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A Critcal Study of Driving Performance of Heavy Duty Vehicle Running on Long Downhill Road Using Engine Brake

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Abstract: For ensuring safety of heavy duty vehicles running on long downhill sections, a model was built for the application of engine brake and service brake combination based on test results. A model of brake temperature rise for heavy duty vehicles running on long downhill sections was also constructed. For different braking modes, gear positions, speed and downhill slopes, brake temperature rising to 250°C was used as the index. Then simulation of brake temperature rise and downhill distance was researched. Simulation results illustrate that the combined braking of low gear and high speed should be adopted for heavy duty vehicles running on long downhill sections.

Keywords: Brake temperature rise, engine brake, heavy duty vehicles, running on long downhill.

1. INTRODUCTION

The implementation of develop-the-west strategy has unfolded emerging opportunities for regional economy. The center of road construction is moving from eastern plains to western mountain areas [1]. Considering cost, environment and natural conditions, standard critical design parameters are strictly followed for designing and constructing roads in steeply sloping mountainous [2-4]. Hence, driving safety on winding and steep mountain roads is one of the most important concerns that needs to be addressed in traffic safety.

When a vehicle moves on downhill roads, gravitational energy translates to kinetic energy, consequently increasing the speed of the vehicle increases. In order to ensure the safety of vehicle, certain brake force is inevitably required to control the speed. However, on long steep downhill distance, the use of brake increases and brake temperature exceeds the margins. It directly affects the brake performance and gradually deteriorates with fast movement of the vehicle [5, 6]. Therefore, while driving on steep downhill roads, continuous brake force is essentially required. Similarly, if continuous brake force fails to meet the need of braking requirements, service brake starts working. For this reason, driving performance with the combination of engine brake and service brake for heavy duty truck has been discussed in this paper.

2. FUNDAMENTALS OF ENGINE CONTINUOUS BRAKE

Common continuous brake methods include engine brake, exhaust brake, JieKebo brake, eddy current retarder, hydrodynamic retarder, *etc.* [7-10]. As compared to others, engine brake is easy to operate and is cost effective. Other assisted components are not required for engine brake. Hence, engine brake is widely used as a continuous method. Engine brake is a term used when the gas pedal is released, supply of fuel is cut off, clutches meet each other and the transmission is not in neutral gear. . Brake effect is generated by compression resistance, internal friction, air intake and exhaust resistance on driving wheels at the engine compression stroke.

3. BRAKE TEMPERATURE RISE MODEL OF HEAVY DUTY TRUCK RUNNING DOWNHILL

3.1. Brake Temperature Rise Model

When a vehicle runs on a downhill road and braking measurements are taken, the vehicle decelerates with service brake force, rolling resistance, air resistance, and continuous brake force. The stress analysis figure for vehicle braking on downhill road is shown in Fig. (**1**). When brake measures are taken on a downhill road, not only altitude and vehicle speed decelerate but also gravitational energy and kinetic energy decrease. The energy translates into thermal energy of service brake due to the work of rolling resistance, air resistance, and continuous brake force [11].

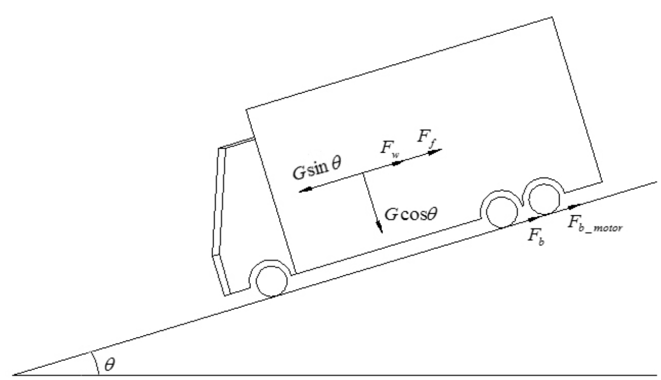

Fig. (1). Stress analysis for vehicle when downhill drive.

According to the work and energy principle in the vehicle brake process, kinetic energy and gravitational energy translate into the energy consumed by service brake, rolling

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resistance, air resistance and continuous brake force. That is to say,

$$\frac{1}{2}m(u_t^2-u_0^2)+mgs\sin\theta=(F_b+F_f+F_w+F_{b\_motor})s \tag{1}$$

where, the symbol u_t is the final velocity, u_0 is the initial velocity, m is the vehicle mass, F_b is the service brake force, F_f is the rolling resistance, F_w is the air resistance, F_{b_motor} is the engine brake force, θ is the gradient and s is the driving distance.

According to energy fundamental, brake temperature rise model was built as follows,

$$\begin{aligned}T_+ &= T_0+\frac{0.95\cdot\varepsilon}{m_g\cdot c_g\cdot n}(\frac{1}{2}m(u_t^2-u_0^2)\\ &+mgs\sin\theta\text{-}(F_f+F_w+F_{b\_motor})s)\end{aligned} \tag{2}$$

where, T_0 is the initial temperature, m_g is brake drum mass, c_g is brake drum specific heat capacity, ε is correction factor, which is related to axle load and the gap between brake shoe and brake drum.

3.2. Brake Temperature Fall Model

According to thermodynamic theory, the ways for cooling are heat conduction, heat convection and thermal radiation [12]. Among them, heat convection plays an important role while the effect of heat conduction and thermal radiation can be ignored in the process of braking. Heat convection is further explained when fluid goes over the solid surface and if temperature is variant heat transfer takes place between fluid and the solid surface. According to Newton cooling formula, brake drum temperature falls due to radiating of the surrounding air [13], Heat flux of heat convection can be calculated with equation (3),

$$P_{\mathrm{d}}=h_r\cdot A_2\cdot\left(T-T_a\right) \tag{3}$$

where, h_r is strength coefficient for heat convection between brake drum and air, T is brake drum temperature, T_a is the average temperature around brake drum, A_2 is the area of extended surface for brake drum.

Formula (4) is made according to energy conservation of brake drum temperature fall [14].

$$\mathrm{m}_g\cdot c_g\cdot\Delta T=-P_-\cdot\Delta t \tag{4}$$

Based on equation (4), the mathematical model of brake drum temperature fall is established.

$$T_-=\left(T_0-T_{\mathrm{a}}\right)e^{-At}+T_a \tag{5}$$

where, A can be calculated as follows,

$$A=\frac{\left(5.224+1.5525\cdot u_a\cdot e^{-0.0027785u_a}\right)\cdot A_2}{\mathrm{m}_g\cdot c_g}$$

3.3. Establishment of Brake Temperature Rise Model for Heavy Duty Truck Running Downhill

Brake temperature changes include the process of brake temperature rise and brake temperature fall. According to equation (2) and (5), the model of brake temperature rise when vehicle running downhill is as follows.

$$\begin{aligned}T &= T_0+T_+-T_-\\ &=2T_0+\frac{0.95\cdot\varepsilon}{m_g\cdot c_g\cdot n}(\frac{1}{2}m(u_t^2-u_0^2)+mgs\sin\theta\text{-}(F_f+F_w)s\\ &-F_{b\_motor}s)-((T_0-T_a)e^{-At}+T_a)\end{aligned} \tag{6}$$

The function relation between engine braking torque and vehicle speed obtained from experiment is formulated as equation (7), and the value of D_1,E_1,F_1 is shown in the following Table **1**.

$$T_{b\_motor}=D_1\cdot u_a^2+E_1\cdot u_a+F_1 \tag{7}$$

Table 1. Coefficient of function relation between engine braking torque and vehicle speed.

Gear Position	1st Gear	2nd Gear	3rd Gear	4th Gear
D_1	-274.706	-129.296	-60.705	-29.022
E_1	5090.029	3077.056	1855.535	1130.805
F_1	9916.007	7381.033	5402.058	3894.267
Gear Position	**5th Gear**	**6th Gear**	**7th Gear**	**8th Gear**
D_1	-13.178	-5.961	-2.514	-0.885
E_1	703.552	432.850	267.034	166.423
F_1	9148.591	8225.069	7499.445	6934.023
Gear Position	**9th Gear**	**10th Gear**	**11th Gear**	**12th Gear**
D_1	-0.855	-0.497	-0.327	-0.245
E_1	90.101	53.530	31.321	17.697
F_1	58.824	-280.429	-544.293	-751.614

The function relation between the sum of rolling resistance, air resistance and vehicle speed obtained from experiment is shown as equation (8)

$$F_f+F_w=0.371{u_a}^2+7.503u_a+3216.143 \tag{8}$$

Based on equation (6), (7) and (8), the brake temperature rise model is,

$$\begin{aligned}T &= 2T_0+\frac{0.95\cdot\varepsilon}{m_g\cdot c_g\cdot n}\{\frac{1}{2}m(u_t^2-u_0^2)+mg\mathrm{s}\frac{i}{\sqrt{1+i^2}}\\ &\text{-}[\left(0.371+D_1\right)\cdot u_a^2+\left(7.503+E_1\right)\cdot u_a+\left(3216.143+F_1\right)]\cdot\mathrm{s}\}\\ &-\left(T_0-T_{\mathrm{a}}\right)e^{-At}-T_a\end{aligned} \tag{9}$$

4. SIMULATION RESEARCH FOR HEAVY DUTY TRUCK RUNNING ON CONTINUOUS DOWNHILL ROAD

4.1. Parameters for Simulation Model

Driving performance on continuous downhill road is tested with Dongfeng Tianlong DRL4251A9 truck, which is considered as a simulation object. Simulation parameters of the tested vehicle are shown in Table **2**.

Table 2. Simulation parameters of the test vehicle.

Parameters	Symbol	Unit	Value
Vehicle mass	m	kg	56000
Brake number	n		12
Brake radius	r_{g1}	m	0.21
Vehicle wheel radius	r	m	0.5377
Brake drum mass	m_g	kg	80.05
Brake drum specific heat capacity	c_g	$J/\left(kg*{}^{o}C\right)$	482
Brake drum area	A_2	m^2	0.39
Transmission ratio	i_0		4.1
Transmission efficiency	η_t		0.89

4.2. Simulation Results

Brake temperature rise model of heavy duty truck running on continuous downhill road is studied with particular focus on different brake methods, gear position, vehicle speed and gradient. Downhill road distance is used as index of downhill driving performance when the temperature of brake rises to 250^{o}C . Comparisons are made between the usage of service brake only and the usage of combined brake, which includes engine brake and service brake. Similarly, driving performance on downhill road at 9th gear and 10th gear is also thoroughly compared with different vehicle speed and diverse gradient..

In the simulation process, it is assumed that initial temperature of brake is 30^{o}C, and the temperature around brake is 35^{o}C. The mathematical value of brake temperature is obtained with different vehicle speed, gear position, brake method and gradient.

(1) Brake temperature rise simulation result under the circumstance of the application of engine brake and service brake at 9th gear, is 50km/h.

(2) Brake temperature rise simulation result under the circumstance of the application of engine brake and service brake combination at 9th gear, is 60km/h.

(3) Brake temperature rise simulation result under the circumstance of the application of engine brake and service brake combination at 10th gear, is 50km/h.

(4) Brake temperature rise simulation result under the circumstance of the application of service brake only at 10th gear, is 50km/h.

4.3. Contrastive Analysis of Simulation Results

(1) According to Figs. (**2**, **3**), if engine brake and service brake are applied together, vehicle travels on 5% downhill road in the 9th gear is at 50km/h. When the brake temperature rises to 250^{o}C and driving distance reaches 8055.56m. Vehicle runs on 5% downhill road is at the speed of 60km/h and the distance reaches 8516.67m.

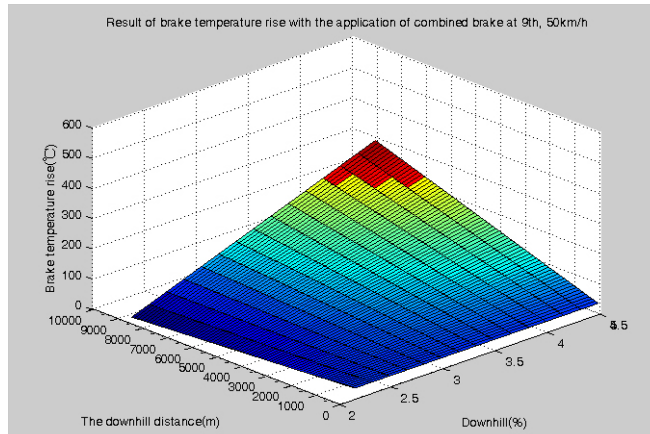

Fig. (2). Result of brake temperature rise with the application of combined brake at 9th, 50km/h.

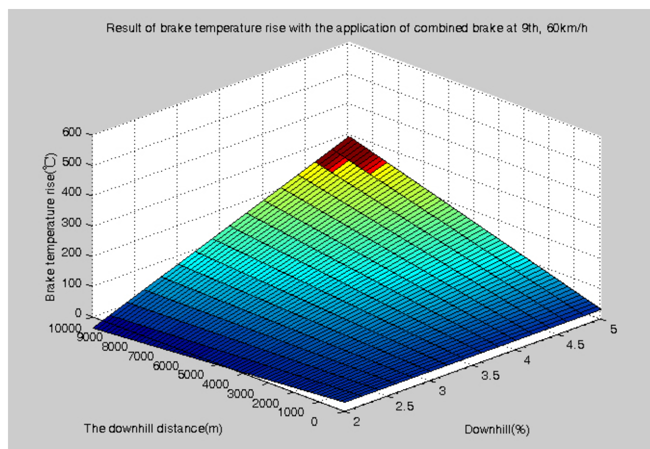

Fig. (3). Result of brake temperature rise with the application of combined brake at 9th, 60km/h.

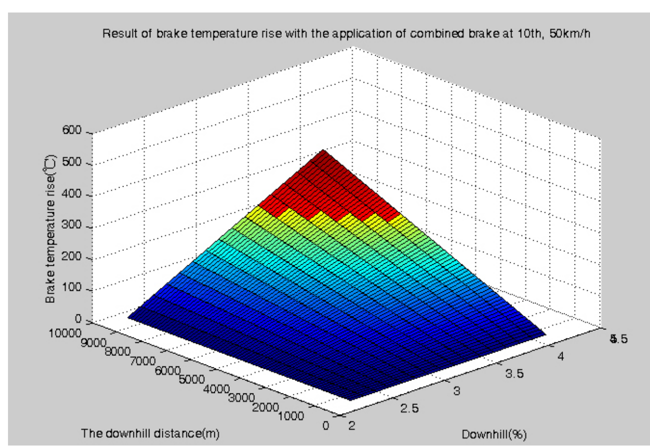

Fig. (4). Result of brake temperature rise with the application of combined brake at 10th, 50km/h.

(2) According to Figs. (**2**, **4**), if engine brake and service brake are applied together, vehicle runs on 5% downhill road in the 9th gear is at 50km/h. When the brake temperature rises to 250^{o}C driving distance reaches 8055.56m. Vehicle runs on 5° downhill road in the 10th gear at50km/h the distance reaches 6805.56m.

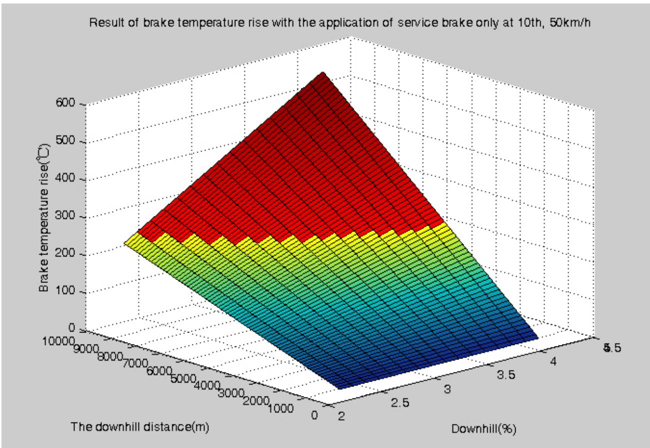

Fig. (5). Result of brake temperature rise with the application of service brake only at 10th, 50km/h.

(3) According to Figs. (**4**, **5**), if engine brake and service brake are applied together, vehicle runs on 5% downhill road in the 10th gear is at 50km/h. When the brake temperature rises to 250^{o}C the driving distance reaches 6805.56m. If service brake is applied only, vehicle runs on 5% downhill road in the10thgear is at50km/h and the distance reaches 5972.22m.

(4) According to Fig. (**4**), if engine brake and service brake are applied together, vehicle runs on 3% downhill road in the 10th gear is at50km/h. When the brake temperature rises to 250^{o}C driving distance reaches 20555.56m. similarly, when vehicle runs on 4% downhill road the distance reaches 10138.89mand vehicle runs on 5% downhill road the distance reaches 6805.56m.

(5) According to Fig. (**5**), if service brake is applied only, vehicle runs on 3% downhill road in the 10th gear is at50km/h. When the brake temperature rises to 250^{o}C, driving distance reaches 14583.33m. When vehicle runs on 4% downhill road the distance reaches 8472.22m. in the same way, when vehicle runs on 5% downhill road the distance reaches 5972.22m.

CONCLUSION

Focussing on safety problem of heavy duty vehicle running on continuous downhill road, the model of combination of engine brake and service brake is ivestigated and analyzed. The brake temperature rise model is constructed, and then brake temperature rise and downhill distance is studied with variant vehicle speed, gear position, brake method and gradient. Conclusions are made as follows through comparative analysis of simulation results.

(1) When combined brake is applied under the circumstance of same gradient and vehicle speed and higher gear position is chosen, then continuous brake force is less . Likewise, the speed of brake temperature rise is also fast and downhill distance remains short. If lower gear position is chosen, then continuous brake force is high . In the same way, the speed of brake temperature rise is slow and downhill distanceremains long.

(2) When combined brake is applied under the circumstance of same gradient and gear position,and the vehicle speed is low, then continuous brake force is also less. Likewise the speed of brake temperature rise is also fast and downhill distance remains short. If the vehicle speed is high, then continuous brake force is also high. The speed of brake temperature rise is slow and downhill distance remains long.

(3) If combined brake is applied Under the circumstance of same gradient, vehicle speed and gear position, the speed of brake temperature rise remains slow and downhill distance remains long. If service brake is applied only, the speed of brake temperature rise is fast and downhill distance remains short.

(4) Under the circumstance of same brake method, vehicle speed and gear position, the speed of brake temperature rise is fast and the downhill distance remains short if the gradient is large.

As a result, combined brake method should be chosen for heavy duty vehicle when it runs on continuous downhill road at low gear position and high speed.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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