The Demand of Specific Power for Trucks Operation Safety on The Uphill Section of Expressway

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Abstract—In this paper, the vehicle dynamics simulation software Trucksim was used to build road models and truck models to test the driving speed and climbing distance of 6-axis trucks under different conditions. By comparing with the correlation of the maximum slope length in the "Road Route Design Specification" (JTG D20-2017), we determine the demand of specific power for trucks on expressways with different design speeds. The results show that the initial speed, specific power and slope of the road affect the maximum slope length of the vehicle. The maximum slope length increases with the increase of the initial speed and the specific power of the vehicle and it decreases with the degree of longitudinal slope increases. The Demand of Specific power for trucks on China's expressways increase with the decrease in design speed, which is 7.0kW/t (120km/h), 8.0kW/t (100km/h), and 9.0kW/t (80km/h) respectively.

1. INTRODUCTION
The proportion of 6-axle trucks on China's expressways has increased from 15.89% in 2008 to 39.49% in 2016. 6-axle trucks have become the leading model of China's expressways [1]. However, the 6-axis truck has low dynamic performance and insufficient climbing power, which results in a large difference in running speed between the 6-axis truck and the passenger bus with good dynamic performance. It leads to the decrease of road capacity and service level, and even leads to collision, rear-end collision and other vicious traffic accidents, resulting in casualties and property losses. According to statistics, among the major and major traffic accidents on national expressways, 21.96% of them were caused by 6-axle trucks from 2013 to 2017. Among them, rear-end collisions accounted for 40.43% of the total number of accidents, which was the main accident pattern[2]. Specific power (unit kW/t) is the ratio between the maximum net power of the engine and the maximum allowable total mass of the motor vehicle. It is calculated by dividing the rated power of the engine by the total full load mass of the vehicle (including the weight of the vehicle). Compared with engine power, specific power can be a more effective measure of vehicle dynamic performance. It can be considered that the higher the specific power, the better the vehicle dynamic performance.
“Technical Conditions for Safe Operation of Motor Vehicles” (GB 7258-2017) stipulate: The specific power of low-speed vehicles and tractor transport units shall be greater than or equal to 4.0kW/t, and the specific power of other motor vehicles except trolleybuses and pure electric vehicles shall be greater than or equal to 5.0kW/t [3]. Among them, low-speed vehicle refers to the design of the maximum speed is less than 70km/h of the car. At present, the maximum speed of 6-axis trucks is mostly 90km/h-120km/h. According to the stipulation, the specific power of China’s trucks should be no less than 5.0kW/t.

Although there are a lot of researches on specific power of large trucks in foreign countries and they started earlier, there are few research achievements in recent years. There are many studies on the speed curve of truck climbing in foreign countries. However, due to the generally good dynamic performance, there is no requirement for the specific power of expressway truck. Us Road Capacity Manual HCM and US National Highway and Transportation Association standard AASHTO designed the climbing lane by studying the performance curve of large trucks’ uphill speed. However, only one type of vehicle with a specific power of 120kg/kW is considered in this study. With the development of the society, the increase of freight, the emergence and growth of heavy vehicles, the emergence of problems caused later scholars to solve them. For example, Gillespie[4] first proposed the specific power model, which he believed was best used for vehicle description. To solve this problem, he collected vehicle mass to power ratio data from five states. According to the data, he pointed out that the selection of representative models in the HCM was not appropriate because there was no representative type feature at all. Rakha[5-7] et al. introduced the parameter of the specific power of large trucks to study the driving characteristics of large trucks along longitudinal slopes, and obtained the running speed curve of large trucks. After that, they modified the model and developed the Trucksim software program to verify the model. Lan C J [8] also believed that AASHTO had problems in the study of truck climbing performance. He pointed out that it only selected one specific power, which could not meet the requirements of subsequent models. As a result, he designed a new calculation model, which introduced the performance parameter of the specific power of large trucks. The model can better reflect the running speed characteristics of different vehicle types, thus reflecting the rationality of the section design.

Chinese scholars have also conducted relevant studies on specific power. Rong Jian [9] introduced $P_q$, which was substituted into the driving equation of longitudinal slope section, and calculated the driving speed at a certain time point. Zhou Ronggui et al [10-12] put forward the index of vehicle specific power, which can be used to predict vehicle longitudinal slope running speed and guide the regulation of China’s design standards on maximum slope and slope length limitation of longitudinal slope index. But his subjects were small- and medium-sized passenger cars. Zhao Yifei [13] proposed a set of test methods for calculating the specific power of light passenger cars by analyzing the operation characteristics of vehicles and the motion equations of vehicles on the sloping road sections where the longitudinal slope degree is greater than 3% and less than or equal to 3%, respectively. Guo teng-feng [14,15] compared China’s foreign longitudinal slope design specifications and the dominant models of freight transportation in past dynasties after the liberation of China. From the point of view of specific power, he puts forward the view that the dynamic performance of 6-axis freight cars in China is insufficient at present. Then he regarded the Specific power of 5.0 kW/t Dongfeng Tianlong 6 axis as the dominant model of truck and carried out actual vehicle experiments in the comprehensive test ground of Changan University and on the Xian-Hanzhong expressway. He used the method of speed measurement and programming to draw the up-slope speed-mileage variation diagram of the 6-axis truck with a power ratio of 5.0kW/t and gave the reference value of slope and slope length design. To sum up, relevant researches at home and abroad introduce the specific power into the speed model of vehicle climbing. According to the model, they can propose the design indexes of slope and slope length, which are essentially the way to realize vehicle-road collaboration by changing the road design. However, the cost of either rebuilding old roads or building new ones is huge. In contrast, it is more cost-effective to change the minimum value of vehicle specific power and improve vehicle dynamic performance to meet the minimum permissible speed requirement of expressway. However, there are
few studies on power demand at home and abroad.

In view of this, the paper will analyze and compare the changing characteristics of the speed with the driving distance in different conditions to determine the influencing factors of the vehicle climbing length and measure the truck climbing length in different conditions. On this basis, we can get the demand of specific power for trucks on the highway at different design speeds.

2. **THE SIMULATION EXPERIMENT**

2.1. **Test purpose**

Vehicle dynamics simulation software Trucksim was used to build vehicle models and road models for the simulation experiment. By analyzing the variation law of the vehicle speed with the driving distance when climbing the hill under different conditions, we can get the driving distance when the vehicle speed drops to the lowest allowable speed under different conditions, so as to determine the specific power demand of the highway truck.

2.2. **The simulation software**

Vehicle dynamics simulation software Trucksim was used for the simulation experiment, which was developed by MSC based on vehicle dynamics experiment data for many years. It has been widely used in truck safety performance research with high reliability.

The experiment uses Trucksim input body size, weight, power system, transmission system, aerodynamics, tires, suspension system, steering system, braking system part of the key parameters such as vehicle modeling, input road center line and line of x, y, z three-dimensional coordinate defines the geometric shape of the experimental road. Then we connect the model to Simulink for co-simulation and output the data and diagrams needed for the experiment.

2.3. **simulation model parameters**

2.3.1. **Vehicle model**

According to the test requirements, this paper takes the 3A cab over model built in the software as the blueprint, and only modifies the external dimensions, load and power system of the vehicle. The specific parameters of vehicle exterior dimensions and load are shown in Table 1, and the vehicle dynamic performance parameters are shown in Table 2. The load mass has no fixed value, so it is adjusted according to the test needs.

| parameter                  | Unit value                  |
|-----------------------------|-----------------------------|
| Tractor mass                | 8200kg                      |
| Semi trailer mass           | 6500kg                      |
| Tractor size                | 6810×2438×3200mm            |
| Semi trailer dimensions     | 12390×2480×2700mm           |
| Load size                   | 10000×2000×2500mm           |

| parameter                  | Unit value                  |
|-----------------------------|-----------------------------|
| Maximum engine power        | 300kW                       |
| Maximum engine speed        | 2100n                       |
| Maximum engine torque       | 2100N·m                     |
| Moment of inertia of crankshaft | 2.75kg·m⁻²                 |
| Idle speed                  | 800rpm                      |
2.3.2. Road model
In this paper, there are 5 simulated roads with slopes of 1%, 2%, 3%, 4% and 5%, which are 6000m long straight line, one-way two lane, 3.75m wide, 2% superelevation, pavement adhesion coefficient 0.5, and rolling resistance coefficient set to the software default value of 1.0.

2.4. Simulation test scheme
The test is planned to be divided into groups according to the initial climbing speed, longitudinal gradient and specific power of vehicles. The real-time running speed of vehicles is measured and the curve is drawn. The test groups are shown in Table 3.

![Table 3: Experimental Grouping Table](image)

3. ANALYSIS OF SIMULATION TEST RESULTS

3.1. The influence of initial speed on climbing distance
The 6-axle freight car with specific power of 6.0kw/t is selected to drive into the longitudinal slope with 3% longitudinal gradient at the initial speed of 70km/h, 80km/h, 90km/h and 100km/h respectively, and the driving speed is measured.

![Figure 1: Comparison of curves of vehicle climbing speed with driving distance under different initial speeds](image)

It can be seen from Figure 1 that the four curves coincide at about 2500 m, which means that after the same vehicle drives into the same longitudinal slope at different initial speeds, the vehicles will eventually travel at the same speed, but the distance to reach the speed is different. When the initial speed is 70 km/h, the vehicle will keep constant speed after running about 1500 m; when the initial speed is 80 km/h, the vehicle will keep constant speed after running about 2000 m; when the initial speed is 90 km/h, the vehicle will keep constant speed after driving about 2300 m; when the initial speed is 100 km/h, the vehicle will keep constant speed after driving about 2500 m. It can be concluded that under the same slope and specific power conditions, when the vehicle enters the ramp at different initial speed, the driving distance will increase with the increase of initial speed. The initial speed has a great influence on the climbing length of vehicles.
3.2. Influence of longitudinal slope gradient on climbing distance
A 6-axle truck with a specific power of 5.0kmwt is selected to drive into the longitudinal slope with a longitudinal gradient of 1% - 5% at the initial speed of 80km/h, and the driving speed is measured. The corresponding driving distance of the vehicle at the speed of 60km/h is compared.

Figure 2: Comparison of speed change trend under different slopes (5.0kwwt)

In Figure 2, the abscissa corresponding to the intersection point of each curve and the black dotted line represents the distance the vehicle travels when the vehicle speed drops to 60 km/h. It can be seen that: when the slope is 1%, the vehicle speed almost does not change, and it is always maintained at about 80km/h; when the slope is 2%, the vehicle speed drops to 60km/h after about 1500m; when the slope is 3%, the vehicle speed drops to 60km/h after 800m; when the slope is 4%, the vehicle speed drops to 60km/h after 400m; when the slope is 5%, the vehicle speed drops to 60km/h after 300m. It can be concluded that when the vehicle with the same specific power drives into the longitudinal slope with different gradients at the same initial speed, when the vehicle speed drops to the same speed value, the driving distance of the vehicle decreases with the increase of the slope effect of specific power on balance speed.

3.3. Effect of specific power on balance speed
Six axle freight cars with a specific power of 5.0kwwt-9.0kwwt are selected to drive into the longitudinal slope with 3% longitudinal slope at the initial speed of 80km/h. The driving speed is measured and the corresponding driving distance of the vehicle at the speed of 60km/h is compared.

Figure 3: Comparison of speed change trend under different specific power

It can be seen from Figure 3 that the abscissa value corresponding to the intersection point of each curve and the black dotted line represents the distance the vehicle travels when the vehicle speed drops to 60km/h. It can be seen that when the specific power is 5.0kw/t, the speed of the vehicle decreases to 60km/h after driving about 900m; when the specific power is 6.0kw/t, the speed drops to 60km/h after about 1200m driving; when the specific power is 7.0kw/t, the speed of the vehicle decreases to 60km/h after about 1200m;When the specific power is 8.0kw/t, the speed of the vehicle decreases to 60km/h after 1800m driving; when the specific power is 9.0kw/t, the speed of the vehicle is always higher than 60km/h. It can be concluded that when the vehicle with different specific power drives into the same longitudinal slope at the same initial speed and the speed drops to the same speed value, the driving distance of the vehicle increases with the increase of the specific power.
4. RESEARCH ON SPECIFIC POWER OF FREIGHT CAR

4.1. Truck climbing length

Select 80km/h as the initial speed of entering the slope, measure the driving distance of vehicles with different specific power when the speed drops to the minimum allowable speed (60km/h, 55km/h, 50km/h) of the expressway with design speed of 120km/h, 100km/h and 80km/h, and compare with the value specified in the code for design of highway alignment (JTG D20-2017). The experimental results are shown in Table 4-Table 8.

TABLE 4. Table 4 Variation of speed and slope length of heavy vehicles with specific power of 5.0kw/t

| Speed (km/h) | slope 1% | slope 2% | slope 3% | slope 4% | slope 5% |
|--------------|----------|----------|----------|----------|----------|
| 80           | 0        | 0        | 0        | 0        | 0        |
| 75           | /        | 325      | 159      | 106      | 75       |
| 70           | /        | 673      | 318      | 209      | 153      |
| 65           | /        | 1043     | 473      | 310      | 227      |
| 60           | /        | 1539     | 637      | 406      | 300      |
| 55           | /        | 2241     | 808      | 507      | 366      |
| 50           | /        | /        | 1009     | 603      | 432      |

As shown in Table 4, when the vehicle with specific power of 5.0kw/t runs on 1% ramp, the vehicle speed is always higher than 75km/h; when driving on 2% ramp, the speed decreases to 60km/h after 1539m, and to 55km/h after 2241m; when driving on 3% ramp, the speed drops to 60km/h after 637m, 55km/h at 808m and 55km/h at 1009m; When driving on 4% ramp, the speed of vehicle decreases to 60km/h after 406m, 55km/h at 507m and 55km/h at 603m; when driving on 5% ramp, the speed decreases to 60km/h after 300m, 55km/h at 366m and 55km/h at 432m.

TABLE 5. Variation table of speed slope length of heavy vehicle with specific power of 6.0kw/t

| Speed (km/h) | slope 1% | slope 2% | slope 3% | slope 4% | slope 5% |
|--------------|----------|----------|----------|----------|----------|
| 80           | 0        | 0        | 0        | 0        | 0        |
| 75           | /        | 480      | 173      | 119      | 84       |
| 70           | /        | 1050     | 353      | 236      | 174      |
| 65           | /        | 1718     | 549      | 350      | 250      |
| 60           | /        | /        | 760      | 462      | 326      |
| 55           | /        | /        | 1015     | 585      | 409      |
| 50           | /        | /        | 1409     | 712      | 486      |

As shown in Table 5, when the vehicle with specific power of 6.0kw/t runs on 1% ramp, the vehicle speed is always higher than 75km/h; when driving on 2% ramp, the vehicle speed drops to 60km/h after 1718m; when driving on 3% ramp, the speed decreases to 60km/h after 706m, 55km/h at 1015m, and 50km/h at 1409m; when driving on 4% ramp, the vehicle speed decreases to 60km/h; The speed of the vehicle decreases to 60km/h after 462m driving, 55km/h at 585m, 50km/h at 715m, and 50km/h after 326m on 5% ramp, 55km/h at 409m and 55km/h at 486m.

TABLE 6. Variation of speed and slope length of heavy vehicles with specific power of 7.0kw/t

| Speed (km/h) | slope 1% | slope 2% | slope 3% | slope 4% | slope 5% |
|--------------|----------|----------|----------|----------|----------|
| 80           | 0        | 0        | 0        | 0        | 0        |

As shown in Table 6, when the vehicle with specific power of 7.0kw/t runs on 1% ramp, the vehicle speed is always higher than 75km/h; when driving on 2% ramp, the vehicle speed decreases to 60km/h after 1718m; when driving on 3% ramp, the speed decreases to 60km/h after 1015m, and 55km/h at 1409m; when driving on 4% ramp, the vehicle speed decreases to 60km/h, The speed of the vehicle decreases to 60km/h after 462m driving, 55km/h at 585m, 50km/h at 715m, and 50km/h after 326m on 5% ramp, 55km/h at 409m and 55km/h at 486m.
As shown in Table 6, when the vehicle with specific power of 7.0kw/t runs on 1% ramp, the vehicle speed is always higher than 65km/h; when driving on 2% ramp, the vehicle speed is always higher than 65km/h; when driving on 3% ramp, the speed decreases to 60km/h after 1054m, and to 55km/h when driving at 1508m; when driving on 4% ramp, the vehicle speed drops to 60km/h after 550m, When driving on a 5% ramp, the vehicle speed will decrease to 60km/h after 366M, 55km/h at 463M and 50km/h at 560m.

| Speed (km/h) | 1%    | 2%    | 3%    | 4%    | 5%    |
|--------------|-------|-------|-------|-------|-------|
| 75           | /     | 672   | 231   | 136   | 93    |
| 70           | /     | 1395  | 479   | 280   | 190   |
| 65           | /     | /     | 730   | 418   | 279   |
| 60           | /     | /     | 1054  | 550   | 366   |
| 55           | /     | /     | 1508  | 676   | 463   |
| 50           | /     | /     | /     | 916   | 560   |

As shown in Table 7, when the vehicle with specific power of 8.0kw/t runs on 1% slope, the vehicle speed is always higher than 75km/h; when driving on 2% slope, the vehicle speed is always higher than 75km/h; when driving on 3% slope, the vehicle speed drops to 60km/h after 1715m; when driving on 4% slope, the speed drops to 60km/h after 617m; When driving on a 5% ramp, the speed of the vehicle decreases to 60km/h after 406m, 55km/h at 517m and 50km/h at 634m.

| Speed (km/h) | 1%    | 2%    | 3%    | 4%    | 5%    |
|--------------|-------|-------|-------|-------|-------|
| 80           | 0     | 0     | 0     | 0     | 0     |
| 75           | /     | /     | 296   | 151   | 102   |
| 70           | /     | /     | 628   | 310   | 206   |
| 65           | /     | /     | 992   | 470   | 307   |
| 60           | /     | /     | 1715  | 636   | 406   |
| 55           | /     | /     | /     | 848   | 517   |
| 50           | /     | /     | /     | 1172  | 634   |

As shown in Table 8, the vehicle speed of 9.0kW/t is always higher than 75km/h when running on 1% of the ramp. When driving on 2% ramps, the vehicle speed is always higher than 75km/h; When traveling on 3% ramp, the vehicle speed drops to 60km/h after traveling about 1530m. When driving on 4% ramps, the vehicle speed drops to 60km/h after traveling about 617m; When driving on 5% ramps, the speed of the vehicle drops to 60km/h after traveling about 453m, to 55km/h after traveling 597m, and to 50km/h after traveling 762m.

| Speed (km/h) | 1%   | 2%   | 3%   | 4%   | 5%   |
|--------------|------|------|------|------|------|
| 80           | 0    | 0    | 0    | 0    | 0    |
| 75           | /    | /    | 400  | 159  | 113  |
| 70           | /    | /    | 910  | 331  | 231  |
| 65           | /    | /    | 1530 | 486  | 346  |
| 60           | /    | /    | /    | 617  | 457  |
| 55           | /    | /    | /    | /    | 593  |
| 50           | /    | /    | /    | /    | 762  |
4.2. Specific Power requirements
According to Table 3-7, it can determine the minimum specific power value required by highway climbing speed at different design speeds (120km/h, 100km/h, and 80km/h), which can be taken as the demand value of specific power of trucks on the highway.

4.2.1. The design speed is 120km/h
According to the Highway Route Design Code (JTG D20-2017), the minimum permissible speed of a highway with a design speed of 120km/h is 60km/h, and the maximum longitudinal slope degree is 3%. The climbing distance of vehicles traveling on 3% longitudinal slope under each specific power and the specified value in the Highway Route Design Code (JTG D20-2017) are shown in the following table.

| Than the power (kW/t) | 5.0 kW/t | 6.0 kW/t | 7.0 kW/t | 8.0 kW/t | 9.0 kW/t | Specification values |
|----------------------|----------|----------|----------|----------|----------|-----------------------|
| Slope length (m)    | 637      | 760      | 1054     | 1715     | /        | 900                   |

The table 9 shows that the design speed of 120 km/h on the highway, in specification allows the most unfavorable conditions of longitudinal slope (3% gradient, slope length, 900 m) speed keep in 60 km/h (minimum allowable speed) stipulated in the codes above, vehicle than the minimum required power is roughly 6.0 kW/t (climbing a length of 760 m) to 7.0 kW/t (grade length 1054 m), under the design speed, should take 7.0 kW/t as van demand than power value.

4.2.2. Design speed: 100km/h
According to the Highway Route Design Code (JTG D20-2017), the minimum permissible speed of a highway with a design speed of 100km/h is 55km/h, and the maximum longitudinal slope degree is 4%. The climbing distance of vehicles traveling on 4% longitudinal slope under each specific power and the specified value in the Highway Route Design Code (JTG D20-2017) are shown in the following table.

| Than the power (kW/t) | 5.0 kW/t | 6.0 kW/t | 7.0 kW/t | 8.0 kW/t | 9.0 kW/t | Specification values |
|----------------------|----------|----------|----------|----------|----------|-----------------------|
| Slope length (m)    | 507      | 585      | 676      | 848      | /        | 800                   |

It can be seen from Table 10 that on the expressway with the design speed of 100km/h, the speed is kept above 55km/h (the minimum allowable speed specified in the specification) under the most adverse longitudinal slope condition (gradient 4%, slope length 800m), and the minimum specific power requirement of the vehicle is roughly between 7.0kW/t (climbing length 676m) and 8.0kW/t (climbing length 848m). Under the design speed, 8.0kW/t should be taken as the specific power demand value of the truck.

4.2.3. The design speed is 80km/h
According to the Highway Route Design Specification (JTG D20-2017), the minimum permissible speed of a highway with a design speed of 80km/h is 50km/h, and the maximum longitudinal slope degree is 5%. The climbing distance of vehicles driving on 5% longitudinal slope under each specific power and the specified value in the Highway Route Design Specification (JTG D20-2017) are shown in the following table.
It can be seen from Table 11 that, on the highway with the design speed of 80km/h, the speed is kept above 50km/h (the minimum allowable speed specified in the code) under the most adverse longitudinal slope condition (slope 5%, slope length 700m), and the minimum specific power requirement of the vehicle is roughly between 8.0kW/t (climbing length 634m) and 9.0kW/t (climbing length 762m). At this design speed, 9.0kW/t should be taken as the specific power demand value of the truck.

To sum up, in accordance with the relevant provisions on maximum slope and maximum slope length in Highway Route Design Specification (JTG D20-2017), in the absence of other factors, the minimum specific power required by vehicles is shown in Table 12 in order to keep the vehicle speed above the minimum permissible speed during uphill climbing.

**TABLE 12. China's freight car specific power demand table**

| Design speed (km/h) | 120 | 100 | 80 |
|---------------------|-----|-----|----|
| Specific power demand (kW/T) | 7.0 | 8.0 | 9.0 |

It can be seen from Table 12 that the specific power requirements of highway vehicles with different design speeds are different. This is because the maximum longitudinal slope of the highway at 120km/h, 100km/h and 80km/h are respectively 3%, 4% and 5%. With the decrease of the design speed, the maximum longitudinal slope increases, so the specific power demand of the vehicle increases with the decrease of the design speed. The specific power requirements of highway vehicles with design speeds of 120km/h, 100km/h and 80km/h are 7.0kW/t, 8.0kW/t and 9.0kW/t, respectively. Therefore, for plain hill area of highway, because the terrain is relatively flat open, longitudinal slope degree is low, the vehicle than the power of 7.0 kW/t can meet the demand of the highway uphill, for highway mountains high, due to large relief, also relatively large longitudinal slope degree, vehicles than the power you need to reach 8.0 kW/t, even 9.0 kW/can t meet the demand of going up to the highway.

**5. CONCLUSION**

The driving speeds of vehicles under different conditions and different climbing distances were measured, the main factors affecting the climbing distances were analyzed, and the specific power demands of trucks that can meet the speed requirements were determined in combination with the relevant provisions of Highway Route Design Code (JTG D20-2017). The following conclusions were drawn:

- In the case of the same slope and specific power conditions, vehicles enter the ramp at different initial speeds, and when the speed drops to a certain same speed, the distance driven increases with the increase of the initial speed, and the initial speed of entry has a great impact on the vehicle's climbing length.
- Vehicles with the same specific power drive into the longitudinal slope with different slope at the same initial speed, and when the speed drops to the same speed value, the driving distance of the vehicle decreases with the increase of slope.
- When vehicles with different specific power drive into the same longitudinal slope at the same initial speed and the speed drops to the same speed value, the distance traveled by the vehicle...
increases with the increase of specific power.

- The specific power demand of trucks on the expressway increases with the decrease of design speed. The specific power requirements of highway vehicles with design speeds of 120km/h, 100km/h and 80km/h are 7.0kW/t, 8.0kW/t and 9.0kW/t, respectively.

**ACKNOWLEDGEMENT**

Thanks to Chongqing Science and Technology Bureau Foundation and Frontier Project (cstc2019jcyj-msxmX0695); Chongqing Education Commission Youth Science and Technology Project (KJQN201900722) and Chongqing Expressway Co., Ltd (CK-KY-0001); Graduate Science and Technology Innovation Project of Chongqing Jiaotong University (2020S0034).

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