Sensitivity Analysis of Vehicle Speed in Rear-end Collision Accidents

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Abstract

The rear-end accident is the main form of highway accidents in China. Among them, this phenomenon is very common that the trucks involved are basically heavily overloaded. When the rear-end accident occurs, the identification of the vehicle speed is very important. In this paper, the vehicle dynamics is used to analyze the influencing factors of vehicle speed under overload condition. Using the method of factor selection, rolling resistance coefficient, road surface gradient and air resistance coefficient on the vehicle speed and sensitivity analysis were analyzed. From the sensitivity analysis can be seen that the rolling resistance coefficient and road surface gradient have significant influence on the vehicle speed, while the air resistance coefficient is slight. Therefore, in the analysis of the actual vehicle speed calculation, the relevant factors should be considered and should be taken after a reasonable choice. A truck rear-end accident was taken as an example, and the vehicle speed sub-discussion and sensitivity analysis were carried out, and a reasonable speed conclusion was obtained.

Keywords: sensitivity, rear-end collision accident, vehicle speed, rolling resistance coefficient, road surface gradient, air resistance coefficient.

1. INTRODUCTION

In recent years, traffic accident injuries in China is very serious. A traffic accident involves human suffering in terms of injuries, loss of productivity and deaths and high socioeconomic costs(Benedetto et al., 2015; Chen and Xie, 2016). According to the Ministry of Public Security Traffic Management Bureau of China, there were 196,812 road traffic accidents, 211,882 injured in traffic crashes, and 58,523 people killed in 2014(Huang et al., 2016). Among them, 56% of the accidents occurred in the grade and highway, resulting in 40,676 people were killed and 120,556 injured(Weng et al. 2015).With the rapid economic development, China's highway in the past decade has developed very fast, and the total mileage of the highway has reached 125,000 km. Therefore, this led to highway traffic accidents have soared(Wang et al., 2016; Wang et al., 2013).Research shows that China 's highway rear-end accidents accounted for about 40% of all traffic accidents, casualties is accounted for 60%(Wu and Thor, 2015; Xiao, 2016).Rear-end accident is very serious in China's highway. Figure 1 is a highway accident statistics, it can be seen that the proportion of rear-end accidents accounted for the largest, which reaching 34.3%(Wang et al., 2016).Therefore, it is necessary to carry out analysis and research on the rear-end accident, and to grasp its characteristics, especially the analysis of vehicle speed.
Highway traffic accident is characterized by rapid speed, vehicle damage and serious casualties, especially the car rear-end collision truck (Abdel-Aty and Abdelwahab, 2003; Alpar and Stojic, 2016). There are many research on early warning of the rear-end accident on highway. The early-warning system usually considers the braking performance, vehicle speed and the vehicle type characteristics (Alpar and Stojic, 2016; Wang et al., 2016; Rakha et al., 2010; Yoshida et al., 2016). When a rear-end accident occurs on a highway, the latter usually leaves the brake imprints and scatters at the scene, which can generally be used to calculate the speed of the vehicle (Kim et al., 2007; Yi et al., 2011). In the accident, the vehicle speed in front of the rear-end collision can be difficult to obtain due to the passive nature and the instantaneous nature of the accident, and it is generally too late to take measures at the moment of the collision (Fildes et al., 2015; Germán, 2013; Yan et al., 2009).

Chinese trucks are often heavily overloaded, some even more than 3-5 times their rated load quality, or even more (Sun et al., 2007). Since the engine output power and torque are rated, the traveling speed and safety of heavily overloaded trucks are generally be reduced (Shibuya et al., 2010; Williams et al., 2015). It will affect the safety of vehicles running on the highway, and rear-end accident is easy to happen. In addition to overload, vehicle’s speed lower than 60 km/h in the highway is to be punished (Cao et al., 2013). Therefore, starting from the vehicle’s driving equation, the front vehicle’s speed in rear-end accident was carried out reasoning, and the use of the theory of vehicle power balance equations to study the speed of rear-end truck has also been discussed. On this basis, the sensitivity of the choice of various parameters in the equation to the final vehicle speed is also analyzed.

2. BASIC THEORY OF VEHICLE DYNAMICS

2.1 BASIC THEORY
the tangential external force of the road when the vehicle travels straight on a good road (Guido et al., 2016; Harb et al., 2007). It represents the ability of a vehicle to engage in transportation at the highest possible average speed. The maximum speed of a vehicle is the maximum speed that can be achieved on a good road (dry concrete or asphalt pavement) when the vehicle is fully loaded (Abdelwahab et al., 2004; Pariota et al., 2016). The maximum speed of the vehicle can be outputted when the maximum driving force acting on the vehicle and the running resistance are in equilibrium, as shown in Equation (1).

\[ F_t = F_f + F_w + F_i + F_j \]  

(1)

In Equation (1), \( F_t \), \( F_f \), \( F_w \), \( F_i \), \( F_j \) represent the driving force, rolling resistance, air resistance, road surface gradient resistance and acceleration resistance respectively when the vehicle is running.

When the vehicle travels to the maximum speed, its acceleration resistance is 0, as shown in Equation (2).

\[ F_t = F_f + F_w + F_i \]  

(2)

The driving force and the driving resistance are balanced with each other when driving, and the power of the vehicle engine and the resistance force of the vehicle are always balanced.

Therefore, taking into account the actual application, Equation (2) on both sides were multiplied by the speed, power balance equation can be obtained as shown in Equation (3).

\[ P_t \eta_t = P_f + P_w + P_i \]  

(3)

In the above, \( P_t \), \( \eta_t \), \( P_f \), \( P_w \), \( P_i \) are respectively the effective power, transmission efficiency, rolling resistance consumption power, air resistance consumption power and road surface gradient resistance consumption power of the engine output when the vehicle is running.

The Equation (3) can be transformed into the Equation (4) according to the relevant technical parameters of the vehicle.

\[ P_t \eta_t = \frac{\mu_a}{3600} (Gf + Gi + \frac{C_D A \mu_a^2}{21.15}) \]  

(4)

In the above, \( G \), \( f \), \( i \), \( C_D \), \( A \), \( \mu_a \) are respectively the vehicle's gravity, rolling resistance coefficient, road surface gradient, air resistance coefficient, vehicle upwind area and speed. Therefore, the maximum speed can be obtained from the power balance Equation (4).

### 2.2 FACTORS VALUE

In the power balance Equation (4), engine rated power, vehicle gravity, vehicle upwind area, and transmission efficiency are known parameters. Rolling resistance coefficient, air resistance coefficient and road surface gradient need to be calculated according to
the road conditions and vehicle types to refer to the relevant empirical formula or obtained by the test measurements. Their range of values is shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>f</th>
<th>i</th>
<th>C_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.01-0.02</td>
<td>0.1-0.3</td>
<td>0.60-1.00</td>
</tr>
</tbody>
</table>

According to the Chinese market for all types of heavy trucks, the statistical average of the parameters obtained in Table 2. Taking into account the overload situation, the vehicle gross weight is set to 4 times.

<table>
<thead>
<tr>
<th>Type</th>
<th>P_e(kw)</th>
<th>M(kg)</th>
<th>G=4<em>M</em>g</th>
<th>A(m²)</th>
<th>ηK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-sized truck</td>
<td>100</td>
<td>5000</td>
<td>196000</td>
<td>6.0</td>
<td>0.90</td>
</tr>
<tr>
<td>Heavy-duty truck</td>
<td>200</td>
<td>10000</td>
<td>392000</td>
<td>7.0</td>
<td>0.85</td>
</tr>
</tbody>
</table>

3. SENSITIVITY ANALYSIS

3.1 The sensitivity of rolling resistance coefficient

In order to study the rolling resistance coefficient on the sensitivity of vehicle speed, the results are analyzed. Assuming the road surface gradient is 0.02 and the air resistance coefficient is 0.80 (0.90 for heavy-duty vehicles), the road surface is mostly asphalt and concrete, and the rolling resistance coefficient is set between 0.010 and 0.020. \( \mu_{a1} \) represents the medium-sized truck’s speed, \( \mu_{a2} \) on behalf of heavy truck’s speed, the results shown in Table 3.

<table>
<thead>
<tr>
<th>f</th>
<th>0.010</th>
<th>0.012</th>
<th>0.014</th>
<th>0.016</th>
<th>0.018</th>
<th>0.020</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_{a1} )</td>
<td>50.22</td>
<td>47.73</td>
<td>45.43</td>
<td>43.31</td>
<td>41.35</td>
<td>39.54</td>
</tr>
<tr>
<td>( \mu_{a2} )</td>
<td>49.05</td>
<td>46.42</td>
<td>44.02</td>
<td>41.83</td>
<td>39.82</td>
<td>37.99</td>
</tr>
</tbody>
</table>

As the ground rolling resistance coefficient increases, the vehicle speed value gradually decreases. This is because the rolling resistance coefficient increases, the energy consumed by the rolling resistance of the wheel and the ground during the traveling of the vehicle is increased. In the case of the engine output power unchanged, the vehicle power will be reduced, which led to the maximum speed is reduced.

In order to study the sensitivity, the relationship between the variation of the rolling resistance coefficient and the variation of the vehicle speed is analyzed, as shown in Figure 3. It can be seen that as the rolling resistance coefficient changes more and more, the speed is reduced significantly. Therefore, the rolling resistance coefficient of the selection on the speed of the calculated results are very sensitive, which should be reasonable selected in the actual situation.
3.2 The sensitivity of road surface gradient

Table 4 Truckspeed 2

<table>
<thead>
<tr>
<th>( i )</th>
<th>0.010</th>
<th>0.012</th>
<th>0.014</th>
<th>0.016</th>
<th>0.018</th>
<th>0.020</th>
<th>0.022</th>
<th>0.024</th>
<th>0.026</th>
<th>0.028</th>
<th>0.030</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_1 )</td>
<td>57.37</td>
<td>54.34</td>
<td>51.54</td>
<td>48.95</td>
<td>46.55</td>
<td>44.35</td>
<td>42.31</td>
<td>40.43</td>
<td>38.68</td>
<td>37.07</td>
<td>35.57</td>
</tr>
<tr>
<td>( \mu_2 )</td>
<td>56.86</td>
<td>53.51</td>
<td>50.46</td>
<td>47.70</td>
<td>45.19</td>
<td>42.89</td>
<td>40.80</td>
<td>38.89</td>
<td>37.13</td>
<td>35.52</td>
<td>34.03</td>
</tr>
</tbody>
</table>

Assuming the rolling resistance coefficient gradient is 0.015, and the air resistance coefficient is 0.80 (0.90 for heavy-duty vehicles), the road surface is mostly asphalt and concrete, and the gradient is set between 0.010 and 0.030, the results shown in Table 4. As the gradient increases from 0.010 to 0.030, the vehicle speed is significantly reduced. This is because the energy consumed in the road surface gradient resistance increases during the course of the vehicle, resulting in a decrease in the maximum vehicle speed. The relationship between the variation of the road surface gradient and the variation of the vehicle speed is analyzed, as shown in Figure 4. When the road surface gradient change amount reaches 0.02, the variation of the vehicle speed has reached 25 km/h. It can be seen that the sensitivity of road surface gradient to vehicle speed is significant.
3.3 The sensitivity of air resistance coefficient

The sensitivity of the choice of air resistance coefficient to the calculated vehicle speed is also analyzed. When the rolling resistance coefficient is 0.015 and the road surface gradient is 0.02, the calculation results are shown in Table 5.

<table>
<thead>
<tr>
<th>$i$</th>
<th>0.60</th>
<th>0.65</th>
<th>0.70</th>
<th>0.75</th>
<th>0.80</th>
<th>0.85</th>
<th>0.90</th>
<th>0.95</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_a$</td>
<td>44.98</td>
<td>44.81</td>
<td>44.65</td>
<td>44.50</td>
<td>44.35</td>
<td>44.20</td>
<td>44.05</td>
<td>43.91</td>
<td>43.76</td>
</tr>
<tr>
<td>$\mu_a$</td>
<td>43.42</td>
<td>43.33</td>
<td>43.0</td>
<td>43.15</td>
<td>43.07</td>
<td>42.98</td>
<td>42.89</td>
<td>42.81</td>
<td>42.72</td>
</tr>
</tbody>
</table>

As the air resistance will also consume the engine power, so with the air resistance coefficient increases, the maximum speed gradually decreased. When the change of air resistance coefficient reaches 0.4, the change of vehicle speed is $1.4 \text{ km/h}$. Therefore, the air resistance coefficient for the speed of the sensitivity is not obvious, as shown in Figure 5.

![Variation of the air resistance coefficient](image)

**Figure 5.** Sensitivity of air resistance coefficient to vehicle speed

4. CASE DISCUSSION

In order to verify the validity of the power balance equation in the calculation of vehicle speed, a rear-end accident occurred on the highway was analyzed and verified. The case: On the morning of May 15, 2015, it was sunny, and a truck collided with a heavy-duty truck on the highway of Chengdu, leading to the death of the driver on the truck and the vehicle were damaged, as shown in Figure 6 and Figure 7. It happened on a dry asphalt road, and it is a typical rear-end accident. Therefore, it can be analyzed using the power balance equation. According to the truck on the staff description, in front of this seriously overloaded trucks speed is very slow, which resulting in the rear-end accident. It is likely not to reach the highway speed should be greater than 60 km/h.
The overloaded trucks in the accident were weighed and the area of the front projection was calculated, and the relevant parameters were consulted, as shown in Table 6. These parameters are substituted into the power balance equation, and the maximum value of the truck speed is obtained. Under the conditions to meet the power balance equation, the truck can reach the maximum speed of about 55 km/h. The truck is fitted with a GPS speed recorder, which is validated in conjunction with its recording and driver's transcriptions.

### Table 6 The overloaded truck’s parameter

<table>
<thead>
<tr>
<th>$P_e$(kw)</th>
<th>$\eta_r$</th>
<th>m(kg)</th>
<th>$f$</th>
<th>$C_D$</th>
<th>$A$(m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>198</td>
<td>0.85-0.90</td>
<td>44950</td>
<td>0.01-0.02</td>
<td>0.8-0.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

### 5. CONCLUSION

The phenomenon of serious overloading of goods trucks in China is very common, and the vehicle dynamic performance will be seriously affected by overloading. The vehicle speed can be analyzed by the power balance method using the vehicle system dynamics principle. From the results of sensitivity analysis, it can be seen that the influence of rolling resistance coefficient and gradient value on the final vehicle speed is very significant, while the selection of air resistance coefficient has a slight influence. Therefore, in order to effectively use the power balance equation to calculate the vehicle speed, the rolling resistance coefficient and the gradient values should be very cautious and be a reasonable choice, and the air resistance coefficient can be appropriately relaxed.

### 6. ACKNOWLEDGMENTS

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