THE EFFECT OF COEFFICIENT OF FRICTION BETWEEN RAIL VEHICLE WHEELS AND RAIL TRACK ON OPERATION POWER CONSUMPTION

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ABSTRACT: The daily cost of rail operation is increasing due to increased rail network size. Therefore, reducing operation power consumption is important for rail operators to optimize daily operation costs. Operation power consumption in rail operation can be divided into 80% traction power, such as vehicle propulsion system, and 20% non-traction power, such as station electrical consumption. Much research has already been conducted on advanced traction systems, such as regenerative braking storage systems, hybrid batteries, and others, which aim to reduce operation power consumption. However, very few address the concern about track condition and maintenance. This research focuses on the interaction between the rail vehicle wheels and the rail track and how the coefficient of friction affects the rail operation power consumption. As rail grinding is an essential rail preventive maintenance to improve track surface, the indirect coefficient of friction has shown an improvement that reduces rail operation power consumption. Train resistance can be expressed in the Davis equation, which is the mathematical model used in rail industries to find train performance. Our findings indicate that the application of the rail grinding method had successfully reduced the track kinetic coefficient of friction, reducing 9% in operation power consumption.

KEYWORDS: *Rail operation, Power consumption, Coefficient of friction, Rail grinding, Davis equation.*

1. INTRODUCTION

The daily cost of rail operation is increasing due to the expanding size of the rail network nationwide [1]. Therefore, reducing energy consumption has played an important role in the urban rail industry, as electric energy is the main source of traction power systems [2]. Good track surface coefficient of friction and profile may improve vehicle wheel and rail track interaction and reduce running resistance, therefore reducing operation energy consumption. One of the methods and strategy is to control the coefficient of friction of the rail track surface by applying good track maintenance plan such as rail grinding. Train resistance compromises a major percentage of the overall traction power losses. In rail industry, the equation of train resistance is commonly known as the Davis equation [3], as the coefficients of the Davis equation are related to different resistance contributions, as train resistance can be expressed in following form,

$$R = A + Bv + Cv^2 \tag{1}$$

Where R is the train resistance in N, v is the train velocity, A is the resistance component independent to train speed such as rolling resistance in N, contacts between the wheel and track surface. B is the coefficient used to define train resistance dependent on train speed such as flange friction, wave action and oscillation and C is the streamlining and aerodynamic coefficient. Davis equation can be generalized into the following equation [4],

$$R = (c_1^r + \frac{c_3^r}{p} + 10i + c_2^r v)G + c_a^r a v^2 \tag{2}$$

Where the value of c_1^r is the coefficient of resistance on track surface or also can be represent as the track coefficient of friction, μ and G is the train weight. Values of c_2^r and c_3^r are the coefficient of resistance due to track alignment, p is the train axile loading in N and i is the track gradient percentage. The value of c_a^r is the coefficient of train body smoothness and the value a is the cross-sectional profile of the train frontal. Therefore, by summarizing the above equation (1) to equation (2) the value A can be represented in terms of the following equation.

$$A = \ mg\mu \tag{3}$$

Where m is the rail vehicle dry mass in kg. The value of g is the gravitational constant which is 9.81 m/s^2. The value μ is the kinematics coefficient of friction of the running track. Value B can be represented in term of the following.

$$B = (\frac{c_3^r}{p} + 10i + c_2^r v)\ G \tag{4}$$

Where coefficient c_3^r is 130 and coefficient c_2^r is 0.009 for rapid transit type of rail vehicle. The value i is the percentage of track gradient and the study took place in low gradient track, the value is 1. Meanwhile, the value C can be represented in the following term,

$$C = c_a^r\ a\ v^2 \tag{5}$$

Where c_a^r is the rail vehicle body smoothness coefficient in term of 0.013 for rapid transit. The value a is the cross-sectional profile of the rail vehicle frontal area.

2. RAIL OPERATION POWER CONSUMPTION WITH THE APPLICATION OF RAIL GRINDING

2.1. Test Methodology

Two sets reading of μ and v is taken for before rail grinding and after rail grinding being applied. The track coefficient of friction is taken and recorded using the weight balance method and train velocity profile is recorded from the train speedometer. Figure 1 is the schematic diagram,

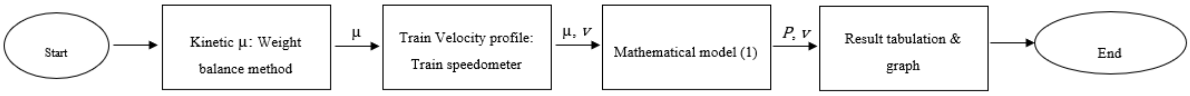

Fig. 1. Schematic diagram of the testing.

The variable for the analysis is the track coefficient of friction before the application of rail grinding and the track coefficient of friction after the application of rail grinding. Therefore, the testing can be divided into two which are before the application of rail grinding (normal track coefficient of friction) and after the application of rail grinding (improved track coefficient of friction). Power consumption graph is constructed using the data from train tractive force, resistance, and velocity profile.

2.2 Test Result

Based on the application weight balance method to measure track coefficient of friction, the following is the measurement of track coefficient of friction before and after rail grinding is being applied for 15 measurement locations along the track,

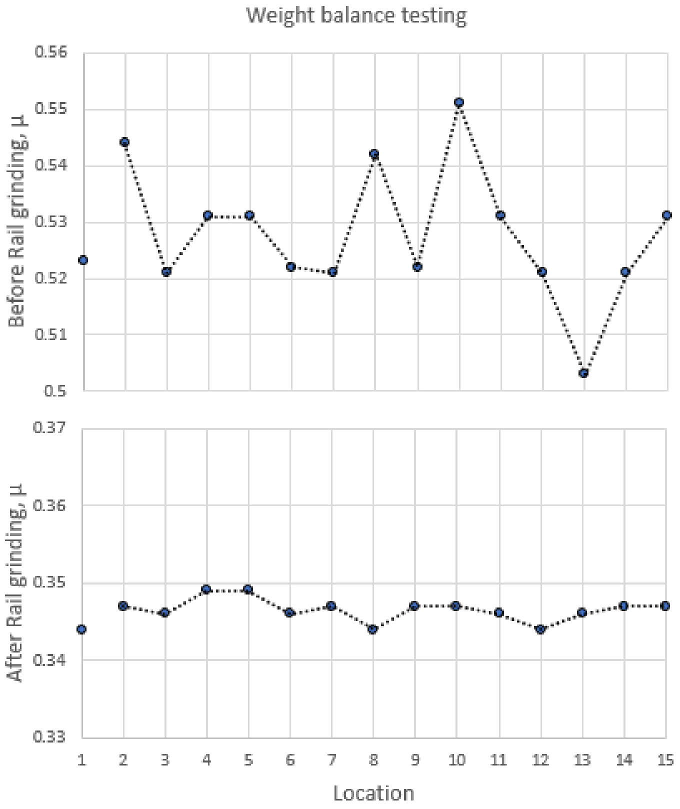

Fig. 2. Graph of weight balance testing for before and after the application of rail grinding to find μ.

Based on the finding, the track coefficient of friction before rail grinding is being applied is approximately μ=0.5 and after rail grinding being applied is approximately μ=0.3. Meanwhile, the following Figure 3 and Table 1 are the test result.

Table 1: Summary of experimental analysis of different of μ.

Coefficient of Friction, μ	**Resistance (kN)**		**Tractive force (kN)**		**Power consumption (kW)**		**Travel time (s)**
	Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2	
0.5	3021	3021	3403	3021	116	104	194
0.3	2749	2749	3157	2749	108	94	190
↓40%	**↓9%**	**↓9%**	**↓6%**	**↓9%**	**↓6%**	**↓9%**	**↓2%**

Where the value of resistance, tractive force, and power consumption is based on the maximum value and compromise two stages of station-to-station operation; Stage 1: acceleration, and Stage 2: constant speed. The difference in the result is shown in terms of percentage.

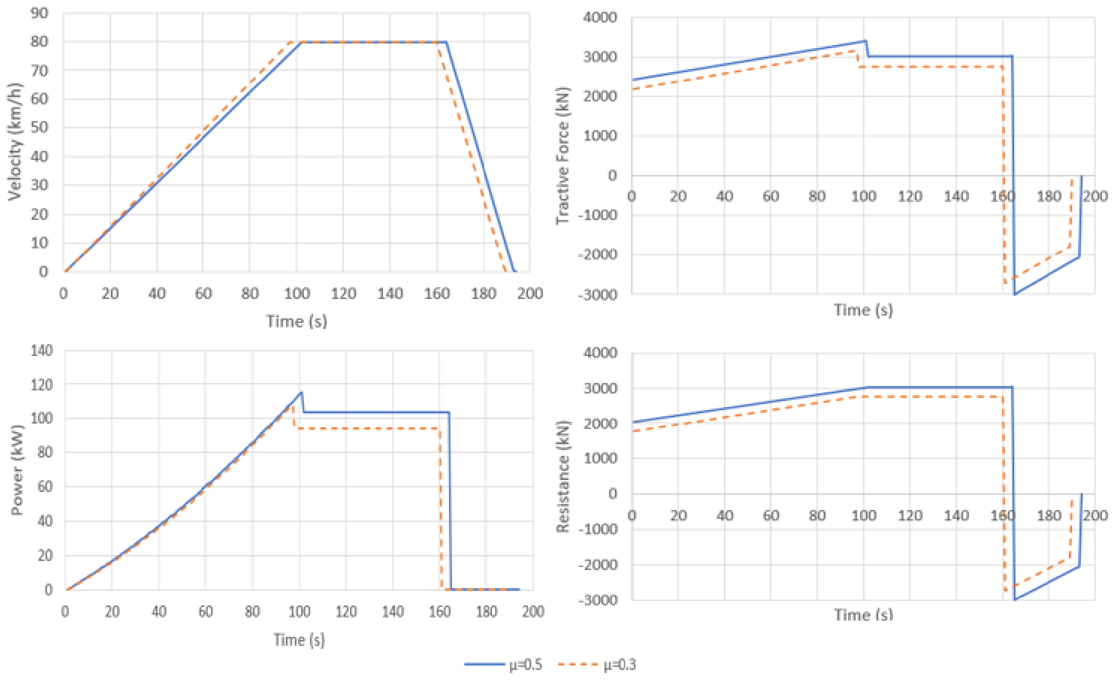

Fig. 3. Graph of velocity profile, resistance, tractive force, and power consumption before and after rail grinding.

2.3 Result discussion

During the first stage of the rail operation, the train moves with positive acceleration and the vehicle speed increases. During this stage of the operation, the train accelerates initially at its maximum rate; the acceleration rate increases for some period and decreases as it approaches its maximum velocity; acceleration starts to decrease as the train approaches its constant speed region. In the first stage of rail operation, μ=0.5 train operation increases its velocity at a rate of 0.21 km/h^2, and μ=0.3 increase its velocity at 0.24 km/h^2. Lower track friction coefficient produces a higher acceleration rate in the first stage of the train operation; therefore, the train operation enters the constant speed region faster. The differences in the μ affect the running resistance; a train with a lower μ achieved its constant speed region faster as its running resistance is lower, producing a higher acceleration rate on the first stage of operation. Therefore, the trip time in the acceleration region is reduced, producing lower operation power consumption as trip time always exerts influence on operation power consumption [4][5].

As the rail vehicle reaches its maximum velocity, it enters its second stage of the operation, which is constant speed operation, the net force is zero, and the tractive force is equal to resistance; the train reaches its constant speed regime, and acceleration is zero. The train operates with the lowest operation power consumption in this region, lower μ producing lower operation power consumption due to lower running resistance value and longer trip time.

In the third stage of operation, the braking operation start (deceleration stage) and the train start to decelerate until it stops momentarily at the station platform. According to the above experimental result, the train propulsion system is not exerting any tractive force due to braking operation. The fastest train operation that reaches the breaking point will produce lower station-to-station travel time. Meanwhile, according to the above finding, the reduction of μ from 0.5 to 0.3 reduced approximately 4 seconds of station-to-station trip due to higher acceleration rate to attain constant speed region; μ=0.3 achieved the breaking point faster compared to μ=0.5. According to research in a metro, an average reduction of 5 seconds is recorded in their research in a decrease of 40% of friction coefficient [5].

The experimental result shows that operation power consumption during acceleration and constant speed stage decresed approximately linear with the decrease of μ from 0.5 to 0.3 from the effect of rail grinding procedure. According to the power consumption profile before and after rail grinding, reduction of $\mu = 0.5$ before rail grinding being applied to $\mu = 0.3$ after rail grinding being applied producing 9% lower operation power consumption rate in 40% reduction in track coefficient of friction. Meanwhile, according to research in Yizhuang Line China metro, that use tasimilar track gauge, type of rolling stock and maximum operation speed, on influnce of running resistance on operation power consumption rate, average of 3% of operation power consumption rate is reduced in every 20% reduction of track coefficient of friction [5]. Therefore, the results refect the finding of Shuai *et ai*., 2016 in China metro system as average reduction of 9% is recorded for 40% (μ =0.5 to μ=0.3) reduction of μ. In addition, according to research on top of rail friction modifier using rail lubrication, an average of 5.3% and 7.8% reduction of operation power consumption rate is recorded in the research for curve and tangent rail track [6].

3. CONCLUSION

According to the finding in the above section on operation power consumption before and after rail grinding being applied, it can be concluded that rail grinding had successfully lower the μ, therefore lower the resistance value in the Davis equation. The operation power consumption after rail grinding is about 9% lower compared to before rail grinding. The train station-to station trip time is also reduced due to the increase in acceleration rate during the first stage of the rail operation (acceleration region), therefore the rail operation enters the breaking point faster. The changes in μ from higher value to much lower value had successfully lower the operation power consumption by the decreasing of the traction force due to the reduction in resistance. In addition, changes in the A value of Davis equation using rail grinding method successfully lower the power consumption value in the study and it can be concluded that the A value of Davis Equation bring significant effect to operation power consumption by reduction of 4% of operation power consumption in μ=0.1 reduction in μ.

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