Reasonable compensation coefficient of maximum gradient in long railway tunnels

Sirong YI*, Liangtao NIE, Yanheng CHEN, Fangfang QIN

School of Civil Engineering, MOE Key Laboratory of High-Speed Railway Engineering, Southwest Jiaotong University, Chengdu 610031, China

Abstract: This paper deals with the theory and calculation methods for compensation of the gradient in railway tunnels through theoretical analysis, numerical calculation, and statistic regression methods. On the basis of the principle that the resultant force is zero, the formula of the maximum calculated gradient was derived for the freight and passenger line and high-speed passenger special line. The formula of aerodynamic drag in tunnel is provided using the domestic and foreign relevant experimental investigations, and revised with modern train and engineering parameters. A calculation model of aerodynamic drag when the train goes through a single-tracked tunnel was built. Finally, the concept of maximum calculated gradient was adopted to revise the formula for compensation of the gradient in railway tunnels.

Key words: railway tunnel; maximum gradient; profile; gradient compensation

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1. Introduction

For freight and passenger lines, at the location where the maximum gradient needs to be used in design, when the train passes through a tunnel of length more than 400 m, its additional resistance increases, but the adhesion coefficient lessens, which leads to the design gradient of the profile plus the equivalent gradient of additional aerodynamic drag in the tunnel being greater than the maximum gradient. Therefore, in the profile design, we need to compensate for the maximum gradient to ensure the general freight train can pass through this location at no less than the stipulated speed. Code for Design of Railway Line (hereinafter referred to as the Line Specification) offers us the maximum gradient compensation coefficients for the corresponding tunnels [1]. However, due to the advancement of railway speed in China, the calculation formula in the existing codes cannot be adapted to the current engineering conditions. In order to revise the principle and parameters of maximum gradient compensation for railway tunnels, we should combine new technical conditions of the railway system to study the theory, method, and compensation model.

Considering the electric railway, this paper will introduce the research achievement on developing a rea-

sonable compensation coefficient for the gradient of a long railway tunnel.

2. Calculation model of maximum gradient of design line

The maximum calculated gradient of a railway line is defined as the gradient value of the consecutive ascending grade on which a given locomotive can haul the train with a specified weight at the calculated, constant speed of the locomotive.

For freight trains and passenger trains with traction mass of G , the maximum calculated gradient of the train is derived based on the principle that the resultant force acting on the train is zero when the freight train runs on a consecutive ascending grade at the specified calculated, constant speed of the locomotive. For a provided traction mass norm, the maximum calculated gradient at the section where the train is hauled by a single locomotive can be calculated as follows [2]:

$$i_{\text{cmax}} = \frac{\lambda_u F_c - (Pw_0' + Gw_0'')g}{(P + G)g},$$

where G is the norm of traction mass, in t; i_{cmax} is the maximum calculated gradient; w_0' is unit basic resistance of locomotive under the calculated speed, in N/kN; w_0'' is unit basic resistance of rolling stock under the calculated speed, in N/kN; F_c is calculated traction force, in kN; P is locomotive mass, in t; λ_u is utilization coef-

cient of traction force; g is acceleration of gravity, in m/s^2 . DOI 10.1007/BF03325733

At the section where the maximum gradient needs to be used, if the equivalent gradient of the profile exceeds the maximum gradient, the freight train will eventually run at a speed less than calculated speed on the consecutive ascending grade, which will result in accidents due to the slow speed, even causing a suspension. Hence, the design gradient of the profile plus the equivalent gradient of additional resistance in the tunnel should not be greater than the maximum gradient. Therefore, for the profile design of railway, we need to reduce the maximum gradient to ensure the freight train passes through this section at no less than calculated or stipulated speed.

2.1. Calculation model of additional aerodynamic drag in single-tracked tunnel

When a train goes through a double-track tunnel, there is no directional airflow, so the average aerodynamic drag formula cannot be deduced theoretically. In the case of no meeting trains, because the train runs through the tunnel of larger cross section, the blockage ratio becomes greater, and the aerodynamic drag is less than that in the single-track tunnel. In the case of meeting trains in double-track tunnel, through mathematical analysis on the energy and momentum of aerodynamic drag, we can analyze the flow field (velocity field and dynamic pressure field) around the location of the meeting trains of different type and length with different speed, and then calculate the increment of aerodynamic drag.

The paper herein deals with a calculation method of additional aerodynamic drag in single-tracked tunnel.

When a train goes through a single-tracked tunnel, there exists directional airflow in tunnel. Then we can deduce average aerodynamic drag formula theoretically.

Air cannot spread due to being restrained by tunnel when train is running in tunnel, leading the piston phenomenon, i.e. the difference between head positive pressure and tail negative pressure, which produces the resistance to the train. Meanwhile, the turbulent flow in tunnel produces friction between the air and the surface of the train and the tunnel, which also generates the resistance to the train. Therefore, when the train is running in the tunnel, aerodynamic drag acting on the train is far more than that in the open. The aerodynamic drag increment is called additional aerodynamic drag in the tunnel.

In the calculation of aerodynamic drag increment in the tunnel, a series of parameters need to be determined first, such as the frictional resistance coefficient of the train surface, frictional resistance coefficient of tunnel surface, the pressure drag coefficient of the train head

and tail, train shape parameters, and tunnel design parameters. These calculation parameters determine the correctness of the result. Especially, the pressure drag coefficient of the train head and tail and the frictional resistance coefficient of the train surface have a great influence on the correctness of the result.

When a train is going through a tunnel, the aerodynamic drag includes three items: pressure drag of the train head, pressure drag of the tail, and surface friction resistance of the body. The key to determining aerodynamic drag when a train passes through a tunnel is to determine the pressure drag coefficient of the train head and tail, surface friction resistance coefficient of the train body and wind speed in the tunnel.

The related studies [3-5] show that additional aerodynamic drag in the tunnel is related to driving speed, length of the train, the superficial area of the train against the air, train shape, tunnel length, area of tunnel cross-section, and tunnel surface roughness. The relation between aerodynamic drag in the tunnel, air pressure difference and tunnel cross-section area can be expressed as follows:

$$W_t = hF_t,$$

where F_t is the area of tunnel cross-section, for the simplification of calculation, can be taken as the value in Table 1.

Table 1 The minimum effective area of cross-section in tunnel (recommended value in calculation) m^2

Design running speed of passenger train (km/h)	Electric traction		Diesel Traction	
	Single-track	Double-track	Single-track	Double-track
≤ 120	37		31	
≤ 160	42	76	42	76
200	50	80	50	80
250	58	90	58	90
350	70	100	70	100
Remarks	Without considering requirements of double-decked container trains			

Unit aerodynamic drag in the tunnel is

$$w_t = \frac{hF_t}{(P+G)g},$$

where h is unit difference of air pressure, in N/m^2 :

$$h = K \frac{\gamma}{2} (v - v_0)^2,$$

where K is the effect coefficient of piston pressure:

$$K = \frac{NL_{tr}}{(1 - F_{tr} / F_t)^2} = \frac{86 \times 10^{-4} L_{tr}}{(1 - F_{tr} / F_t)^2},$$

where L_{tr} is length of train, in m, and F_{tr} is area of cross-section of train, taken as 12.6 m²; γ is the density of air, taken as 1.2 kg/m³; v is speed of train, in m/s; v_0 is wind speed in piston, in m/s:

$$v_0 = \frac{v}{1 + \sqrt{\zeta_t / K}},$$

where ζ_t is total resistance coefficient of tunnel:

$$\zeta_t = \sum \zeta + \lambda \frac{L_t - L_{tr}}{d},$$

where $\sum \zeta$ is the sum of part resistance coefficient at the entrances to the tunnel, taken as 1.5; λ is internal friction coefficient in the tunnel, taken as 0.025; L_t is length of the tunnel, in m; d , in m, is equivalent diameter of the tunnel:

$$d = 4F_t / R_t,$$

where R_t is tunnel perimeter. When design speed is less

$$h = K \frac{\gamma}{2} (v - v_0)^2 = 0.05K\gamma v^2 \left(1 - \frac{1}{1 + \sqrt{\zeta_t / K}}\right)^2 = 0.5K\gamma v^2 \left(1 - \frac{1}{1 + \sqrt{(1.5 + 0.025 \frac{L_t - L_{tr}}{4F_t / R_t}) / K}}\right)^2 =$$

$$0.5 \frac{0.0086L_{tr}}{(1 - F_{tr} / F_t)^2} \gamma v^2 \left(1 - \frac{1}{1 + \sqrt{(1.5 + 0.025 \frac{L_t - L_{tr}}{4F_t / R_t}) / (0.0086L_{tr} / (1 - F_{tr} / F_t)^2)}}\right)^2 =$$

$$0.0003318 \frac{\gamma L_{tr} V^2}{(1 - F_{tr} / F_t)^2} \left(1 - \frac{1}{1 + \sqrt{(174.419 + 2.907 \frac{L_t - L_{tr}}{4F_t / R_t}) / (L_{tr} / (1 - F_{tr} / F_t)^2)}}\right)^2.$$

The formula of the unit aerodynamic drag in a tunnel is

$$w_t = \frac{hF_t}{(P + G)g} = \frac{0.00003318\gamma F_t}{(1 - F_{tr} / F_t)^2} \frac{L_{tr} V^2}{(P + G)} \left(1 - \frac{1}{1 + \sqrt{(174.419(1 - F_{tr} / F_t)^2 + 2.907 \frac{(1 - F_{tr} / F_t)^2}{4F_t / R_t} (L_t - L_{tr})) / L_{tr}}}\right)^2 =$$

$$\frac{AL_{tr}}{(P + G)} V^2 \left(1 - \frac{1}{1 + \sqrt{\frac{B + C(L_t - L_{tr})}{L_{tr}}}}\right)^2,$$

where

$$A = \frac{0.00003318\gamma F_t}{(1 - F_{tr} / F_t)^2},$$

$$B = 174.419(1 - F_{tr} / F_t)^2,$$

$$C = 2.907 \frac{(1 - F_{tr} / F_t)^2}{4F_t / R_t}.$$

than 160 km/h, it is taken as 22.5 m for single-track tunnel, and 31.55 m for a double-track tunnel. When design speed is in the range of 160 to 200 km/h, it is taken as 34.5 m for a double-track tunnel. When design speed is in range of 200 to 250 km/h, it is 28.0 m for a single-track tunnel and 35.0 m for a double-track tunnel. When design speed is in the range of 250 to 350 km/h, it is 32.0 m for a single-track tunnel and 37.5 m for a double-track tunnel.

After substitution of the above parameters, the total resistance coefficient in the tunnel is

$$\zeta_t = \sum \zeta + \lambda \frac{L_t - L_{tr}}{d} = 1.5 + 0.025 \frac{L_t - L_{tr}}{4F_t / R_t}.$$

According to the above parameters, the calculation formula of unit air pressure difference can be deduced as follows.

2.2. Maximum calculated gradient of the tunnel section

At the tunnel section where the maximum gradient is fully used, when the train goes through the tunnel, if the calculated gradient of locomotive approaches the ruling gradient of the design line, the gradient equivalent to additional resistance should be deduced to ensure the

train passes through this tunnel with no less than the calculated speed of the locomotive.

Only the additional aerodynamic drag in the tunnel affects the compensation of maximum gradient for the tunnel when using electric traction. For diesel-traction, however, not only the additional tunnel aerodynamic drag, but also the speed of train through the tunnel influences the compensation of maximum gradient.

Let the compensation of maximum gradient in the tunnel be Δi_t . Then the maximum design gradient of tunnel, i (‰), is

$$i = i_{\max} - \Delta i_t.$$

In order to simplify the calculation, the maximum gradient compensation value for the tunnel, Δi_t , can be converted to maximum gradient coefficient β_t . The relationship of β_t with design grade i is as follows:

$$i = i_{\max} - \Delta i_t = \left(1 - \frac{\Delta i_t}{i_{\max}}\right) i_{\max} = \beta_t i_{\max}.$$

For electric traction

$$\beta_t = \begin{cases} 1 - \frac{w_t - (i_c - i_{\max})}{i_{\max}} = \frac{i_c - w_t}{i_{\max}}, & i_c - i_{\max} \leq w_t, \\ 1, & i_c - i_{\max} > w_t. \end{cases}$$

For diesel-traction

$$\beta_t = \begin{cases} 1 - \frac{w_t - (i_v - i_{\max})}{i_{\max}} = \frac{i_v - w_t}{i_{\max}}, & i_v - i_{\max} \leq w_t, \\ 1, & i_v - i_{\max} > w_t, \end{cases}$$

where w_t is additional aerodynamic drag in tunnel, in N/kN; $i_{\max}$ is maximum gradient of design line (‰); i_c is calculated gradient of locomotive, namely the gradient value when the train runs at a constant speed (for the freight train, it refers to the equilibrium gradient when the locomotive runs at a minimum calculated speed (‰)); i_v is the equilibrium gradient under the train speed through the tunnel, and it equals the unit resultant force value under the train speed through the tunnel, i.e., $i_v = f - w_0$, where f is unit traction force and w_0 is the unit basic resistance.

3. Maximum calculated gradient in bright line section (outside of tunnel)

3.1. Relationship between traction mass and calculated gradient for several types of freight locomotives

According to the calculation, the relationship between traction mass and calculated gradient for several types of freight locomotives (SS1, SS3, SS4, SS7, 6K,

8G) is shown in Fig. 1. The relationship is decreasing quintic function; namely, the adapted calculated gradient decreases by quintic function with the increase in the traction mass.

Fig. 1 The relationship between traction mass and calculated gradient for six types of locomotives

3.2. Surplus value of traction power of electric locomotive for ruling gradients

For the railway of freight and passenger lines hauled by electric locomotive in our country, the ruling gradient should not be greater than values in Table 2.

Table 2 Maximum ruling gradient value ‰

Classification of railways	Terrain type		
	Plain	Hilly land	Mountainous area
I	6.0	12.0	15.0
II	6.0	15.0	20.0
III	9.0	18.0	25.0

At present, most of railways for freight trains and passenger trains in China employ the ruling gradient of 6‰, 9‰, or 12‰. The surplus of traction force of electric locomotive on the corresponding ruling grade is shown in Table 3, where i_r is ruling gradient.

3.3. Comprehensive analysis of dynamic characteristics for a freight train running on ascending grade

Table 3 shows that, for freight train and passenger train using locomotives SS4, SS7, 8K and 6G, when traction mass are 1 800 and 2 000 t, trains can run on the grade with the ruling gradient of no more than 15‰ at certain accelerated speed. When traction mass is 1 800 t, the accelerated allowance of locomotive SS4 is greater than the maximum compensation of gradient in the tun-

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Table 3 Surplus of traction force of electric locomotive on ruling grade

N/kN

Locomotive type	Traction mass/ruling gradient											
	1 800 /15	2 000 /15	1 800 /12	2 000 /12	2 500 /9	2 800 /9	3 000 /6	3 500 /6	4 000 /6	5 000 /6	4 000 /4	5 000 /4
SS1	-2.16	-3.49	0.84	-0.49	0.07	-0.99	1.41	0.21	-0.71	-2.0	1.29	0.0
SS3	-1.57	-2.96	1.43	1.04	0.49	-0.63	1.74	0.48	-0.47	-1.83	1.53	0.17
SS4	3.18	1.38	6.18	4.38	4.05	2.58	4.76	3.10	1.83	0.03	3.83	2.03
SS7	0.22	-1.34	3.22	1.66	1.8	1.59	2.85	1.44	0.36	-1.52	2.36	0.84
6K	0.39	-1.18	3.39	1.82	1.93	0.66	2.96	1.53	0.44	-1.09	2.44	0.91
8G	4.38	2.47	7.38	5.47	4.94	3.39	5.52	3.76	2.42	0.51	4.42	2.51
$(1-\beta_t)i_t$	0.75 for $400 < L_t < 1\ 000$		0.6 for $400 < L_t < 1\ 000$		0.45 for $400 < L_t < 1\ 000$		0.3 for $400 < L_t < 1\ 000$				0.2 for $400 < L_t < 1\ 000$	
	1.5 for $1\ 000 < L_t < 4\ 000$		1.2 for $1\ 000 < L_t < 4\ 000$		0.9 for $1\ 000 < L_t < 4\ 000$		0.6 for $1\ 000 < L_t < 4\ 000$				0.4 for $1\ 000 < L_t < 4\ 000$	
	2.25 for $4\ 000 < L_t$		1.8 for $4\ 000 < L_t$		1.35 for $4\ 000 < L_t$		0.9 for $4\ 000 < L_t$				0.6 for $4\ 000 < L_t$	

nel. In the railway of plain and hilly regions, in the case of locomotives SS1 and SS3 at 1 800/12, 2 500/9, 3 000/6, and 3 500/6 (trailing load/ruling gradient), the calculated gradient is greater than the corresponding ruling gradient, and the locomotives run at the calculated speed with a certain acceleration allowance. In the remaining calculation conditions, except for 3 000/6, the allowance is always less than the corresponding compensation of gradient in tunnel in the current Line Specifications [1]. Hence, when using electric locomotives SS1 and SS3, we should take the compensation of maximum gradient in the tunnel into consideration to ensure that the locomotive hauls the train with no less than the calculated speed through this tunnel. When the traction mass is 5 000 t, on the grade with 6‰ gradient, train can run at the calculated, constant speed of the locomotive with a certain acceleration allowance, but the allowance is less than the compensation of gradient in tunnel. When traction mass is less than 5 000 t, in the case of locomotives SS4, SS7, 6K and 8G running on the grade with gradient of 6‰, 9‰ and 12‰, calculated gradient are all more than the ruling gradient, and the traction force is surplus.

The above analysis shows that for different ruling gradient and corresponding traction mass, we can ensure the locomotive hauls the train to run with certain acceleration allowance on limiting ascending grade by properly choosing electric locomotive.

For high-power electric locomotives SS4, SS7, 6K, 8G, etc., according to the current Line Specifications, even in a tunnel section, locomotives still are able to pass through at no less than the calculated speed with certain acceleration allowance.

4. Model of relationship between aerodynamic drag in tunnel and train speed

When trains with the same traction mass pass through tunnels with the same length, aerodynamic drag in tunnel is in direct proportion to the square of train speed. As the length difference among different types of locomotives is tiny, aerodynamic drags in a tunnel are very close, tending to the same quadratic curve. Therefore, when the norm of traction mass is certain, the aerodynamic drag in a tunnel can be regressed to the uniform calculation formula. Table 4 provides the relationship of the aerodynamic drag in a tunnel and the speed (V) of the train with traction mass of 4 000 t.

Table 4 General formula of aerodynamic drag of electric traction freight train with 4 000 t traction mass in tunnel

L_t (m)	w_t
1 000	$w_t = 0.55V^2 \times 10^{-4} + 0.331V \times 10^{-5} + 0.000\ 049\ 6$
5 000	$w_t = 1.66V^2 \times 10^{-4} + 0.998V \times 10^{-5} + 0.00\ 149\ 7$
10 000	$w_t = 2.265V^2 \times 10^{-4} + 0.136V \times 10^{-5} + 0.000\ 102$
15 000	$w_t = 2.63V^2 \times 10^{-4} + 0.157\ 9V \times 10^{-5} + 0.000\ 236\ 9$
20 000	$w_t = 2.89V^2 \times 10^{-4} + 0.173\ 5V \times 10^{-5} + 0.000\ 130\ 1$
25 000	$w_t = 3.088V^2 \times 10^{-4} + 0.185\ 4V \times 10^{-5} + 0.000\ 139$
30 000	$w_t = 3.245V^2 \times 10^{-4} + 0.194\ 9V \times 10^{-5} + 0.000\ 292\ 4$

5. Maximum aerodynamic drag in tunnel

According to Table 4, we can calculate the aerodynamic drag for different electric locomotive when it

passes through the tunnel at the calculated speed. Table 5 shows the aerodynamic drag in a tunnel when locomotives SS4 and SS7 haul trains through the tunnel with different length.

6. Comprehensive analysis

6.1. Comparison between calculated gradient and aerodynamic drag in tunnel

According to above analysis, Table 6 shows the relationship between acceleration allowance and aerody-

namic drag in a tunnel when the electric locomotives run with calculated speed on ruling grade.

Comprehensive analysis for Tables 5 and 6, and Fig. 1 shows that when using locomotives SS4, SS7, 8K, and 6G and traction mass is 1 800 or 2 000 t, the trains could run on the grade with the ruling gradient of no more than 15‰ at certain accelerated speed. When traction mass is 1 800 t, acceleration allowance of locomotive SS4 is greater than the maximum compensation of gradient in the tunnel. For the railway in plain and hilly in the case of locomotives SS1 and SS3 at 1 800/12, 2 500/9, 3 000/6, and 3 500/6, the calculated gradient is

Table 5 Aerodynamic drag in a tunnel when an electric traction freight train passes through at the calculated speed N/kN

L (m)	Locomotive type	G (t)				Passenger train
		3 000	3 500	4 000	5 000	
1 000	SS4	0.195 231	0.164 893	0.138 807	0.095 333	0.494 253
	SS7	0.172 301	0.145 636	0.122 741	0.084 656	0.434 538
5 000	SS4	0.452 779	0.417 774	0.387 635	0.337 852	1.212 022
	SS7	0.395 471	0.364 854	0.338 499	0.294 980	1.065 321
10 000	SS4	0.664 143	0.627 960	0.596 365	0.543 296	1.592 419
	SS7	0.578 286	0.546 814	0.519 313	0.473 097	1.399 675
15 000	SS4	0.760 329	0.724 740	0.693 443	0.640 411	1.818 034
	SS7	0.661 349	0.630 485	0.603 312	0.557 220	1.595 986
20 000	SS4	0.827 564	0.792 828	0.762 129	0.709 781	1.975 440
	S7	0.719 361	0.689 307	0.662 704	0.617 278	1.736 336
25 000	SS4	0.878 547	0.844 700	0.814 674	0.763 226	2.096 116
	SS7	0.763 323	0.734 095	0.708 118	0.663 531	1.842 405
30 000	SS4	0.923 000	0.891 600	0.856 700	0.806 200	2.190 327
	SS7	0.801 800	0.774 100	0.744 200	0.700 400	1.925 199

Table 6 Comparison between surplus value of traction force and aerodynamic drag in a tunnel when the electric locomotive runs on ruling grade N/kN

Locomotive type	Traction mass/ruling gradient							
	3 000/9	3 500/9	3 000/6	3 500/6	4 000/6	5 000/6	4 000/4	5 000/4
SS1			1.41	0.21		-2.0	1.29	0.0
SS3			1.74	0.48		-1.83	1.53	0.17
SS4	1.76	0.10	4.76	3.10	1.83	0.03	3.83	2.03
SS7			2.85	1.44	0.36	-1.52	2.36	0.84
6K			2.96	1.53	0.44	-1.09	2.44	0.91
8G	2.52	0.76	5.52	3.76	2.42	0.51	4.42	2.51
W_t	0.20 for $400 < L_t < 1\ 000$, 0.75 for $10\ 001 < L_t < 15\ 000$,			0.45 for $1\ 001 < L_t < 5\ 000$, 0.85 for $15\ 001 < L_t < 20\ 000$, 0.95 for $25\ 001 < L_t < 30\ 000$		0.65 for $5\ 001 < L_t < 10\ 000$, 0.90 for $20\ 001 < L_t < 25\ 000$,		

greater than the corresponding ruling gradient, and the locomotives run at calculated speed with a certain acceleration allowance. However, in the rest calculation conditions except for 3 000/6, the allowance is always less than the gradient compensation for corresponding tunnel in the current Line Specifications. For example, when using electric locomotives SS1, SS3, we should take the compensation of maximum gradient in the tunnel into consideration to ensure that the locomotive hauls train with no less than calculated speed through this tunnel. When traction mass is 5 000 t, train can run on 6‰ grade at the calculated speed of locomotive constantly with a certain acceleration allowance, but the allowance is less than the compensation of gradient in tunnel. When traction mass is less than 5 000 t and using locomotives SS4, SS7, 6K, and 8G to haul train on the ruling grade of 6‰, 9‰, and 12‰, the calculated gradient is more than the ruling gradient, and the allowance is greater than the equivalent gradient of the aerodynamic drag in the tunnel.

6.2. Comparison between calculated aerodynamic drag and compensation of gradient in a tunnel in current Line Specifications

Table 7 shows the compensation of gradient in tunnel in current Line Specifications and the calculated aerodynamic drag in tunnel.

The comparison of the calculated value with compensation value in current line specifications shows that for the electric traction lines with the ruling gradients of 6‰, 9‰, and 12‰, when the tunnel length is less than 20 000 m, calculated value is not more than the aerodynamic drag in the tunnel when $L_t > 4\ 000$ m that is stipulated in the current Line Specifications.

Table 7 Comparison between calculated aerodynamic drag and compensation for gradient in a tunnel in current Line Specifications N/kN

Ruling gradient (%)	Length of tunnel (m)		
	$400 < L_t \leq 1\ 000$	$1\ 000 < L_t \leq 4\ 000$	$L_t > 4\ 000$
15	0.75	1.5	2.25
12	0.6	1.2	1.8
9	0.45	0.9	1.35
6	0.3	0.6	0.9
Calculated aerodynamic drag	$L_t = 20\ 001\text{--}25\ 000$: 0.90; $L_t = 25\ 001\text{--}30\ 000$: 0.95		

7. Conclusions

(1) For the different ruling gradient and traction mass, we can properly choose the locomotive from the current electric traction locomotives in China to ensure the locomotive hauls train to run on limiting ascending grade with certain acceleration allowance. The high-power electric locomotives SS4, SS7, 6K, 8G, etc., even in tunnel location, still run at no less than the calculated speed with certain acceleration allowance through the tunnel.

(2) In the electric traction railway for freight and passenger lines, when passenger train is passing tunnel, locomotive traction allowance is greater than the increment of aerodynamic drag in tunnel. Therefore, the design of maximum gradient of tunnel is not affected by the passenger train.

(3) In the design of railway for freight train and passenger train, the influence of aerodynamic drag should be taken into account when a fast-speed passenger train passes through a tunnel. The calculation results of this paper show that when trains have the same length and outside shape, for the same type of locomotive, if the traction mass is less, the unit aerodynamic drag is greater. For the same traction mass, if the calculated speed is greater, the aerodynamic drag in tunnel is greater. For electrical freight locomotive, the calculated speed of locomotive SS4 is the greatest, i.e. 51.2 km/h, and accordingly its aerodynamic drag in tunnel is the greatest. According to the above analysis, for electric traction, calculation of aerodynamic drag in tunnel can be divided into seven grades: 401–1 000, 1 001–5 000, 5 001–10 000, 10 001–15 000, 15 001–20 000, 20 001–25 000, and 25 001–30 000, the corresponding additional aerodynamic drag can be calculated in terms of 0.20, 0.45, 0.65, 0.75, 0.85, 0.90, and 0.95 N/kN, respectively.

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