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BASIS FOR SELECTING THE CONFIGURATION OF HIGH-SPEED DISTRIBUTED-POWER TRAINS

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Abstract. In conventional railways, when utilizing concentrated power, the train configuration is determined based on the locomotive's power and the types of cars used in the train. The total train mass must first be defined for a given limiting gradient. Based on the total train mass and the load and tare weight of the cars, the specific train composition (the number of cars) is determined. For urban rail and high-speed trains, which primarily serve passenger transportation, a different approach is required, particularly for distributed-power trains. In such cases, basic resistance is not calculated separately for each car but for the entire train. The number of cars is typically structured into fixed modules, requiring an assessment of how many motor cars should be included within a given train configuration. To address this issue, the article presents the basis for selecting the configuration of high-speed trains with distributed traction. Based on this, configurations for several different options were selected, and the feasibility of utilizing kinetic energy to overcome limiting gradients along the line was also verified.

Keywords: train configuration, distributed power, high-speed train, train resistance, motor car.

1. INTRODUCTION

In many countries, urban railway transportation systems have a long-established history and continue to develop. Additionally, 22 countries have rapidly expanding high-speed railway networks with increasing scale and advancing technology.

Meanwhile, in Vietnam, only three urban railway lines have been put into operation, and the high-speed railway is still at the pre-feasibility study stage. Therefore, for Vietnam, both urban railway and high-speed railway transportation remain entirely new fields, with no prior experience or precedent in operational organization.

Currently, in conventional railways in Vietnam and some countries such as Russia and China, when utilizing concentrated power for passenger and freight trains, the train configuration is determined based on the locomotive's power and the types of cars used in the train. To determine the train composition, the total train mass must first be identified for a given limiting gradient, corresponding to the speed and the locomotive's continuous tractive effort.

The total train mass is determined as follows [1-6]:

$$Q = \frac{F_{tr} - P(\omega_o^{'} + i_c)g}{(\omega_o^{''} + i_c)g}\text{, tons} \tag{1}$$

Where:

Q - Total train mass, tons;

F_{tr} - Calculated tractive force (wheel rim tractive force) of the locomotive, N;

P - Calculated mass of the locomotive, tons;

$\omega_0^{'}$ and $\omega_0^{''}$ - Unit basic resistance of the locomotive and cars at the calculated speed, N/kN;

i_c - Calculated gradient or limiting (equivalent) gradient of the railway line, ‰;

g - Gravitational acceleration, g = 9.81 m/s^2.

This means that the train composition primarily depends on the locomotive’s power and the types of cars used, which can vary significantly.

Meanwhile, for urban rail and high-speed trains, which primarily serve passenger transportation, a different approach is required, particularly for distributed-power trains. In this case, train resistance is not calculated separately for each car but for the entire train. The train composition, also referred to as the train configuration (i.e., the number of cars in the train), is typically structured into fixed modules. In urban rail systems, train configurations commonly consist of three, four, six, or eight cars. For high-speed rail, train configurations typically include eight, ten, twelve, or sixteen cars. The key issue is determining the appropriate number of motor cars within a given train configuration.

To address this issue, this article presents the basis for selecting the configuration of high-speed distributed-power trains.

2. OVERVIEW OF RESISTANCE ACTING ON HIGH-SPEED TRAINS

The types of resistance acting on high-speed trains can be classified into three main categories:

2.1. Rolling resistance

Rolling resistance depends on the rolling resistance coefficient, the train weight, and the characteristics of the contact surface between the wheels and the rails [6,7]:

$$F_r = \mu mg \text{, N} \tag{2}$$

Where:

μ - Rolling resistance coefficient (typically around 0.001 to 0.005 for high-speed trains);

m - Train mass, kg;

g - Gravitational acceleration (9.81 m/s^2).

2.2. Aerodynamic drag

Aerodynamic drag depends on the aerodynamic shape, air density, and the train's travel speed [7,8]:

$$F_d = \frac{1}{2}\rho C_d A v^2 \text{, N} \tag{3}$$

Where:

ρ - The air density is typically around 1.225 kg/m^3 under standard conditions;

C_d = 0.3 - The aerodynamic drag coefficient, which depends on the train design, generally ranges from 0.2 to 0.4;

A - The frontal cross-sectional area of the train, m^2 (approximately 10 -12 m^2);

v - The train speed, m/s^2.

2.3. Gradient resistance

When a train moves uphill or downhill, the gradient resistance depends on the track inclination angle [7,8]:

$$F_g = mg\sin\theta \text{, N} \tag{4}$$

Where:

θ - The gradient inclination angle (in radians) can be calculated from the gradient percentage as tan^{-1} (gradient 1/100).

2.4. Curvature resistance

This resistance is associated with the centrifugal force when the train moves through a curved track section [8, 9]:

$$F_c = \frac{mv^2}{R} \text{, N} \tag{5}$$

Where:

R - Curve radius of the track section, m;

m - Train mass, kg;

v - Train speed, m/s.

Thus, the combined resistance of the train in an open environment is determined as follows:

$$F_{total} = F_r + F_d + F_g + F_c \text{, N} \tag{6}$$

These resistances act simultaneously on high-speed trains and directly affect performance, speed, and energy consumption. Therefore, minimizing these resistances, especially aerodynamic resistance, is a crucial factor in the design and operation of high-speed trains..

2.5. Tunnel resistance of high-speed trains

Tunnel resistance is a significant factor affecting the performance of high-speed trains when traveling through tunnels. This resistance primarily arises from the aerodynamic interaction between the train and the tunnel walls, leading to pressure variations and additional resistance.

Tunnel resistance can be calculated using the following equation [10]:

$$F_t = \frac{1}{2}\rho C_t A v^2 \text{, N} \tag{7}$$

Where:

ρ - The air density is typically around 1.225 kg/m^3 under standard conditions;

C_t - The aerodynamic drag coefficient in tunnels (depends on the tunnel and train dimensions, usually higher than the coefficient in open air);

A - The frontal cross-sectional area of the train, m^2 (10 - 12 m^2);

v - The train speed, m/s^2.

2.5.1. Approximate equation for calculating the aerodynamic drag coefficient in tunnels C_t

The aerodynamic drag coefficient in tunnels C_t depends on multiple factors, including [10]:

- The ratio of the train's cross-sectional area to the tunnel's cross-sectional area $\frac{A}{A_t}$;
- Train shape (nose and body design);
- Tunnel shape and dimensions;
- Tunnel length (longer tunnels result in higher air pressure);
- Train speed.

The aerodynamic drag coefficient in tunnels C_t is significantly higher than in open space due to the confined environment, which increases air pressure and resistance. The approximate equation for C_t is given as follows [10]:

$$C_t = C_d\left(1 + \frac{A}{A_t}\right) \tag{8}$$

Where:

A_t - Cross-sectional area of the tunnel, m^2;

A - Frontal projected area of the train, m^2;

$\frac{A}{A_t}$ - Train-to-tunnel area ratio: the larger the ratio, the higher the resistance.

2.5.2. Total resistance when the train passes through a tunnel

The total resistance of the train when traveling through a tunnel consists of:

$$F_{total} = F_r + F_g + F_d + F_t \text{, N} \tag{9}$$

Where: F_t can account for a significant portion of the overall resistance when the train operates at high speeds in a narrow tunnel.

If the tunnel has a considerable length, aerodynamic pressure can generate additional shock forces when the train enters and exits the tunnel.

2.5.3. Typical values of C_t [10]

In an open environment (without tunnels), the aerodynamic resistance coefficient of high-speed trains typically ranges: C_d = 0.2 – 0.4.

When a train operates in a tunnel, the aerodynamic resistance coefficient increases significantly due to the confined space and the compressed aerodynamic effect, reaching values of: C_t = 1.5 – 3.5.

This coefficient depends on the ratio between the train's cross-sectional area and the tunnel's cross-sectional area $\frac{A}{A_t}$:

If $\frac{A}{A_t} \leq 0.2$, then $C_t \approx 1.5 - 2.0$.

If $0.2 < \frac{A}{A_t} \leq 0.3$, then $C_t \approx 2.0 - 3.0$.

If $\frac{A}{A_t} > 0.3$, then $C_t > 2.0$.

The aerodynamic resistance coefficients of several high-speed trains in tunnels are presented in Table 1 [9,10].

Table 1. Aerodynamic drag coefficients in tunnels for selected high-speed trains.

No.	Train type	Aerodynamic drag coefficient
1	Shinkansen N700 (Japan)	1.8 – 2.5
2	TGV Duplex (France)	2.0 – 2.8
3	ICE 3 (Germany)	1.7 – 2.4
4	CRH380A (China)	2.0 – 3.0

Thus, C_t typically ranges from 1.5 to 3.5, significantly higher than C_d in environments without tunnels. This value depends on train design, the ratio of train cross-sectional area to tunnel cross-sectional area, and operating speed.

Modern high-speed trains, such as the Shinkansen N700, TGV, and ICE, feature specialized aerodynamic designs to minimize tunnel resistance.

3. BASIS FOR VERIFYING THE ABILITY OF A HIGH-SPEED TRAIN TO USE KINETIC ENERGY FOR GRADIENT ASCENT

To verify whether a train can use its kinetic energy to ascend a gradient, it is necessary to calculate the energy required to overcome the incline and compare it with the train's available kinetic energy.

3.1. Kinetic energy of the train

The kinetic energy of a train moving at velocity v is given by the equation [8,10]:

$$E_k = \frac{1}{2} m v^2 \tag{10}$$

Where:

m - Train mass, kg;

v - Train velocity, m/s.

3.2. Work done against gravity

When a train moves uphill, the work required to overcome the gravitational resistance is given by [8,10]:

$$A_g = F_g L \tag{11}$$

$$F_g = mg \sin\theta \tag{12}$$

$$A_g = mgL \sin\theta \tag{13}$$

Where:

F_g - Gravitational resistance force, N;

m - Train mass, kg;

g - Gravitational acceleration, 9.81 m/s^2;

L - Length of the gradient section, m;

θ - Track inclination angle, rad.

3.3. Verification of kinetic energy utilization for gradient ascent

To verify whether a train can ascend a gradient using only its kinetic energy, we compare its current kinetic energy with the work required to overcome gravity. The condition for successful ascent is [10]:

$$E_k \geq A_g \tag{14}$$

Substituting the equations:

$$\frac{1}{2}mv^2 \geq mgL\sin\theta \tag{15}$$

Canceling m (since $m \neq 0$):

$$\frac{1}{2}v^2 \geq gL\sin\theta \tag{16}$$

Or:

$$v^2 \geq 2gL\sin\theta \tag{17}$$

Thus, the verification condition is:

$$v \geq \sqrt{2gL\sin\theta}\text{, m/s} \tag{18}$$

If the train's velocity v is sufficiently high (the kinetic energy is large enough), the train can ascend the gradient using kinetic energy alone, without additional traction force from the motor. However, if the train's velocity is lower than the calculated threshold, it will not be able to ascend the gradient using kinetic energy alone and will require additional traction from the motor to complete the climb.

4. BASIS FOR SELECTING THE CONFIGURATION OF HIGH-SPEED TRAINS

4.1. Key differences between high-speed trains and conventional trains

The selection of the composition (configuration) of high-speed trains differs fundamentally from that of conventional trains due to requirements related to speed, safety, operational efficiency, and economic factors. Some key differences between high-speed trains and conventional trains are presented in Table 2.

Table 2. Key differences between high-speed trains and conventional trains.

No.	Parameters	High-Speed trains	Conventional trains
1	Power system	Primarily utilizes a **distributed power system**, where multiple motor cars are equipped with electric motors, ensuring evenly distributed traction, rapid acceleration, and reduced track stress.	Mainly employs a **concentrated power system**, where a single locomotive provides traction for the entire train, suitable for lower speeds.
2	Aerodynamic design	Features an aerodynamic nose design to reduce air resistance, enhance operational efficiency, and minimize noise.	Less emphasis on aerodynamics due to lower speeds, resulting in simpler train shapes.

No.	Parameters	High-Speed trains	Conventional trains
3	Wheel and suspension system	Uses advanced wheel and suspension systems to reduce vibrations and ensure stability at high speeds (above 250 km/h).	Simpler suspension system, designed for lower-speed operations.
4	Braking system	Incorporates multiple advanced braking technologies, such **as rheostatic braking, pneumatic braking, electromagnetic braking, and disc braking,** ensuring safe deceleration at very high speeds.	Primarily relies on **pneumatic braking and disc braking** with lower braking capacity.
5	Car body structure and materials	Constructed using lightweight, high-strength materials such as aluminum alloys and composites to reduce weight and improve operational efficiency.	Uses heavier materials (steel, traditional alloys) as weight reduction is not a primary concern.
6	Electrical system and power supply	Operates using high-voltage overhead electric power (AC 25kV or DC 1.5–3kV) to provide sufficient power output.	Can run on **diesel locomotives** or **lower voltage** electrical systems, requiring less robust power infrastructure than high-speed trains.
7	Control and safety systems	Equipped with advanced control and automation systems, minimizing human intervention and ensuring operational safety.	Typically features simpler control systems, relying more on manual operation.
8	Train configuration	Typically operates as a **unit train**, with integrated and standardized cars that are difficult to modify.	Allows for flexible composition, enabling changes in the number of cars or locomotive replacement based on operational needs.
9	Operating environment	Requires dedicated infrastructure, specialized tracks, optimized gradients, and curve radius to ensure safe operation.	Can operate on mixed-use infrastructure with fewer stringent track conditions.

The selection of high-speed train configurations involves various approaches, considering factors such as aerodynamics, dynamics, safety systems, and materials to ensure optimal operational performance. In the absence of sufficient information on these specific technical parameters, a generalized theoretical approach can be applied as follows.

4.2. Illustrative example of high-speed train configuration selection

4.2.1. Calculation parameters

Consider a high-speed railway line with a limiting gradient of i_c = 25‰ and no curves. The train configuration needs to be selected based on the following initial parameters:

- Number of cars in the train n_{car} = 8;

- Axle load of a car q_0 = 16 tons/axle;

- Number of axles per car n_{axle} = 4;

- Power of a single traction motor: P_m = 400 kW.

The objective is to determine the required number of motor cars to enable the train to operate on a 25‰ gradient in open space at speeds of 150 km/h, 125 km/h, and 100 km/h.

4.2.2. Calculation results

The calculations are based on Eq. (2), (3), and (4). The results are summarized in Table 3.

Table 3. Calculation results for train configuration selection.

No.	Calculation Parameters	Option 1	Option 2	Option 3
1	Number of cars in the train, n_{car}	8	8	8
2	Axle load of a car q_0, tons/axle	16	16	16
3	Number of axles per car n_{axle}	4	4	4
4	Mass of one car $m_{car,}$ tons	64	64	64
5	Total train mass m_{train}, tons	512	512	512
6	Limiting gradient i_c, °/oo	25	25	25
7	Train speed on the limiting gradient v, km/h (m/s)	150 (41.67)	150 (41.67)	150 (41.67)
8	Gradient resistance, N $F_g = m_{train}.g.\sin(\theta)$	125,376	125,376	125,376
9	$\sin(\theta) = \tan(\theta)$	0.025	0.025	0.025
10	Aerodynamic resistance, N $F_d = 1/2.\rho.C_d.A.v^2$	84,818.33	84,818.33	84,818.33
11	Air density ρ, kg/m^3	1.225	1.225	1.225
12	Aerodynamic drag coefficient C_d	0.3	0.3	0.3
13	Train frontal area A, m^2	12	12	12
14	Rolling resistance,N $F_r = \mu.m_{train}.g$	10,045.44	10,045.44	10,045.44
15	Rolling friction coefficient, μ	0.002	0.002	0.002
16	Total resistance, N $F_{total} = F_g + F_d + F_r$	220,239.77	197,030.66	175,056.31
17	Total required power, kW $P_{total} = F_{total}.v$	9.18 MW (9180 kW)	6.83 MW (6830 kW)	4.86 MW (4860 kW)
18	Power of one traction motor P_m, kW	400	400	400
19	Power of one motor car $P_{m.car}$, kW	1600	1600	1600
20	Number of motor cars, $n_{m.car} = P_{total}/P_{car}$	6	5	4

4.2.3. Selection of train configuration options

The proposed train configurations (Fig. 1 - 3) are determined based on the calculation parameters presented in Table 3. For each configuration, the corresponding speed on a limiting gradient (25‰) is 150, 125, and 100 km/h, respectively. For each option, the arrangement of power cars and trailer cars can vary depending on the design and operational requirements of the train. In each proposed configuration, only the two most common car arrangement combinations are presented. Where Tc is a trailer car with a driver's cab; T is a trailer car without a driver's cab; Mc is a motor car with a driver's cab; M is a motor car without a driver's cab.

Several train configurations can follow Option 1:

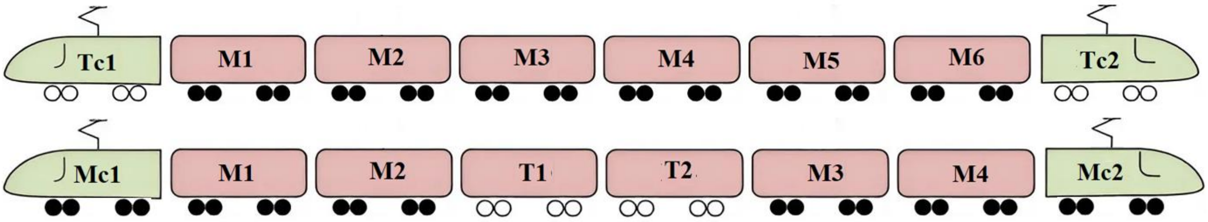

Figure 1. Diagram of a high-speed train configuration with 6 motor cars out of 8.

Several train configurations can follow Option 2:

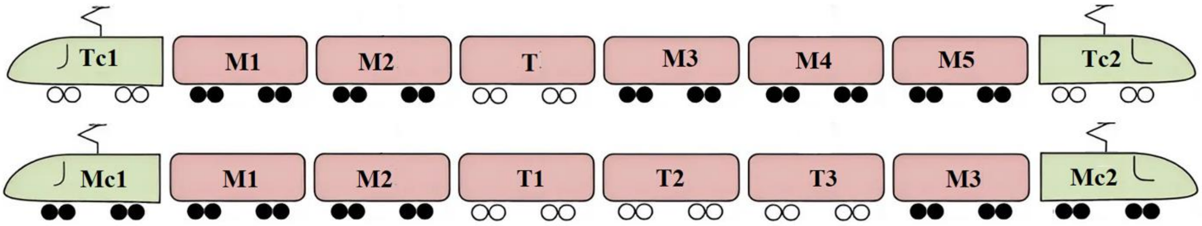

Figure 2. Diagram of a high-speed train configuration with 5 motor cars out of 8.

Several train configurations can follow Option 3:

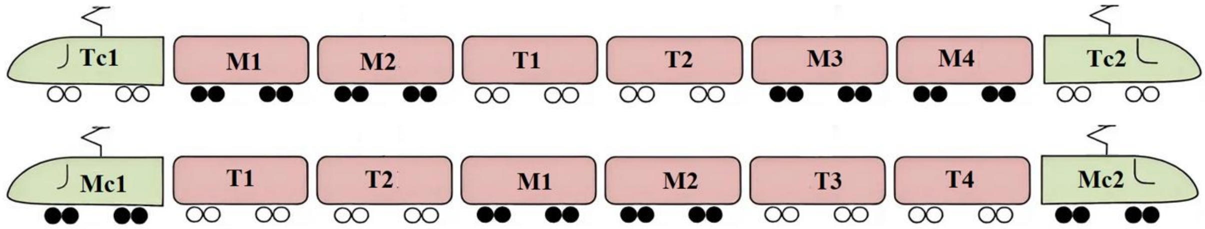

Figure 3. Diagram of a high-speed train configuration with 4 motor cars out of 8.

4.3. Illustrative example of using kinetic energy for high-speed train gradient climbing

4.3.1. Calculation parameters

The high-speed train has the following specifications:

- Number of cars in the train $n_{car} = 8$;
- Axle load of a car $q_0 = 16$ tons/axle;
- Number of axles per car $n_{axle} = 4$;
- Power of a single traction motor $P_m = 400$ kW.

The feasibility of using the train's kinetic energy to climb a gradient of $35^{o}/_{oo}$ over a 1,000 m segment with an initial speed of 100 km/h needs to be verified.

4.3.2. Calculation results

a. Kinetic energy of the train, calculated using Eq. (10)***:***

$$E_k = \frac{1}{2} mv^2 = 1/2 \times 512{,}000 \times 27.78^2 = 199{,}667{,}520 \text{ J}$$

With:

$m = 512{,}000$ kg - Total train mass

$v = 100$ km/h = 27.78 m/s

b. Gradient resistance force, calculated using Eq. (12):

$$F_g = mg \sin\theta = 512{,}000 \times 9.81 \times 0.035 = 176{,}900.16 \text{ N}$$

c. Required work to overcome the gradient, calculated using Eq. (11):

$$A_g = F_g L = 176{,}900.16 \times 1{,}000 = 176{,}900{,}160 \text{ J}$$

d. Comparison of kinetic energy and required work for gradient climbing

E_k = 199,667,520 J > A_g = 176,900,160 J

Thus, the train's kinetic energy is sufficient to climb a 35‰ gradient.

e. Minimum speed required to use kinetic energy for gradient climbing, calculated using Eq. (18):

$$v \geq \sqrt{2gL\sin\theta} = \sqrt{2\times 9.81\times 1,000\times 0.035} = \sqrt{686.7} = 26.2 \text{ m/s} = 94.32 \text{ km/h}$$

5. CONCLUSION

The selection of a high-speed train configuration depends on multiple factors and can be approached in different ways. In Vietnam, the high-speed railway system may only be developed in the coming years; therefore, the content presented in this article serves as an initial theoretical contribution, providing insights and direction. A comprehensive and complete selection of train configurations can only be conducted once specific technical parameters regarding the railway line and rolling stock are available.

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