Study of Heavy Vehicles Rollover Warning Method Based on Suspension Distortion Perception

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Abstract: With the features of high centroid, high load capacity and high aspect ratio, heavy vehicles prone to rollover when running at high speeds in the corners, so the study of heavy vehicle rollover warning method has important realistic meanings. Firstly, analysis the composition of early warning systems, and then propose the principles of rollover warning method based on suspension distortion perception; Secondly, establish the wheels sprung suspension force formula when the vehicle is cornering, take lateral load transfer rate as the rollover warning threshold and determine the size of wheel suspension pressure warning threshold when cornering; Finally, Taking a test vehicle for example, validated the rollover warning method. The simulation results show that the early warning method is capable of warning the vehicles that in the curve and has a rollover risk to avoid rollover, and improve the traffic efficiency in curve.

Keywords: Heavy vehicle, rollover, suspension distortion, suspension load, warning method.

1. INTRODUCTION

Highway curve is the Black-spots of accident, the probability of the accident to occur and the high-severity of the accident make it concerning Issue in research institutes and universities in domestic and abroad [1,2]. National Highway Traffic Safety Administration statistics show that the degree of hazard of vehicles rollover accident is just second to the car crash accident in all accidents. According to the University of Michigan Transportation Research Center statistics, during the period 2002-2006, heavy vehicles rollover accident average occur 5200 times annually in US (average deaths is 5,300), the deaths due to heavy vehicles rollover accidents are increasing year by year [3]. The deaths due to heavy vehicle rollover accidents are 4-6 times of European and American countries in our country. Visibly, heavy vehicle rollover accidents are the major traffic accidents that cause the loss of life and property, which have become the important issues affecting transportation safety.

In recent years, scholars in domestic and abroad do much relevant research on rollover warning of heavy vehicles traveling on a curve. Rollover warning methods are mainly consist of rollover warning time TTR (time to rollover) [4,5], rollover risk prediction [6] and use of lateral acceleration and the lateral load transfer rate as the early warning indicators to determine the degree of risk of vehicle rollover warning [7,8] and so on. Although scholars has done a lot of research on vehicle rollover warning method, but in the view of to improve the accuracy and timeliness of rollover warning, there is still a lot of work to do by further exploration and research.

In this paper, the rollover warning system of vehicles running in curve is analyzed; propose a rollover warning method based on suspension distortion perception which takes lateral load transfer ratio as vehicle rollover evaluation index. When index of one of the wheels reach the threshold calculated by warning system, the system can timely warning, alert the driver to control the vehicle to prevent rollover.

2. ROLLOVER WARNING SYSTEM AND THE PRINCIPLE

2.1. Composition of Rollover Warning System

Rollover warning system is composed of the suspension system, the data acquisition module, vehicle mounted device. Leaf spring is as the buffer unit in the suspension system; there are leaf spring displacement sensors, lateral acceleration sensor, cross slope sensor in the data acquisition module to monitor vehicle operating status timely; vehicle mounted device include processor module, data receiving module, alarm module and so on.

2.2. Principle of Rollover Warning System

Because the vertical load on wheels of the vehicle are constantly changing, and they are difficult to measure, so this paper takes displacement of the leaf spring in the process of compression as measured parameters, use displacement sensors to monitor compression displacement for warning [9]. According to the pressure is equal to the product of the spring rate and the amount of displacement, make Pressure threshold values are equivalent to displacement threshold which are $H_{\text{min}}$, $H_{\text{max}}$, $H_{\text{max}}$, $H_{\text{min}}$.

Fig. (1) shows the process of principle of rollover warning.
Rollover warning follows:

a) When driving the sensor operation real-time monitoring vehicles states. The lateral acceleration sensor detects the vehicle when to turn and the steering direction, the transverse cross slope sensor monitor s the slope when the vehicle is traveling, the displacement sensor of the leaf spring detects the changes of compression displacement amount of the leaf spring of suspension system to characterize the change of wheel loads.

b) After when the vehicle steer and steering direction is judged by monitoring data from the lateral acceleration sensor, the system will transfer the various parameters monitored to the processor means for calculating the real-time warning threshold of compression of the vehicle wheel suspension, and then compare with the current actual amount of displacement, and determines whether there is a danger of rollover.

c) If there is risk of rollover, the alarm unit sends an alarm signal to the driver and alerts the driver to take real-time measures to reduce the speed or decrease the steering angle of rotation to avoid vehicle rollover.

d) If there is no risk of rollover, the system will keep silent and re-calculated warning thresholds in real time for comparing again.

e) The system will be silent if vehicle steering completed.

3. ROLLOVER WARNING THRESHOLD

3.1. Steering Wheel Suspension Sprung Pressure when Turning Left

Fig. (2) is the schematic diagram of force of the front suspension spring force when turning left, the parameters in Fig. (1) have the following meanings: \( M_{1F} \) is the front axle sprung mass, \( M_{1B} \) is the rear axle sprung mass, \( N_{RF} \) is the sprung pressure value of outside of the right front wheel when turning left, \( N_{LF} \) is the sprung pressure value of outside of the left front wheel when turning right, \( a_{yF} \) is the front axle lateral acceleration, \( a \) is cross slope angle, \( B_F \) is the left-right spring spacing of front suspension, \( B_R \) is the left-right spring spacing of rear suspension, \( h_F \) is the vertical distance form front suspension sprung mass centroid height to the front axle, \( h_R \) is the vertical distance form rear suspension sprung mass centroid height to the rear axle, \( g \) is the acceleration of gravity.

From Torque balance we get:

\[
N_{LF} \cdot B_F - h_F \cdot (M_{1F} \cdot a_{yF} \cdot \cos \alpha - M_{1F} \cdot g \cdot \sin \alpha) = \frac{B_F}{2} \cdot M_{1F} \cdot a_{yF} \cdot \sin \alpha + M_{1F} \cdot g \frac{B_F}{2} \cdot \cos \alpha
\]
So the sprung pressure value of inside of the left front wheel is:

$$M_{1F} \cdot g \cdot \left( \frac{B_f}{2} \cdot \cos \alpha + h_f \cdot \sin \alpha \right) +$$

$$M_{1F} \cdot a_{vF} \cdot \left( \frac{B_f}{2} \cdot \sin \alpha - h_f \cdot \cos \alpha \right)$$

$$N_{LF} = \frac{B_f}{B_f}$$

(2)

As the same, the sprung pressure value of inside of the left rear wheel is:

$$M_{1R} \cdot g \cdot \left( \frac{B_s}{2} \cdot \cos \alpha + h_s \cdot \sin \alpha \right) +$$

$$M_{1R} \cdot a_{vR} \cdot \left( \frac{B_s}{2} \cdot \sin \alpha - h_s \cdot \cos \alpha \right)$$

$$N_{LR} = \frac{B_s}{B_s}$$

(3)

From force balance, we can get:

$$N_{R} = M_{1F} \cdot g \cdot \cos \alpha + M_{1F} \cdot a_{vF} \cdot \sin \alpha - N_{LF}$$

(4)

So the sprung pressure value of outside of the right front wheel is:

$$M_{1F} \cdot g \cdot \left( \frac{B_f}{2} \cdot \cos \alpha - h_f \cdot \sin \alpha \right) +$$

$$M_{1F} \cdot a_{vF} \cdot \left( \frac{B_f}{2} \cdot \sin \alpha + h_f \cdot \cos \alpha \right)$$

$$N_{RF} = \frac{B_f}{B_f}$$

(5)

As the same, the sprung pressure value of outside of the right rear wheel is:

$$M_{1R} \cdot g \cdot \left( \frac{B_s}{2} \cdot \cos \alpha - h_s \cdot \sin \alpha \right) +$$

$$M_{1R} \cdot a_{vR} \cdot \left( \frac{B_s}{2} \cdot \sin \alpha + h_s \cdot \cos \alpha \right)$$

$$N_{RR} = \frac{B_s}{B_s}$$

(6)

3.2. Steering Wheel Suspension Sprung Pressure when Turning Right

Fig. (3) is the schematic diagram of force of the front suspension spring force when turning right.

From Torque balance we get:

$$N_{RF} \cdot B_r - M_{1F} \cdot a_{vF} \cdot h_f \cdot \cos \alpha$$

$$= \frac{B_f}{2} \left( M_{1F} \cdot g \cdot \cos \alpha - M_{1F} \cdot a_{vF} \cdot \sin \alpha \right) + M_{1F} \cdot g \cdot h_f \cdot \sin \alpha$$

(7)

So the sprung pressure value of inside of the right front wheel is:

$$M_{1F} \cdot g \cdot \left( \frac{B_f}{2} \cdot \cos \alpha + h_f \cdot \sin \alpha \right) +$$

$$M_{1F} \cdot a_{vF} \cdot \left( h_f \cdot \cos \alpha - \frac{B_f}{2} \cdot \sin \alpha \right)$$

$$N_{RF} = \frac{B_f}{B_f}$$

(8)

As the same, the sprung pressure value of inside of the right rear wheel is:

$$M_{1R} \cdot g \cdot \left( \frac{B_s}{2} \cdot \cos \alpha + h_s \cdot \sin \alpha \right) +$$

$$M_{1R} \cdot a_{vR} \cdot \left( h_s \cdot \cos \alpha - \frac{B_s}{2} \cdot \sin \alpha \right)$$

$$N_{RR} = \frac{B_s}{B_s}$$

(9)

3.3. Determine of Rollover Warning Threshold

Lateral load transfer ratio is introduced, which is defined as the ratio of the difference and the sum of wheels vertical load [10]: This method can predict the emergency that one side of the vehicle is going to off the ground according to the magnitude of displacement of the leaf spring. LTR is defined as follows:

$$LTR = \frac{|N_l - N_o|}{N_l + N_o}$$

(10)
In the formula above, \( N_l \) —— support reaction of left wheel; \( N_r \) —— support reaction of left wheel.

Take vehicles turning left for example, when LTR is 0.85, steering wheel inside suspension sprung pressure when turning is warning threshold of the system. According to equation (13), support reaction of left and right wheels front axle meet \( \frac{N_l}{N_r} = \frac{3}{37} \).

According to the proportional conditions satisfied with left and right wheel of front Axle support reaction force and the equation (2)and(5), it can get warning lateral acceleration \( a_{l\text{max}} \).

\[
a_{l\text{max}} = \frac{17B + 40h_g \cdot \tan a}{17B \tan a - 40h_g} \cdot g \quad (14)
\]

Take \( a_{l\text{max}} \) into equation (2), it can get rollover warning threshold of pressure on the left side of the suspension \( N_{l\text{min}} \); \( a \) s the same it can get rollover warning lateral acceleration of the right side suspension and the corresponding pressure threshold \( N_{r\text{max}} \).

When the vehicle turning right, it can be obtained that rollover warning threshold of pressure of the suspensions is \( N_{l\text{max}}, N_{r\text{min}} a s \) the same.

**3.4. Examples of Simulation**

Take a 35-ton truck for vehicle mounted unit, the length is 12.5 m, the width is 3 m, the height 2.7 m, and other parameters are in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Structural parameters of trucks.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid Height ( h_c/m )</td>
<td>( g/(m/s^2) )</td>
</tr>
<tr>
<td>2</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Selecting a junction as the experimental zone path parameters: \( a \) s the inclination angle of curve 3. R is turn radius 25 m. A case study of experimental vehicles turn left, from equation (13) get the relationship between the vehicle vertical loads of wheels is \( \frac{N_l}{N_r} = \frac{3}{37} \). Put data that we have into equation (2) and (5) to get the parameters calculation results which shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Calculation results of threshold.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_l/kN )</td>
<td>( h_c/mm )</td>
</tr>
<tr>
<td>28.578</td>
<td>16.154</td>
</tr>
</tbody>
</table>

\[
V_{\text{max}} = 3.6\sqrt{Ra_{l\text{max}}} = 3.6 \times \sqrt{25 \times 21.034} = 82.6 \text{Km/h}
\]

This speed left turn is not approaching or exceeding 82.6 Km/h. Once the displacement sensor monitored the spring displacement is less than 16.154 mm on the left side or right side spring displacement is greater than 199.244 mm, switch on the alarm system.

**CONCLUSION**

1) The method of selection of pressure displacement sensor sensing pressure overcome the question that measurement of the vertical load of the vehicle is difficult, on this basis, based on this, the principle of rollover warning based on suspension deformation was proposed.

2) The calculation method of the wheel suspension sprung pressure when the vehicle is turning, and the warning method that takes the lateral load transfer rate as rollover warning threshold, thereby determining the size of warning threshold of wheel suspension pressure when cornering.

3) Taking a test vehicle for example, rollover warning simulation was done in accordance with the early warning methods proposed. The results show that the rollover warning method proposed by this paper can predict the state of the vehicle well and real-time, amount of calculation is small.

**CONFLICT OF INTEREST**

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

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**REFERENCES**


[8] W. Jian, Y. Guizhen, Z. Wei, D. Nenggen, “Real time rollover prediction for vehicle based on principles of sliding mode and
