction situations caused by emergencies, how to quickly formulate a scientific, efficient, and resilient train operation adjustment plan to minimize the negative impact of safety speed restrictions on punctuality has become a key issue for ensuring the quality of high-speed rail transportation and enhancing the system's dynamic recovery ability, with significant practical significance [4].

However, as the railway network continues to densify and the transportation volume continues to increase, the issue of energy-saving operation of high-speed railways has become increasingly prominent. Especially on high-density operating lines such as Beijing-Shanghai and Shanghai-Nanjing, trains often need to frequently start and stop, and the station spacing is relatively short. Under such line conditions, simply relying on increasing the maximum speed to compress travel time has become increasingly ineffective, because as soon as the train reaches the top speed and starts to decelerate to enter the station, it has to sacrifice just a few minutes to pay a huge energy cost - the increase in speed will lead to a quadratic increase in air resistance, meaning that energy consumption will increase exponentially[5]. This is like driving in a crowded urban area, frequent starting and braking will not only be dangerous but also extremely fuel-consuming; conversely, a smooth driving habit can significantly save fuel. Therefore, on these "bus-like" operating lines, our focus should shift from "how fast to run" to "how to run smartly", that is, through dynamic optimization of acceleration, cruise, and coasting strategies, to significantly reduce traction energy consumption while basically not losing the punctuality rate. The optimization of this operation strategy is more in line with current practical significance and economic benefits than the extreme exploitation of hardware speed.

1. Introduction to the Simulation Background

This paper is based on the basic theories of the dynamic mechanics and energy consumption calculation of high-speed trains. It uses the Python language to independently develop a simulation calculation program on the PyCharm platform, builds a simulation model for the operation of high-speed trains under limited speed conditions, and realizes precise calculation of the energy consumption and running time of the train under different operation scenarios. Compared with traditional single-condition simulation tools, this self-programming model can flexibly adapt to different combinations of running mileage and speed limit levels, and has the advantages of adjustable parameters, strong expansion of conditions, and high data output accuracy. It can meet the requirements for comparing and analyzing the energy consumption and punctuality characteristics of trains in multiple scenarios.

All simulation examples adopt unified basic parameters of the train and line environment to ensure the uniqueness of variables. Only by changing the section mileage and speed limit standards, the influence of different condition parameters on the energy consumption level and running time of the train can be accurately compared. During the simulation process, the program automatically records, counts, and outputs the energy consumption data and total running time of each group of conditions, providing reliable simulation data support for subsequent analysis of the influence laws of mileage and speed limit on the energy-saving characteristics and punctuality of trains, as well as the collaborative matching and

optimization research of energy consumption and punctuality rate.

2. Construction of the Energy Consumption Calculation Model for Train Operation

This paper takes the CRH2 EMU as the research object. Based on the train traction dynamics, running resistance theory and energy transfer efficiency, an integrated calculation model for train operation energy consumption and time under multiple operating conditions is constructed. This provides theoretical support for the subsequent analysis of energy consumption and punctuality rate matching under different speed limit combinations.

2.1. Basic Parameters and Operating Characteristics of the Train

The key technical parameters of the CRH2 EMU are as follows: The train's total weight is 408.5 tons, the total traction power is 4800 kW, provided by 16 traction motors, with each motor having a power of 300 kW; the maximum operating speed is 350 km/h, the constant power conversion point speed is 125 km/h, and the starting acceleration is 0.406 m/s^2 ; the vehicle dimensions are a width of 3.38 m, a height of 3.7 m, and a length of 201 m. The traction drive system adopts the AC-DC-AC AC-DC-AC direct current-DC-AC direct current transmission method, with the traction motor being a three-phase asynchronous motor, and the control strategy combining field-oriented control (FOC) and space vector pulse width modulation (SVPWM). The train operation process is divided into three core modes: traction, constant speed, and braking. In the coasting condition, the deceleration is set at -0.08 m/s^2 , and in the braking condition, the energy recovery efficiency is set at 30%[6].

2.2. Calculation Model of Running Resistance

The total running resistance of the train is divided into two categories: basic resistance and additional resistance. This study focuses on the straight-line track condition and mainly calculates the basic resistance of the train.

The unit basic resistance is determined by three linear and quadratic term parameters. The formula includes fixed coefficients a , b , and c , as well as the train's operating speed v . Among them, coefficient a is set at 8.63, coefficient b at 0.07295, and coefficient c at 0.00112. The unit of speed v is km/h. Multiplying the unit basic resistance by the train's total mass M gives the overall total basic resistance W_0 .

When the train's operating speed exceeds 50 km/h, the air resistance accounts for 75% to 95% of the total resistance, and it continues to increase as the operating speed rises. Thus, the accuracy of the resistance calculation directly determines the reliability of the subsequent train energy consumption calculation results (as shown in Figure 1).

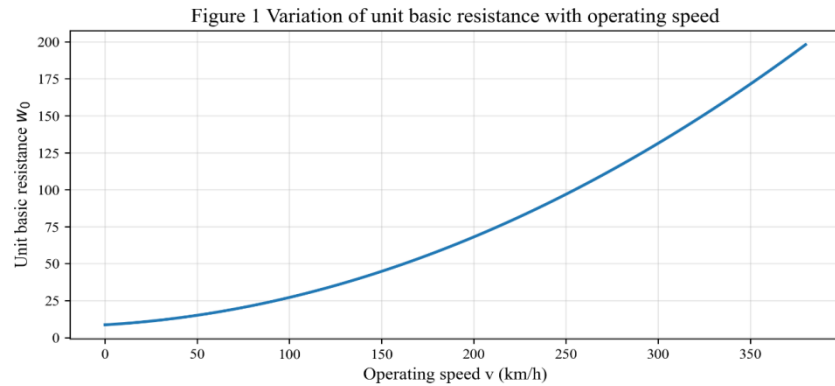


Figure 1. Variation of unit basic resistance with operating speed

2.3. Calculation Method for Traction Energy Consumption and Running Time

The total energy consumption of the train throughout the entire journey takes into account the energy consumed by overcoming resistance during each operating stage, the energy consumed by the train's acceleration, and the energy recovered during braking. This is then converted based on the overall energy conversion efficiency of the system[7].

In this study, n is defined as the total number of stages for the train's operation, W_{res} represents the energy consumed by the train overcoming the running resistance in a single stage, W_{accel} represents the energy consumed by the train during acceleration in a single stage, W_{rec} represents the energy recovered in a single braking stage, and η_{total} is the comprehensive energy conversion efficiency of the entire transmission system. In this calculation, η_{total} is set at 0.9212. This parameter combines the efficiency of components such as gear transmission and traction motors, and incorporates performance coefficients and speed correction coefficients to ensure calculation accuracy(as shown in Figure 2).

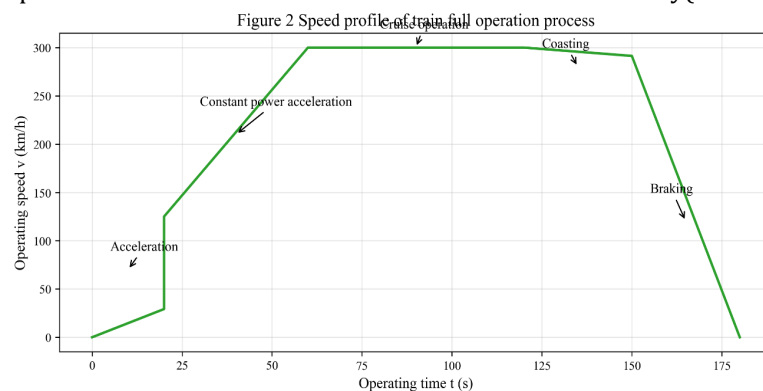


Figure 2. Speed profile of train full operation process

Based on the traction characteristics of the CRH2 EMU, different acceleration control methods are adopted for different operating intervals. When the train's operating

speed is within the range of 0 to 125 km/h, the train operates in a constant traction force mode, with a fixed starting acceleration of 0.406 m/s^2 ; when the speed is within the range of 125 to 250 km/h or 250 to 350 km/h, the train switches to a constant power mode, with the acceleration gradually decreasing as the speed increases; in a constant-speed running state, the train's acceleration is 0, and it only needs to continuously overcome the line resistance; in coasting conditions, the train has no traction power output, and decelerates at a fixed deceleration rate; for different speed intervals, the braking conditions are also matched with corresponding deceleration parameters.

In the study, the resistance work and acceleration work in each operating stage are solved separately. The calculation rules for the entire journey are unified and can meet the requirements of multi-condition simulation.

2.4. Brake Energy Recovery and Engineering Simplification Model

This study divides the brake energy recovery standards according to the operating speed intervals and sets two sets of energy recovery coefficients β (as shown in Figure 3). When the train's operating speed is below 250 km/h, the recovery coefficient β is set at 0.3; when the operating speed is greater than or equal to 250 km/h, the recovery coefficient β is set at 0.25. The recoverable energy during the braking stage is obtained by converting the corresponding recovery coefficient in the interval and the kinetic energy generated during braking. This setting conforms to the law in actual operation of high-speed trains that the braking energy recovery efficiency decreases in high-speed conditions[8].

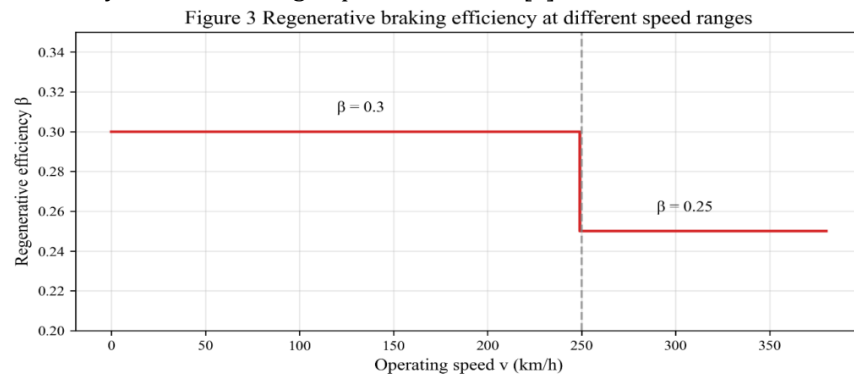


Figure 3. Regenerative braking efficiency at different speed ranges

Combining the resistance energy consumption, acceleration energy consumption, and braking recovery energy, this study obtains a simplified calculation method suitable for engineering calculations. This calculation method is highly versatile and can be directly applied to the simulation operation of various combinations of line mileage and different speed limit standards. It can provide a complete calculation basis for the analysis of energy consumption and operation time for 50 km and 100 km line sections, along with speed limit conditions of 200 km/h, 300 km/h, and 380

km/h.

3. Simulation Result Analysis

3.1. The Regulation Law of Speed Limit Levels on Energy Consumption and On-time Rate

Under the condition of fixed running mileage, the change of train speed limit levels plays a decisive role in the energy consumption level and the on-time rate, and completely presents the game feature of "low energy consumption, low on-time rate, high on-time rate, high energy consumption" (as shown in Figure 4). When the train operates at a low speed limit of 200km/h, the overall running speed is relatively low, and the air resistance and mechanical resistance during operation are significantly reduced. The traction system does not need to continuously output high-power power, and the overall traction energy consumption is significantly reduced, with the most prominent energy-saving effect. However, the low-speed speed limit mode will greatly prolong the total running time of the train, deviating significantly from the standard running time of the line, and easily causing train delays, significantly reducing the on-time rate of train operation[9].

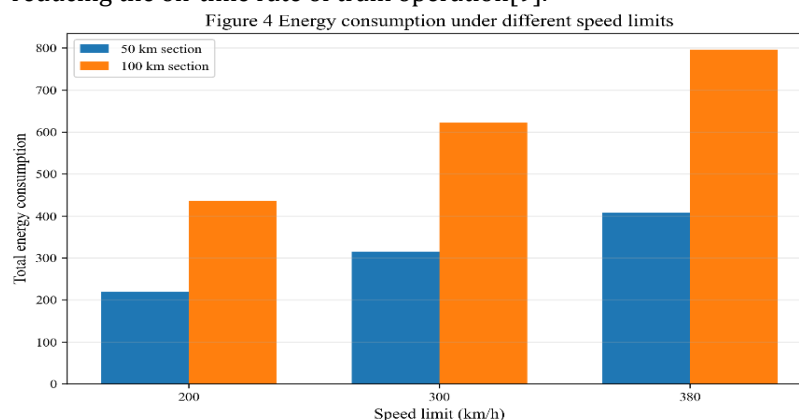


Figure 4. Energy consumption under different speed limits

As the speed limit levels gradually increase to 300km/h and 380km/h, the average running speed of the train significantly increases, and the total running time continuously shortens. It can effectively match the standard running schedule of the line, basically guaranteeing the on-time operation of the train, and meeting the core requirements of efficient operation of high-speed railways. However, the speed increase will cause the running resistance of the train to grow non-linearly, the traction system needs to output greater power to overcome the running resistance, and the efficiency of braking energy recovery slightly decreases under high-speed conditions, resulting in further energy loss, ultimately leading to a significant increase in the overall running energy consumption of the train. Thus, a single adjustment of speed limit parameters cannot simultaneously achieve the dual goals of energy saving and on-time operation. The optimization of speed limit levels is

essentially a process of balancing energy consumption and on-time rate(as shown in Figure 5).

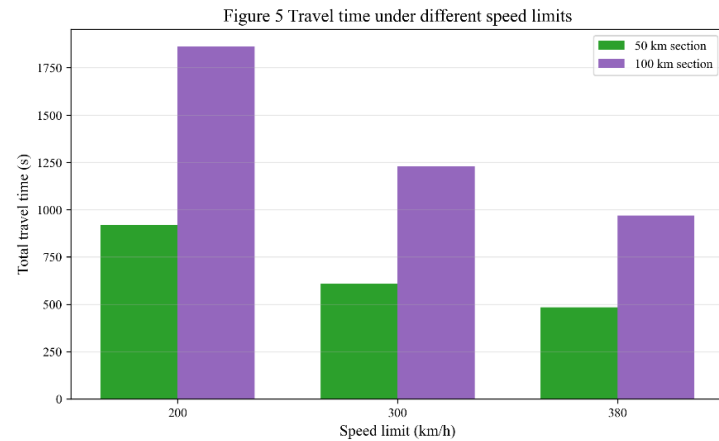


Figure 5. Travel time under different speed limits

3.2. The Regulation Law of Running Mileage on the Matching Characteristics of Energy Consumption and On-time Rate

The length of the running mileage will further amplify the game gap between energy consumption and on-time rate under the speed limit conditions, and form a significant regulatory effect on the matching characteristics of the two. By comparing the simulation results of the 50km short mileage section and the 100km long mileage section, it can be found that in the short mileage condition, the energy difference and running time difference brought by different speed limit levels are relatively small, the conflict between energy consumption and on-time rate is relatively weak, the energy-saving loss and on-time loss caused by a small speed limit are at a relatively low level, and the adaptability of the condition is relatively flexible(as shown in Figure 6).

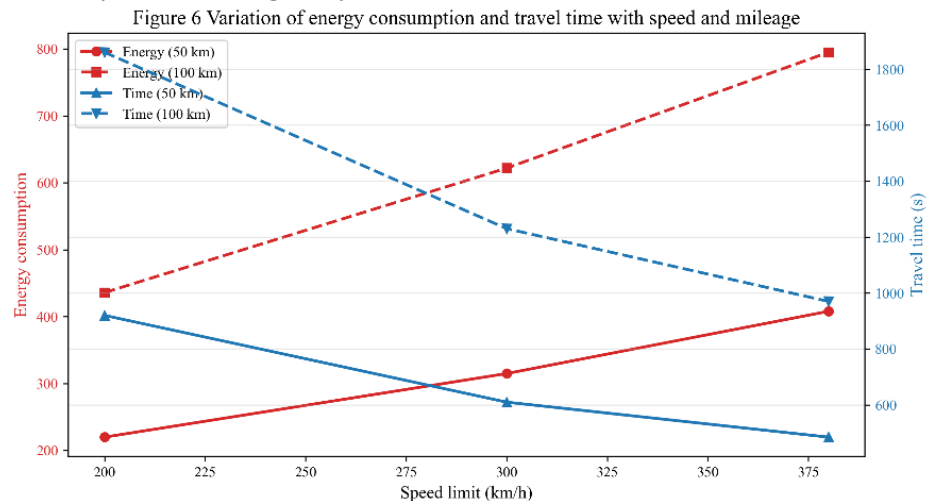


Figure 6. Variation of energy consumption and travel time with speed and mileage

In the 100km long mileage operation scenario, the positive and negative effects brought by the speed limit are continuously accumulated and amplified. In the low-speed limit condition, long-distance low-speed operation will significantly improve the energy-saving effect, but the total delay time increases significantly, and the problem of on-time rate loss becomes more prominent; in the high-speed limit condition, although it can ensure the on-time operation of the entire journey and shorten the running time to the greatest extent, the resistance loss caused by long-distance high-speed operation continues to accumulate, the energy consumption increase is much higher than that in the short mileage condition, and the energy waste problem becomes more obvious. This law indicates that the longer the mileage, the more significant the balancing relationship between energy consumption and on-time rate is. In actual operation, long-distance lines need to precisely match the speed limit strategy to achieve the optimal balance of energy-saving benefits and on-time operation[10].

4. Conclusions

Based on the Python simulation platform, this paper established a calculation model for the energy consumption of high-speed trains. For two typical line sections of 50 km and 100 km, multiple simulation calculations were conducted at speed limits of 200 km/h, 300 km/h, and 380 km/h. The study systematically explored the influence patterns of speed limit levels and running mileage on the energy consumption of trains and the punctuality rate of operation. The research results show that in the scenario of speed-limited operation of high-speed trains, the energy consumption level and punctuality rate exhibit a significant game relationship. Reducing the train's running speed can effectively reduce running resistance, significantly lower the overall traction energy consumption, and achieve the effect of energy conservation operation. However, it will continuously prolong the total running time and deviate from the standard operation time, directly causing a decrease in punctuality rate; conversely, increasing the running speed can compress the running time, ensure the punctual operation of the train, and meet the requirements of efficient operation of high-speed railways. However, due to the nonlinear increase in resistance, the energy consumption will increase significantly. By comparing different mileage scenarios, it can be observed that the mileage of the route further amplifies the balancing contradiction between the two. Compared to short mileage sections, the energy consumption changes and time delay effects brought about by the speed limit strategy on long-distance routes accumulate continuously, making the conflict between energy saving and punctuality more prominent. The simulation model constructed in this study is convenient to operate and has strong applicability. It can efficiently complete numerical calculations for multiple scenarios and the simulation data and changing patterns are in line with the actual operation characteristics of the train. The related research results can

provide certain theoretical references and data support for the temporary speed limit control of high-speed trains, the formulation of operation plans, and the coordinated optimization of energy saving and punctuality. In actual operation management, speed limit standards should be comprehensively formulated based on actual conditions such as route length, transportation tasks, and transportation organization, and a reasonable balance point should be found between energy saving and efficiency and punctuality.

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