Research on Traction Load Characteristics of Sichuan-Tibet Railway Under Different Weather

Qi Wang, Junyi Jia, Jingjing Ye*
Department of Electrical Engineering Beijing Jiaotong University Beijing, China
18121506@bjtu.edu.cn

Abstract—The Sichuan-Tibet Railway faces severe challenges such as changeable weather and long ramps. In order to reduce the ramp stop accidents of locomotive, the traction characteristic curve and braking characteristic curve of the locomotive are revised considering the wheel-rail adhesion limit under different weather conditions. Then the traction quality of dry rail, wet rail and ice rail is given. The modified characteristic curves and traction quality are used to simulate the traction load of Sichuan-Tibet Railway under different rail surface conditions. The results show that under dry rail conditions, the traction quality is 2500 tons and the driving power and regenerative braking power are extremely large, respectively 20MW and 16MW. Under wet rail and ice rail conditions, traction quality and regenerative braking power are significantly limited by adhesion. When ice rail, the traction quality is only 1200 tons; the driving power and the regenerative braking power are only respectively 14MW and 9 MW. At the same time, the running interval when growing uphill is 7 minutes longer than that under dry rail conditions. It provides a reference for the layout of the train operation diagrams and the design of the traction power supply system.

1. INTRODUCTION
The Sichuan-Tibet Railway is of harsh natural environment, with four characteristics: "significant terrain height difference, strong plate activity, frequent mountain disasters, and fragile ecological environment". and it is one of the most difficult railway projects all over the world [1].

Restricted ramp is one of the important technical standards for the calculation of traction quality. There were as many as 43 stop-over accidents of Hexie series electric locomotives in the early stage of Shanghai-Kunming railway. When the Yiwan Railway with a restricted slope of 18‰ was in operation, the theoretical traction quality was about 3300 tons. However, field tests indicated that the train could not start when the traction quality is 3000 tons [2]. When the traction quality was 3,200 tons, the train dropped directly. The restricted slope of the Sichuan-Tibet Railway is as large as 30‰, the problem of "false height" of traction quality should be paid more attention.

The wheel-rail adhesion coefficient reflects the possible degree of the locomotive's traction or braking force transmitted to the steel rail. Many scholars have studied the wheel-rail adhesion coefficient through experiments. Wang & Mo [3] have concluded by testing in the Harbin Railway Section: the wheel-rail adhesion coefficient is the largest under dry rail conditions, decreased under wet rail conditions, and smallest under ice conditions. Some scholars have concluded through the wheel-rail adhesion tests [4-5]: the wheel-rail adhesion coefficient showed a downward trend with increasing speed, and the adhesion coefficient under dry rail condition was larger than that under the wet rail condition. At present, most of the wheel-rail adhesion is still only on the study of the adhesion
coefficient law, and the actual impact of the adhesion limitation on the locomotive performance has not been considered. Reference [6] proposed that the continuous traction force would also be limited by adhesion, and the theoretical traction quality has been corrected. But the difference in different weather is not taken into account.

The weather conditions on the Sichuan-Tibet line are harsh, and it is of great significance to study the wheel-rail adhesion for the safe operation of the train. The first section of this paper introduces the research background of the project. In Section II, the traction characteristic curve and braking characteristic curve of the locomotive are corrected according to the wheel-rail adhesion limit under the conditions of dry rail, wet rail, and ice rail. In the next section, the correction of traction quality under different weather conditions is completed. In Section III, the traction load simulation of the Sichuan-Tibet Railway under different weather conditions is realized according to the actual line data. And the last section summarizes the whole paper.

2. WHEEL-RAIL ADHESION

2.1. Wheel-rail adhesion coefficient

The traction force and braking force of the locomotive are the reaction forces generated by the adhesion between the wheels and the rails, acting on each wheel to cause the locomotive to move in translation [7]. Traction and braking forces are limited by adhesion and cannot be increased indefinitely. The wheel-rail adhesion coefficient can be divided into traction adhesion coefficient $\mu_f$ and brake adhesion coefficient $\mu_b$:

$$\mu_f = \frac{\Delta F_{\text{max}}}{P} \quad (1)$$

$$\mu_b = \frac{\Delta B_{\text{max}}}{P} \quad (2)$$

Where $\Delta F_{\text{max}}$ is the maximum achievable traction force; $\Delta B_{\text{max}}$ is the maximum achievable braking force; $P$ is the weight of the locomotive.

2.2. Determination of wheel-rail adhesion coefficient

Wheel-rail adhesion is a special physical state where there is fretting in static and creep in rolling. In this paper, Oldrich Polach's wheel-rail creep calculation method [8] is used. This method can accurately simulate various actual wheel-rail contact situations by using a set of empirical parameter sets. The description is as shown in equation (3).

$$F = \frac{2Qf}{\pi} \left[ \frac{k_s \xi}{1 + (k_s \xi)^2} + \arctan(k_s \xi) \right]$$

Where $\xi = \frac{2 C_h a b^2}{3} S$, $C = \frac{3G}{8a}$, $f = f_0 (1 - A) e^{-b_0 r} + A$.

In equation (3), $F$ is the adhesion force; $f$ is the friction coefficient between the wheels and rails; $Q$ is the positive pressure; $S$ is the creep rate; $C_h$ is the Kalker coefficient; $a$ and $b$ are the half-axis length of the elliptical contact spot; $G$ is the rigid modulus; $k_s$ and $k_s$ are the adjustment parameter; $f_0$ is the maximum friction factor between wheels and rails; $A$ and $B$ are friction factor adjustment parameters.

Table 1. Known adhesion coefficient calculation formula

| Rail Surface Condition | Calculation Formula          |
|------------------------|------------------------------|
| Traction wet rail      | $0.24+12/(100+8v)$          |
| Brake dry rail         | $0.0624+45.6/(260+v)$        |
| Brake wet rail         | $0.0405+13.55/(120+v)$       |
Table 2. Rail surface condition parameters of Polach calculation model

| Rail Surface Condition | $k_A$ | $k_S$ | $F_0$ | $A$ | $B$ |
|------------------------|------|------|------|-----|-----|
| Traction dry rail       | 1    | 0.4  | 0.1  | 0.4 | 0.2 |
| Traction ice rail       | 1    | 0.4  | 0.05 | 0.4 | 0.1 |
| Brake ice rail          | 1    | 0.4  | 0.03 | 0.4 | 0.1 |

Figure 1. Cohesion coefficient under different wheel and rail conditions

Table 1 shows the adhesion coefficients already given in “Regulations on Railway Train Traction Calculation” [9] (will be referred to as “RRTTC” hereinafter in this paper). “RRTTC” is China’s national standard rule for train traction calculation, and it contains adhesion coefficients under 3 wheel-rail conditions (shown in Table 1). The other adhesion coefficients are given based on Oldrich Polach's wheel-rail creep calculation method. The rail surface condition parameters of Polach's wheel-rail creep calculation model [10] is shown on Table 2. Fig. 1 shows the simulated wheel-rail adhesion coefficient under different conditions according to Table. 1 and Table. 2.

2.3. Correction of traction and braking characteristic curves

The HXD2 locomotive with dual-machine plans to be selected as the traction locomotive on the Sichuan-Tibet line. Equation (1) and equation (2) are used to modify the traction and braking characteristic curve of HXD2 locomotive under the adhesion limit in good weather (dry rail), rain (wet rail), snow (ice rail).

Figure 2. Original and modified traction characteristic curves
The original traction characteristic curve and braking characteristic curve of the locomotive are mainly limited by the performance of the traction motor itself. When considering the wheel-rail adhesion limitation, the locomotive can really achieve the smaller of them.

Table 3. Range of traction characteristic curve that is corrected

| Rail Surface Condition | Starting Point | Ending Point |
|------------------------|----------------|--------------|
| Dry rail               | (0,1447.0)     | (65.0,1037.2) |
| Wet rail               | (0,997.0)      | (95.4,716.6)  |
| Ice rail               | (0,787.0)      | (120,554.3)   |

Table 4. Range of braking characteristic curve that is corrected

| Rail Surface Condition | Starting Point | Ending Point |
|------------------------|----------------|--------------|
| Dry rail               | (9.4,928.8)    | (88.3,774.2) |
| Wet rail               | (6.1,589.5)    | (120,397.4)  |
| Ice rail               | (5.9,493.3)    | (120,322.7)  |

The original traction characteristic curve and the corrected traction characteristic curve is shown in Fig. 2; the range of the traction characteristic curve that needs to be corrected is shown in Table 3. The original braking characteristic curve and the corrected braking characteristic curve is shown in Fig. 3; the range of the braking characteristic curve that needs to be corrected is shown in Table 4. It can be seen that compared with the speed range under dry rail conditions, there is larger speed range that is limited by wheel-rail adhesion limit under wet rail conditions. It is of greatest impact under ice conditions.

The coordinate points marked in the Fig. 2 are the continuous traction force at the continuous speed, which will be mentioned in the next section.

3. DETERMINATION OF TRACTION QUALITY

Based on the calculation method of locomotive traction quality in “RRTTC” [9], this paper adds the correction of traction quality under different weather conditions. The specific process is shown in Fig. 4. Among them, part (a) is the calculation method in “RRTTC”, and part (b) is the wheel-rail adhesion correction method this paper proposes.
Calculation of traction quality under restricted ramp

3.1. Calculation of traction quality under restricted ramp

The traction quality of the train is related to the continuous speed under the restricted ramp. The continuous speed is the minimum continuous running speed allowed by the cooling device capacity of the locomotive at full power.

Continuous speed is an important speed value when calculating the traction quality, usually given in “RRTTC” [9]. The continuous speed of HXD2 electric locomotive is 62.4km/h, and the corresponding continuous traction force is 1080kN. The traction quality $G$ under the continuous traction force is calculated according to equation (4).

$$G = \frac{F_c \cdot \lambda_s - P(\omega'_0 + i) \cdot g \cdot 10^{-3}}{(\omega'_0 + i') \cdot g \cdot 10^{-3}}$$

In equation (4): $F_c$ (kN) is the continuous traction force of the locomotive, which is the traction force corresponding to the traction characteristic curve at the continuous speed. The physical meaning and value of other parameters are shown in Table 5 (according to “RRTTC”).

Table 5. Traction quality parameters under restricted ramp

| Parameter | Physical Meaning                                      | Value         |
|-----------|-------------------------------------------------------|---------------|
| $\lambda_i$ (%‰) | Restricted slope                                      | 30            |
| $F_c$ (kN) | Continuous traction force of locomotive               | 1080          |
| $\lambda_s$ | Coefficient of traction, a fixed value                | 0.9           |
| $P$ (t)   | The quality of locomotive                             | 200           |
| $\omega'_0$ (N/kN) | Unit basic resistance of locomotive at calculated speed, from the formula in “RRTTC” | 2.692         |
| $\omega'_0$ (N/kN) | Unit basic resistance of vehicle at calculated speed, from the formula in “RRTTC” | 1.7062        |
| $G$ (t)   | The obtained traction quality                         | 2713.5        |

3.2. Checking of traction quality

The checking of traction quality process including the formulas used, are based on the “RRTTC”.
3.2.1. The checking of the starting-up traction force
Since the starting-up resistance of the train is large, the maximum traction quality of the train when
starting on a ramp should be calculated. According to “RRTTC”, the checking of starting-up traction
force is according to equation (5).
\[
G_t = \frac{F_p \cdot \lambda - P (\omega + i) \cdot g \cdot 10^{-3}}{(\omega_0 + i) \cdot g \cdot 10^{-3}}
\] (5)

The physical meaning and values of the corresponding parameters in the formula are shown in Table 6 (according to “RRTTC”). The obtained traction quality is 3640.7 tons larger than 2713.5 tons, which meets the requirements.

| Parameter | Physical Meaning | Value |
|-----------|------------------|-------|
| \(F_p\) (kN) | Maximum starting-up traction force of locomotive | 1482 |
| \(\omega_0\) (N/kN) | Unit basic resistance of locomotive, a fixed value | 5 |
| \(\omega_1\) (N/kN) | Unit basic operation resistance of vehicle, a fixed value | 3.5 |
| \(G_t\) (t) | The obtained maximum traction quality when starting on a ramp | 3640.7 |

3.2.2. The checking of the effective length of the arrival line
The traction quality controlled by the effective length \(L_{xy}\) of the station to the departure line is according to equation (6).
\[
Q = (L_{xy} - l_s - l)q
\] (6)

The physical meaning and values of the corresponding parameters in equation (6) are shown in Table 7 (according to “RRTTC”). When 650m is taken, the obtained quality reaches 3086 tons more than 2713.5 tons, which meets the requirements.

| Parameter | Physical Meaning to arrival line | Value |
|-----------|----------------------------------|-------|
| \(L_s\) (m) | Length of locomotive | 76.4 |
| \(L_{xy}\) (m) | Effective length from station to departure line | 650 |
| \(q\) (t/m) | The quality corresponding to the extension of the train by one meter, a fixed value | 5.66 7 |
| Q(t) | The obtained quality | 3086 |

3.2.3. Checking of the braking distance under a long ramp
The effective distance of emergency braking is determined by equation (7) to equation (9).
\[
b = 1000 \cdot \vartheta_b \cdot \varphi_b
\] (7)
\[
c = -(w_0 + b + i)
\] (8)
\[
S = \sum_{i=1}^{4.17} \frac{v^2 - v_i^2}{c}
\] (9)

In equation (7)-(9): \(\vartheta_b\) is the train's converted braking rate; \(\varphi_b\) is the converted friction coefficient, which takes the minimum value of 0.15; \(c\) is the unit train total force (kN) during air emergency braking;
\( \omega_0 \) is the unit train basic running resistance (kN); \( b \) is the unit train braking force (N/kN); \( S \) is the running distance of the train (m); \( v_1 \) is the initial speed of the speed interval (km/h); \( v_2 \) is the final speed of the speed interval (km/h); \( i_c \) is the restricted slope, taking 30‰. When calculating the emergency braking distance, \( v_1 \) is taken as 0, \( v_2 \) is the restricted speed value during train emergency braking, and \( S \) is the emergency braking distance of train.

It can be seen that the emergency braking distance of the train is mainly determined by the restricted slope. Therefore, the restricted speed value is mainly related to the restricted distance of emergency braking and the restricted slope. When the slope takes a fixed value of 30‰, the limited speed is mainly determined by the emergency braking distance. When \( \phi_i \) takes the minimum value of 0.15 and the distance of emergency braking is widened to 1400m, the limited speed will be increased to 75km/h enough high, which meets the requirement.

3.3. Correction of the traction quality under the adhesion limit
Continuous traction force is limited by wheel-rail adhesion, then traction quality will also be affected. In order to avoid the “false height” of theoretical traction quality, the traction quality under different rail surface conditions is corrected according to equation (4). The continuous traction force under different rail surface conditions is shown in Fig. 4. According to the “RRTTC”, the traction quality should be rounded. The values of traction quality are shown in Table 8.

| Rail Surface Condition | Continuous Traction force (kN) | Traction Quality (t) | Rounded Quality (t) |
|------------------------|-------------------------------|----------------------|---------------------|
| Dry rail               | 1040                          | 2596.8               | 2500                |
| Wet rail               | 728                           | 1694.1               | 1600                |
| Ice rail               | 572                           | 1242.7               | 1200                |

4. SIMULATION OF SICHUAN-TIBET TRACTION LOAD
The Ya'an-Xinduqiao section of the Sichuan-Tibet Railway is used as the simulation route, with 183.23 kilometers length of the whole line and 30% of the restricted slope. The traction characteristic curve and braking characteristic curve of the locomotive under the three weathers are given in Fig. 2 and Fig. 3. The locomotive traction load in different weather is simulated through the locomotive traction quality, locomotive traction characteristic curve and braking characteristic curve under different rail surface conditions.

4.1. Power under dry rail, wet rail, ice rail conditions
The active power of uphill ramps, active power of downhill ramps, regenerative braking power of uphill ramps, and regenerative braking power of downhill ramps under dry rail, wet rail, and ice rail conditions is shown respectively in Fig. 5, Fig. 6, Fig. 7, and Fig. 8.
Under dry rail conditions, when the train travels uphill, the train power is very large, and the power of a single train reaches 20MW. When driving downhill, the regenerative braking power will reach more than 16MW.

Under the conditions of wet rail and ice rail, the maximum power of the train has dropped significantly, respectively 17MW and 14MW. When driving downhill continuously, the regenerative power generated under wet rail and ice rail conditions has significantly decreased due to the wheel-rail adhesion, which is about 10MW and 9MW respectively.

### 4.2. Comparison of running interval

Table 9 shows the running interval of the train from Ya'an to Xinduqiao under different wheel-rail conditions. It can be concluded that the running interval of different rail surfaces when continuously traveling downhill ramps is not much different, while the running interval difference of different rail surfaces when traveling uphill ramps is more than 7 minutes. Under special weather conditions, the train operation diagram should be adjusted reasonably.

|                | Downhill Ramps | Uphill Ramps |
|----------------|----------------|--------------|
| Interval (s)   | Dry Rail       | Wet Rail     | Ice Rail    |
|                | 8664           | 8592(-72s)   | 8578(-85s)  |
|                | 9123           | 8700(-423s)  | 8684(-439s) |
5. CONCLUSION
This paper corrects the traction quality, traction characteristic curve and braking characteristic curve of the Sichuan-Tibet railway locomotive by analyzing the wheel-rail adhesion under the conditions of dry rail, wet rail and ice rail, and draws the following conclusions:

1. The theoretical calculated traction quality of the Hexie series electric locomotive is 2713.5 tons. Under the condition of dry rail, it is limited by the wheel-rail adhesion. The continuous adhesion traction force is less than the calculated traction force, and the traction quality is 2500 tons. Under the conditions of wet rail and ice rail, the value of the continuous adhesion traction force is reduced, and the traction quality is respectively 1600 tons and 1200 tons. It provides a reference for railway operation scheduling.

2. Under the conditions of wet rail and ice rail, due to the influence of locomotive performance on wheel-rail adhesion restrictions, the interval under the conditions of wet rail and ice rail when driving uphill is reduced by about 7 minutes compared to that of dry rail. When driving downhill, the wheel-rail conditions have little effect on the running interval. The train operation diagram needs to be adjusted in special weather.

3. Under dry rail conditions, the power of a single train can reach 20MW when going uphill. The regenerative braking power when going downhill will also reach 16MW, which are of very large values. But under the wet rail and ice rail, the driving power and the regenerative braking power are reduced significantly. It places high demands on the traction power supply system of Sichuan-Tibet Railway.

ACKNOWLEDGMENT
This work was supported in part by the Science and Technology Research Project of China Railway under Grant P2018X011.

REFERENCES
[1] Y. C. Deng, and Z. L. Lin. (2019) “Sichuan-Tibet Railway Electrification Project: Challenges and Countermeasures,”. Electric Railway, 30(S1):5-11+15.
[2] X. H. Gan, B. Li, and Y. H. Shao. (2011) “Reason analysis and preventive measures of slope stop for HX_D1C locomotive,”. Electric Locomotives & Mass Transit Vehicles, 34(01):69-72.
[3] Y. P. Wang, J. Mo, and Z. F. Chen. (1991) “Experimental Research on the Adhesion Coefficient of my country Railway Brake,”. China Railway Science, (02):1-19+108.
[4] B. Wu, Z. F. Wen, H. Y. Wang, X. S. Jin. (2013) “Research on Influencing Factors of Adhesive Characteristics of High Speed Wheel-rail,”. Journal of the China Railway Society, 35(03):18-22.
[5] W. H. Zhang, W. X. Zhou, L. Q. Chen, X. S. Jin and L. X. Huang. (2000) “Experimental study on the adhesion mechanism of high-speed wheel-rail,”. Journal of the China Railway Society, (02):20-25.
[6] X. C. Zhang. (2014) “Research on Traction Quality of Harmony Series Freight Electric Locomotive;”. Journal of Railway Engineering Society, (02):96-102.
[7] J. Wu. (2013) “Train traction calculation,”. Southwest Jiaotong University, Chengdu.
[8] O. Polach. (2004) “Creep forces in simulations of traction vehicles running on adhesion limit,”. Elsevier B.V., 258(7).
[9] TB/T 1407—1998, “Train traction calculation rules”.
[10] Z. M. Chen, D. D. Liang and J. L. Zhang. (2018) “Simulation Research on Braking Performance of High-speed Train in Alpine Region,”. Journal of Chongqing Jiaotong University(Natural Science), 37(09):128-134.