Research of Driving Performance for Heavy Duty Vehicle Running on Long Downhill Road Based on Engine Brake

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Abstract: For the safety problem 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. And a model of brake temperature rise for heavy duty vehicles running on long downhill sections was also established. For different braking modes, gear positions, speed and downhill slopes, brake temperature rising to 250°C was used as the index. And then simulation of brake temperature rise and downhill distance was researched. Simulation results show 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 provided positive conditions for regional economy. The center of road construction is moving from eastern plains to western mountain areas [1]. Considering factors of cost, environment and natural conditions, critical parameters of design standard were chosen when designing and constructing the roads, so that the roads were steep and the slope was continuous [2-4]. As a result, safety driving on the continuous and steep mountain roads is a key scientific issue to be solved at the present stage in traffic safety field.

When vehicle runs on continuous downhill roads, gravitational energy translates to kinetic energy, so the vehicle speed increases. In order to ensure safety, certain brake force is required for the vehicle. However, with the increase of downhill distance and brake temperature, brake performance degrades [5, 6]. Therefore, certain continuous brake force is required when driving on downhill roads. And if continuous brake force fails to meet the need of braking requirements, service brake starts working. Driving performance of the combination of engine brake and service brake for heavy duty truck is discussed in this paper.

2. FUNDAMENTAL OF ENGINE CONTINUOUS BRAKE

Common continuous brake methods include engine brake, exhaust brake, JieKebo brake, eddy current retarder, hydrodynamic retarder and so on [7-10]. Compared with other ways, engine brake is easier to operate and costs less. Other assisted components are also unneeded for engine brake. As a result, engine brake is widely used as a continuous brake method.

Engine brake is a term used when the gas pedal is released, supply of fuel is cut, clutches meet each other and the transmission is not in neutral gear, engine is rotated by high speed vehicle. 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 vehicle was running on downhill road and braking measurements were taken, vehicle decelerated 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 were taken on downhill road, altitude and vehicle speed decreased. Gravitational energy and kinetic energy were also decreased. The energy translated to thermal energy of service brake in addition to the work of rolling resistance, air resistance, and continuous brake force [11].

![Stress analysis for vehicle when downhill drive.](image)

According to work and energy principle in the vehicle brake process, kinetic energy and gravitational energy translated to the energy consumed by service brake, rolling...
resistance, air resistance and continuous brake force. That is to say,
\[
\frac{1}{2}m(u_f^2 - u_i^2) + mg\sin\theta = (F_b + F_r + F_w + F_{\text{motor}})s
\]
where, the symbol \(u_f\) is final velocity, \(u_i\) is initial velocity, \(m\) is vehicle mass, \(F_b\) is service brake force, \(F_r\) is rolling resistance, \(F_w\) is air resistance, \(F_{\text{motor}}\) is engine brake force, \(\theta\) is gradient, \(s\) is driving distance.

According to energy fundamental, brake temperature rise model was built as follows,
\[
T_a = T_0 + \frac{0.95 \cdot \varepsilon \cdot (1 - m(u_f^2 - u_i^2))}{m_b \cdot c_g \cdot n^2} + mg\sin\theta\cdot(F_b + F_w + F_{\text{motor}})s
\]
where, \(T_0\) is the initial temperature, \(m_b\) is brake drum mass, \(c_g\) is brake drum specific heat capacity, \(\varepsilon\) is correction factor, which is related with 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 that fluid goes over the solid surface and fluid goes over the solid surface and surrounding air [13], Heat flux of heat convection can be calculated with equation (3),
\[
P_a = h_s \cdot A_2 \cdot (T - T_a)
\]
where, \(h_s\) 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) was made according to energy conservation of brake drum temperature fall [14],
\[
m_b \cdot c_g \cdot \Delta T = -P_a \cdot \Delta t
\]
Based on equation (4), the mathematical model of brake drum temperature fall was established.
\[
T_a = (T_0 - T_a)e^{-\alpha t} + T_a
\]
where, \(A\) can be calculated as follows,
\[
A = \left(5.224 + 1.5525 \cdot u_a \cdot e^{-0.002785s}\right) \cdot A_2
\]
where, \(u_a\) is brake drum specific heat capacity, \(A_2\) is the area of extended surface for brake drum.

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

Brake temperature changes included 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 was as follows.
\[
T = T_0 + T_r - T_a
\]
\[
= 2T_0 + \frac{0.95 \cdot \varepsilon \cdot (1 - m(u_f^2 - u_i^2)) + mg\sin\theta \cdot (F_b + F_w)}{2 m_b \cdot c_g \cdot n^2} - F_{\text{motor}}\cdot T_a - (T_0 - T_a)e^{-\alpha t} + T_a
\]

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.
\[
T_{\text{motor}} = D_1 \cdot u_a^2 + E_1 \cdot u_a + F_1
\]
Table 1. Coefficient of function relation between engine braking torque and vehicle speed.

<table>
<thead>
<tr>
<th>Gear Position</th>
<th>1st Gear</th>
<th>2nd Gear</th>
<th>3rd Gear</th>
<th>4th Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_1)</td>
<td>-274.706</td>
<td>-129.296</td>
<td>-60.705</td>
<td>-29.022</td>
</tr>
<tr>
<td>(E_1)</td>
<td>5090.029</td>
<td>3077.056</td>
<td>1855.535</td>
<td>1130.805</td>
</tr>
<tr>
<td>(F_1)</td>
<td>9916.007</td>
<td>7381.033</td>
<td>5402.058</td>
<td>3894.267</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gear Position</th>
<th>5th Gear</th>
<th>6th Gear</th>
<th>7th Gear</th>
<th>8th Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_1)</td>
<td>-13.178</td>
<td>-5.961</td>
<td>-2.514</td>
<td>-0.885</td>
</tr>
<tr>
<td>(E_1)</td>
<td>703.552</td>
<td>432.850</td>
<td>267.034</td>
<td>166.423</td>
</tr>
<tr>
<td>(F_1)</td>
<td>9148.591</td>
<td>8225.069</td>
<td>7499.445</td>
<td>6934.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gear Position</th>
<th>9th Gear</th>
<th>10th Gear</th>
<th>11th Gear</th>
<th>12th Gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_1)</td>
<td>-0.855</td>
<td>-0.497</td>
<td>-0.327</td>
<td>-0.245</td>
</tr>
<tr>
<td>(E_1)</td>
<td>90.101</td>
<td>53.530</td>
<td>31.321</td>
<td>17.697</td>
</tr>
<tr>
<td>(F_1)</td>
<td>58.824</td>
<td>-280.429</td>
<td>-544.293</td>
<td>-751.614</td>
</tr>
</tbody>
</table>

The function relation between the sum of rolling resistance and air resistance and vehicle speed obtained from experiment is shown as equation (8).
\[
F_j + F_w = 0.371 u_a^2 + 7.503 u_a + 3216.143
\]

Based on equation (6), (7) and (8), the brake temperature rise model is,
\[
T = 2T_0 + \frac{0.95 \cdot \varepsilon \cdot (1 - m(u_f^2 - u_i^2)) + mg\sin\theta \cdot i}{\sqrt{1 + i^2}}
\]
\[
-\left[(0.371 + D_1) u_a^2 + (7.503 + E_1) u_a + (3216.143 + F_1)\right] s - (T_0 - T_a)e^{-\alpha t} - T_a
\]
4. SIMULATION RESEARCH FOR HEAVY DUTY TRUCK RUNNING ON CONTINUOUS DOWNHILL ROAD

4.1. Parameters for Simulation Model

Driving performance on continuous downhill road was researched with Dongfeng Tianlong DRL4251A9 truck, which was established as a simulation object. Simulation parameters of the test vehicle are shown in Table 2.

Table 2. Simulation parameters of the test vehicle.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle mass</td>
<td>m</td>
<td>kg</td>
<td>56000</td>
</tr>
<tr>
<td>Brake number</td>
<td>n</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Brake radius</td>
<td>r_S1</td>
<td>m</td>
<td>0.21</td>
</tr>
<tr>
<td>Vehicle wheel radius</td>
<td>r</td>
<td>m</td>
<td>0.5377</td>
</tr>
<tr>
<td>Brake drum mass</td>
<td>m_b</td>
<td>kg</td>
<td>80.05</td>
</tr>
<tr>
<td>Brake drum specific heat capacity</td>
<td>c_x</td>
<td>J/(kg°C)</td>
<td>482</td>
</tr>
<tr>
<td>Brake drum area</td>
<td>A_2</td>
<td>m²</td>
<td>0.39</td>
</tr>
<tr>
<td>Transmission ratio</td>
<td>i_0</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>Transmission efficiency</td>
<td>η_t</td>
<td></td>
<td>0.89</td>
</tr>
</tbody>
</table>

4.2. Simulation Results

Aimed at different brake methods, different gear position, different vehicle speed and different gradient, brake temperature rise model of heavy duty truck driving on continuous downhill road was researched. Downhill road distance was used as index of downhill driving performance when the temperature of brake rises to 250°C. Comparisons were made between the usage of service brake only and the usage of combined brake, which included engine brake and service brake. Comparisons were made between driving performance on downhill road at the 9th gear and 10th gear. Comparisons were also made for downhill driving performance with different vehicle speed and different gradient.

In the simulation process, assumed that initial temperature of brake was 30°C, and the temperature around brake was 35°C. The mathematical value of brake temperature was 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, 50km/h.

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

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

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

4.3. Contrastive Analysis of Simulation Results

(1) According to Figs. (2, 3), if engine brake and service brake were applied together, vehicle travelled on 5% downhill road in the 9th gear at 50km/h. When the brake temperature rose to 250°C and driving distance reached was 8055.56m. Vehicle run on 5% downhill road at the speed of 60km/h and the distance reached was 8516.67m.
(2) According to Figs. (2, 4), if engine brake and service brake were applied together, vehicle run on 5% downhill road in the 9th gear at 50km/h. When the brake temperature rose to 250°C and driving distance reached was 8055.56m. Vehicle run on 5° downhill road in the 10th gear at 50km/h and the distance reached was 6805.56m.

(3) According to Figs. (4, 5), if engine brake and service brake were applied together, vehicle run on 5% downhill road in the 10th gear at 50km/h. When the brake temperature rose to 250°C and the driving distance reached was 6805.56m. If service brake was applied only, vehicle run on 5% downhill road in the 10th, at 50km/h and the distance reached was 5972.22m.

(4) According to Fig. (4), if engine brake and service brake were applied together, vehicle run on 3% downhill road in the 10th gear at 50km/h. When the brake temperature rose to 250°C and driving distance reached was 20555.56m. Vehicle run on 4% downhill road and the distance reached was 10138.89m. Vehicle run on 5% downhill road and the distance reached 6805.56m.

(5) According to Fig. (5), if service brake was applied only, vehicle run on 3% downhill road in the 10th gear at 50km/h. When the brake temperature rose to 250°C, driving distance reached was 14583.33m. Vehicle run on 4% downhill road and the distance reached was 8472.22m. Vehicle run on 5% downhill road and the distance reached was 5972.22m.

CONCLUSION

Aimed at safety problem of heavy duty vehicle running on continuous downhill road, the model of combination of engine brake and service brake is established and analyzed. The brake temperature rise model was built, and then brake temperature rise and downhill distance was researched according to different vehicle speed, gear position, brake method and gradient. Conclusions were made as follows through comparative analysis of simulation results.

(1) When combined brake was applied under the circumstance of same gradient and vehicle speed. If higher gear position was chosen, continuous brake force was smaller, the speed of brake temperature rise was faster and downhill distance was shorter. If lower gear position was chosen, continuous brake force was bigger, the speed of brake temperature rise was slower and downhill distance was longer.

(2) When combined brake was applied under the circumstance of same gradient and gear position. If the vehicle speed was lower, continuous brake force was smaller, the speed of brake temperature rise was faster and downhill distance was shorter. If the vehicle speed was higher, continuous brake force was bigger, the speed of brake temperature rise was slower and downhill distance was longer.

(3) Under the circumstance of same gradient, vehicle speed and gear position, the speed of brake temperature rise was slower and downhill distance was longer if combined brake was applied. The speed of brake temperature rise was faster and downhill distance was shorter if service brake was applied only.

(4) Under the circumstance of same brake method, vehicle speed and gear position, the speed of brake temperature rise was faster and the downhill distance was shorter if the gradient was larger.

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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Research of Driving Performance for Heavy Duty Vehicle


