Truck Rollover Simulation on Curved Section of Freeway Based on ADAMS

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Abstract. Truck’s rollover is one of the most single truck accident forms happened on freeway. This paper took three axis Hercules truck of Dongfeng series as the prototype, and used the ADAMS simulation software to build the rigid-flexible coupling truck vehicle model of 529 Gruebler count. The 3D coordinate of road center, road width, road super-elevation, left and right side friction co-efficient of road were used to achieve the building of road model. The road center coordinates’ tracking, the input of steering wheel angle and running speed’s controlling were used to implement the driver model’s building. Then four simulation experiment conditions, including the road conditions, traffic conditions, input conditions of steering wheel angle and the feature points of non-measured section, were set up and the rollover simulation experiment of truck were carried on. The tire vertical force values were selected as quantitative indicators to estimate rollover accidents, and mathematical statistics and numerical interpolation method were used to calculate the critical rollover safety driving speed threshold for truck of different mass center height on different ultra-high curved section, which was of great significance for understanding the mechanism of the rollover accident and putting forward the truck speed limit standard.

Introduction

Highway traffic accidents are inevitable small probability events. However, the loss of life and personal injury caused by traffic accidents is more severe than any natural disasters or man-made disasters. According to statistics, nearly 50% of traffic accidents are caused by trucks and because of severe consequences, truck accidents are deemed as a serious threat to normal highway operation. Specifically, due to truck accidents, the proportions of deaths and injuries are 60.32% and 67.1%, and property loss accounts for a high proportion—74.22%. Among truck accidents, truck’s rollover is one of the most common single truck accident forms and the most casualties happened on freeways. Up till now, how to solve truck’s rollover has attracted much attention from academia. Xu Jun and Yang Liyong have studied the influence of deformable suspensions and tires on truck’s rollover, which emphasizes suspension effects and provides a theoretical basis for truck’s rollover stability studies[1]. Combining with tire mechanics models, Hua Jiashou and Liu Hefa have set up a suspension roll mathematical model based on the analysis of independent and dependent suspensions, and after conducting roll test bench simulation tests, results show that it is reasonable to use this mathematical model to calculate the critical roll angle of vehicles[2]-[3]. Besides, Zhang Yongde and Hefeng have put forward a feasible and accurate way to obtain static rollover threshold values with the consideration of tire and suspension rolls [4]. Based on the analysis of non-linear factors influences of tire, Jin Zhilin has built a four degree-of-freedom truck rollover model and a fuzzy differential braking control strategy[5]-[6]. In addition, Professor Gao Li has studied the influence of different curve radius on driver’s safety perception under different running speed through simulation. Apart from that, D.J.M. Sampson and D. Cebon have established a mathematical model to study truck’s rollover controlling system [7]. B. Johansson has come up with a vehicle braking system that the kinetic energy value and force changing value on output chassis can be measured by
controller and force changing value can be can delivered to vehicles by distributors\textsuperscript{[8]}. S.B.CHOI has obtained a control strategy for rollover prevention to calculate rollover index and explain its feasibility through SUV model simulation\textsuperscript{[9]}.

It is believed that truck’s rollover is strongly related to the coupling of vehicle, infrastructure and adverse environment. Due to this special coupling condition, it is difficult to explain and predict the traffic accident risk under different driving and road section circumstances from historical accident data in a given section or zone without any actual accident data. Therefore, in addition to the analysis of historical accident data, a practical simulation model which can achieve the implementation of accident reconstruction and obtain the prediction of potential risk factors without enough historical accident data is essential to research the mechanism of truck’s rollover. In this paper, truck model, curved section model and driver model are established to investigate the truck’s rollover stability degree under vehicle’s sharp turning condition based on ADAMS simulation software. Besides, the critical travelling speed threshold value on highway curved section is obtained. All these are beneficial to study the mechanism of truck’s rollover and the determination of speed limit value of trucks.

**ADAMS Simulation Establishment**

**Truck Simulation Software Establishment Based on ADAMS**

A three-axis hercules truck of Dongfeng series with 10 tons load capacity was selected as the prototype vehicle when using ADAMS simulation software. The actual picture of prototype vehicle is shown in Figure 1 and its performance parameters are shown in Table 1.

![Prototype vehicle](image)

**Table 1. Performance parameters of prototype vehicle.**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Three-Axis Hercules Truck of Dongfeng Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass(t)</td>
<td>6.270</td>
</tr>
<tr>
<td>Load Capacity(t)</td>
<td>10</td>
</tr>
<tr>
<td>Actual Load(t)</td>
<td>10</td>
</tr>
<tr>
<td>Bodywork Length</td>
<td>7.7</td>
</tr>
<tr>
<td>Bodywork Height</td>
<td>3.95</td>
</tr>
<tr>
<td>Bodywork Width</td>
<td>2.50</td>
</tr>
<tr>
<td>Steering Gear Ratio</td>
<td>20</td>
</tr>
<tr>
<td>Rack Rates</td>
<td>471.0</td>
</tr>
<tr>
<td>Maximum Front Brake Torque Brake (N·m)</td>
<td>16000</td>
</tr>
<tr>
<td>Maximum Rear Brake Torque Brake (N·m)</td>
<td>4000</td>
</tr>
<tr>
<td>Brake Bias</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Mode 1(Leaf Spring): generally, multiple-leaf springs are deemed as traditional leaf springs, but in order to simplify leaf spring model and calculation process, non-uniform cross-section few-leaf-springs are selected as the leaf spring model. It is made up of uniform cross-section few-leaf-springs whose moving part number is 60 and Gruebler count is 360 in total (Gruebler count is similar to DOF, and its value is deemed as the difference between the connecting rod DOF and the sum of kinematic pair constraint number and additional driving number).
Mode 2 (Front Suspension): due to the steering function of front suspension, there must be a steering tie rod, a stabilizer bar, a damper, a steering tie rod arm and a knuckle triangle arm in one front suspension model. In this paper, the front suspension model includes two cylindrical pairs, four revolute joints, two spherical pairs, three fixed joints, one vertical constraint. In total, the number of moving parts is 33 and the Gruebler count is 13.

Mode 3 (Rear Suspension): rear suspension system has the function of driving. In this paper, the rear suspension system is a dual-drive tandem. In order to simplify selected model, two drive axles are identical. In this paper, the rear suspension includes five cylinder pair, four revolute joints, sixteen fixed joints, one point-to-surface constraint pin, one vertical constraint pin and one drive. In total, there are thirty-three moving parts and fifty-six Gruebler count.

Mode 4 (Steering System): steering system comprises a steering wheel, a steering shaft, a steering column and so on. In this paper, the steering system includes a cylinder pair, four revolute joints, a spherical pair, a moving pair, a constant-speed pair, two fixed joints, two universal joints and three couplers. In total, there are ten moving parts and one Gruebler count.

Mode 5 (Power Transmission System): a power transmission system mainly comprises an engine, a transmission and a drive axle. In detail, the power transmission system selected in this paper is made up of seven revolute joints, three couplers. In total, there are eight moving parts and ten Gruebler count.

Mode 6 (Tires): the tire model set up in this paper is PAC2002 tire model. This PAC2002 tire model meets both experimental accuracy requirement and practical requirement. It includes a set of steering wheel and a set of driving wheel. A set of steering wheel is composed of two fixed pairs and two vertical constraints. The number of its moving parts is 2 and the Gruebler count is -2. Besides, a set of driving wheel comprises four fixed pairs and two vertical constraints. The number of its moving parts is 2 and the Gruebler count is -2.

All above-mentioned models are bound and connected by communicator in ADAMS software, and the rigid-flexible coupling truck vehicle model of 529 Gruebler count is finally established as shown in Figure 2.

Figure 2. Truck vehicle model.

Figure 3. Road model.

1.2 Road Model Establishment Based on ADAMS

3D spline road surface is adopted to establish non-measured highway curved sections model.

1) The selection of road radius and longitudinal gradient of non-measured highway curved sections;

2) The determination of the 3D coordinate (X, Y, Z) of road center line landmarks (pile spacing on straight and curved section are 5m and 2m respectively);

3) The setting of characteristic parameter’s values (road width, super-elevation and left and right side friction coefficient) by Road Builder;
4) The establishment of non-measured road property file and the completion of curved road model as shown in Figure 3.

**Driver Model Establishment Based on ADAMS**

The driver model adopting closed-loop control mode is shown in Figure 4. The interaction of vehicle and road under different conditions is simulated based on the following necessary assumptions: road center line is the preliminary target trace; it always operating under the steering angular velocity control and angle magnitude control; constant speed control principle is adopted; travelling speed and steering wheel angle of trucks are controlled by the previously set driver control file which is in the format of .xml.

![Figure 4. Flow chart of closed-loop control.](image)

**Setting of Adams Rollover Test Operation Condition**

**Setting of Road Condition**

The design speed of this bi-directional four-lane highway is 100km/h; the route direction is left; the total width of road right side is 11.25m the start point coordinate is (0, 0, 0). Then eight curved section is established on the basis of different radii (400m, 500m, 600m, 700m, 800m, 1000m, 1500m, 2500m) and their correspondent super-elevation values (10%, 8%, 7%, 6%, 5%, 4%, 3%, 2%).

Assuming the pavement surface is absolutely smooth, the only one influence factor of pavement property is road surface attachment co-efficient. Moreover, in terms of pavement materials, dry asphalt concrete pavement is selected as representing pavement whose attachment co-efficient value is 0.6.

**Setting of Vehicle Condition**

Considering full load condition of trucks (load capacity is 10t) and different loading heights (concrete values are 4.5m, 3.5m and 2.5m), the height values of trucks’ mass centers are 2.276m, 1.968m and 1.661m.

In consideration of simulation test accuracy and vehicle maximum speed values, the number of selected initial speeds is 3 and the concrete values are 100km/h, 80km/h and 60km/h.

**Setting of Truck’s Steering Wheel Angle**

Fish-hook experiment is selected as truck’s rollover simulation test under full load condition. Under such circumstance, the speed of turning the steering wheel is 720 (° /s) after trucks reach a stable state. This steering amplitude is 6.5 times of the steering wheel angle when lateral acceleration is 0.3g.

According to the experiment results, the steering wheel angle is 27(° ) when the lateral acceleration is 0.3g, so the input steering wheel angle in fish-hook experiment is 175.5(° ).

**Setting of Characteristic Points on Non-measured Highway Sections**

In order to study the truck’s rollover model at different locations when vehicle brakes, it is significant to make the characteristic points location determination on non-measured highway whose radii range from 400m to 2500m. The location settlement of T1 to T7 is shown in Figure 5.
Truck’s Rollover Simulation on Highway Curved Section

Single truck’s rollover simulation experiment was conducted on the basis of the orthogonal analysis of all mentioned experimental operating conditions. The simulation process is shown in Figure 7.

Under truck’s rollover circumstance, the vertical force acting on the left inside tire which is next to truck’s last axle is 0N. Therefore, the vertical force acting on truck’s left rear inside tire is regarded as the standard to determine truck’s rollover possibility. In simulation results show that running on different super-elevation highway curved section, trucks with different mass center height in different travelling speed shows different rollover results. When highway curved section’s super-elevation value is 7%, road surface attachment co-efficient is 0.6, truck’s operating conditions at different characteristic points are particularly explained as follows. Truck’s mass center height is 1.968m and travelling speed is 80km/h. The input figure of the vehicle steering angle and truck tire’s vertical force figure are shown in Figure 7 and Figure 8.
Based on experimental results, under vehicle’s sharp turning condition, the tire’s vertical force value of truck traveling with a speed of 80 km/h when the road super-elevation value is 7%, road surface attachment coefficient is 0.6 and the mass center height is 1.968m.

<table>
<thead>
<tr>
<th>Characteristic Points</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire’s Vertical Force Value of Truck (N)</td>
<td>0</td>
<td>0</td>
<td>4.1</td>
<td>525.1</td>
<td>1171.6</td>
<td>2770.2</td>
<td>2849.6</td>
</tr>
</tbody>
</table>

Combining the results in Figure 8 and Table 2, we can obtain that:

1) Under the sharp turning operation condition at characteristic point 1, the vertical force value of truck’s left rear inside side tire declines to 0N. It means the phenomenon of truck’s rollover. The characteristic point 1 is located in the highway straight section and cross slope is -2%, so the mass center of truck tends to the right side. Due to truck’s sharp turning to the left, truck’s rollover results from the function of highway cross slope’s negative super-elevation and lateral acceleration.

2) The truck operation condition at characteristic point 3 is similar to characteristic point 3’s. The vertical force of truck’s left rear inside tire rises slightly after it declines to 0N. Due to the influence of mass center deviation and lateral acceleration, force acting on left rear inside tire attains its limit value—the tire’s vertical force becomes 0N when a truck is turning at characteristic point 2 and 3. However, the slight rise in vertical force results from truck’s self-adjustment to ensure adequate stability, after a short time period, a truck crashes into a guardrail, so the vertical force acting on left rear inside tire goes up again after it declines to 0N.

3) When truck is under the sharp turning condition at characteristic point 4~7, the vertical force acting on left rear inside tire goes up again after it declines to a certain value. This phenomenon means there no truck’s rollover under sharp turning condition.

4) As for truck’s rollover, the direct cause of is sharp turning of steering wheel, main reason is the mutation of vehicle’s lateral acceleration mutation. The expression of truck’s rollover is that left rear inside tire’s vertical force becomes 0N.

Critical Rollover Safety Driving Speed Threshold Value on Highway Curved Section

The vertical force acting on truck’s left rear inside tire is selected as a quantitative index to judge truck’s rollover possibility. The truck’s critical tire vertical force range is from 0N to 600N. When vertical force is larger than 600N, there’s no possibility of truck’s rollover. When vertical force is 0N, truck’s rollover will happen or has happened. When vertical force value is between 0N to 600N, truck is in the critical state of rollover.

According to truck’s left rear inside tire vertical force statistics, critical truck’s rollover safety speed at different characteristic points on different highway curved sections are obtained by numerical interpolation method. The critical rollover safety driving speed thresholds of trucks with different mass center height on different super-elevation curved sections are shown in Table 3.
Table 3. Critical rollover safety driving speed threshold on different ultra-high-different mass center height.

<table>
<thead>
<tr>
<th>Mass Center Height (m)</th>
<th>Super –Elevation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>H1=1.661</td>
<td>101.57</td>
</tr>
<tr>
<td>H2=1.968</td>
<td>89.67</td>
</tr>
<tr>
<td>H3=2.276</td>
<td>74.57</td>
</tr>
</tbody>
</table>

Conclusions

1) This paper used the ADAMS simulation software to build the rigid-flexible coupling truck vehicle model of 529 Gruebler count. The 3D coordinate of road center, road width, road super-elevation, left and right side friction coefficient of road were used to achieve the building of non-measured road model. The road center coordinates’ tracking, the input of acceleration or deceleration, and running speed’s controlling were used to implement the driver model’s building under closed-loop control. Then four simulation experiment conditions, including the road conditions, traffic conditions, input conditions of steering wheel angle and the feature points of non-measured section, were set up and the rollover simulation experiment of truck were carried on.

2) The tire vertical force values were selected as quantitative indicators to estimate rollover accidents, and mathematical statistics and numerical interpolation method were used to calculate the critical rollover safety driving speed threshold for truck of different mass center height on different super-elevation curved section, which was of great significance for understanding the mechanism of the rollover accident and putting forward the truck speed limit standard.

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