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Determination of the Rollover Limitation of a Vehicle When Moving by 4-dimensional Plots

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Abstract:

A vehicle rollover can occur when the driver steers at high speed. The vehicle is rolled over when the wheels are entirely separated from the road surface, i.e., the vertical force at the wheel will approach zero. This article aims to determine the rollover limitation of the vehicle under different conditions. The model of a complex dynamic is used to simulate vehicle motion. This model is a combination of three more petite models. It considers the impact of additional nonlinear variables. Therefore, it is considered the first novelty of the article. The calculations and simulations are performed in the MATLAB environment with specific conditions. Simulation results are given in the form of 4-dimensional plots; this is the second novel point of the article. This graph can fully show the dependence of the rollover limitation on other parameters. According to this result, if the vehicle's speed or height is increased, the vehicle's limited roll angle also increases. This reduces the vertical at the wheel. Once this force value reaches zero, the vehicle's roll angle will reach its maximum. The vehicle has the ability to roll over at any time. In addition, the magnitude of the steering angle also increases the risk of rollover. The article's results can be used to establish a rollover function, which describes the relationship between the rollover limitation and other factors. This content will be further developed in the upcoming studies.

Keywords: Rollover; Simulation; 4-dimensional Plot; Vehicle dynamics.

1. INTRODUCTION

The automotive industry has been developing comprehensively for more than 130 years. Today, vehicles are much larger in size and travel speed than those of the past. Therefore, the vehicle's stability and safety are important issues that need full attention. The vehicle's instability when moving on the road can be described by several phenomena, of which the phenomenon of vehicle rollover is the most dangerous. Rollover accidents often have significant consequences for passengers and cargo on board [8].

The rollover phenomenon occurs when the wheels are entirely lifted off the road, i.e., the vertical force at the wheels will approach zero [2,20,22]. It is different from the phenomenon that the wheel is separated from the road surface when the vehicle body vibrates (this problem is often studied in the control problems of the suspension system). As for the problem of rolling over, the wheel cannot return to its original state after being lifted off the road. The vehicle is rolled over due to the excessive roll angle of the vehicle's body. The roll angle will reach its maximum limit once the vertical force at the wheel is zero [1]. The rollover phenomenon usually occurs when the vehicle steers to avoid an obstacle or enters a roundabout [4]. Then, centrifugal force can appear. This force is referred to as the center of gravity of the vehicle. Therefore, it will cause a moment that causes the vehicle's body to tilt [2]. There are four common causes of rollovers. Firstly, external factors such as lateral wind force can affect the vehicle when traveling in bad weather conditions [9,26]. However, the value of the lateral wind force is usually not significant. The cases of rolling over due to the lateral wind force are not many. The second cause of this phenomenon is the size of the vehicle. The larger the vehicle's height and the smaller the wheelbase, the more the vehicle's roll moment will increase. This was pointed out by Nguyen et al. [15]. It is not easy to adjust the size of the vehicle because it will affect the performance of the vehicle. The third cause of this phenomenon is the speed of the vehicle. This is considered to be the leading cause of the transverse rollover phenomenon. If the velocity is more significant than remarkable, the centrifugal force will increase proportionally to the square of the velocity. Therefore, the risk of a rollover will be higher. Finally, the value of the steering angle also dramatically affects the problem of vehicle instability. If the steering angle or steering acceleration is greater, the rollover limitation will be reduced rapidly, making the vehicle more prone to rolling over.

In [12], Li and Bei introduced the concept of a static roll index. According to Xin et al., this index depends on the size of the vehicle [25]. However, the static roll index was not significant in the study. Therefore, the dynamic roll index replaces the static roll index. The dynamic roll index, also known as LTR (Load Transfer Ratio), is described in [24]. According to Shin et al., this index is a function of the difference in vertical force between the wheels. The vehicle rolls over once the value of this indicator reaches 1 [10]. This index is used in many rollover studies [5,28].

When studying roll dynamics, there are several commonly used dynamical models. In [27], Zhang et al. combined a half-dynamics model and a linear single-track dynamics model. This is a fairly common model. However, it is relatively simple. However, the accuracy is usually not high. With this model, the tire is treated as a linear deformation [6]. A spatial dynamics model should be used to comprehensively evaluate the vehicle's motion. This model takes into account the influence of all wheels [29]. It can be used for commercial vehicles or special vehicles [13]. The spatial dynamics model must be integrated with nonlinear double-track dynamics. Nguyen in [19] did this combination. However, establishing this model is quite complicated. Several solutions have been used to improve the vehicle's stability when traveling at high speed. According to Nguyen, the stabilizer bar can reduce the roll angle of the vehicle body when steering [21]. In addition, the active suspension system also improves vehicle stability [11,16,18,23]. Besides, redistributing power to the drive wheels can also reduce the rollover phenomenon [7]. The rollover phenomenon can be correctly predicted if the rollover limitation is predefined.

This article focuses on investigating the vehicle's rollover limitation when steering. Simulation methods are used to collect the data. A model of complex dynamics is used to simulate vehicle oscillations. This model combines a spatial dynamics model, a nonlinear double-track dynamics model, and a nonlinear tire model. This is the first new point in the article. The article's results are presented in the form of a 4-dimensional plot. It describes the dependence of the rollover limitation on the vehicle's velocity and the height of the center of gravity. This is considered the second novelty of the article. The layout of the article consists of four sections: introduction, material, results, and conclusions. The specific contents are presented in the sections below.

2. METHOD

A dynamics model describes a vehicle's oscillations. This article uses a complex dynamic model, a combination model of spatial dynamics (7 DOFs), and a nonlinear double-track dynamics model (3 DOFs). Considering the model of the spatial dynamics in Figure 1, the system of equations describing the vehicle's oscillation is given as follows:

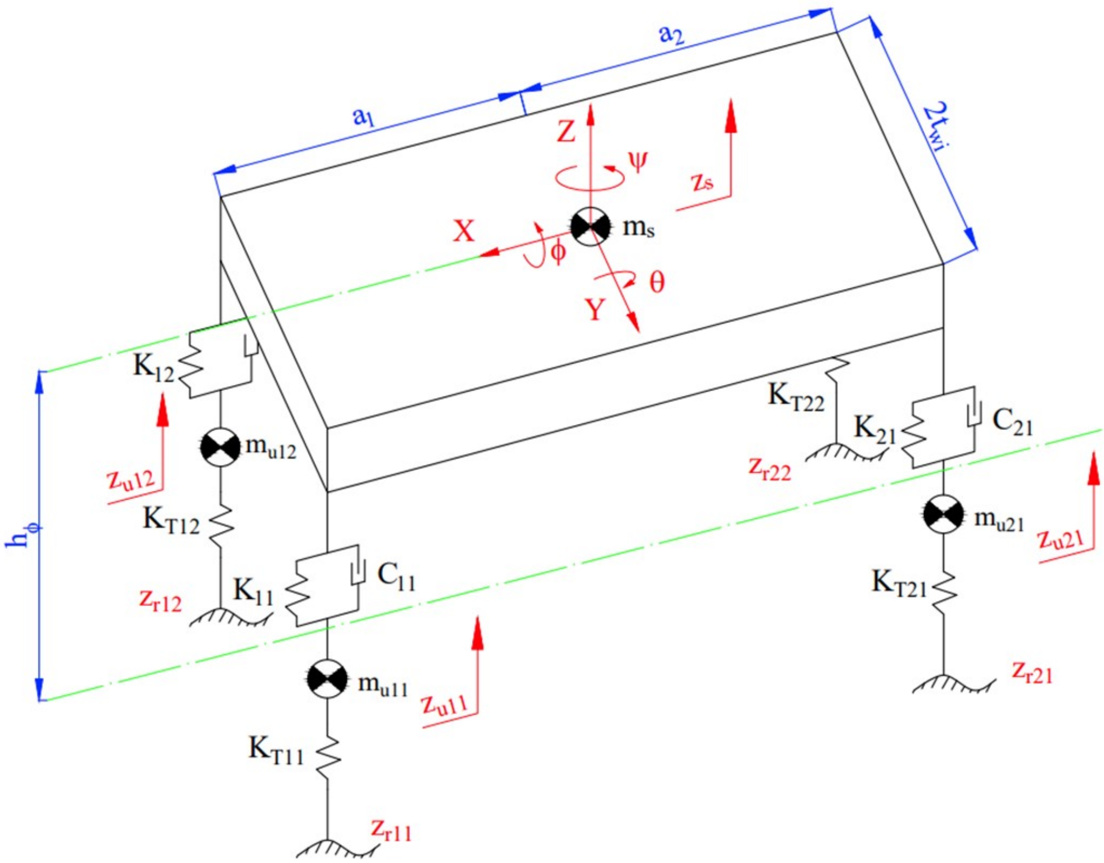

Fig. 1. Model of the spatial dynamics.

$$m_s\ddot{z}_s=\sum_{i,j=1}^{2}\left(K_{ij}\left[z_s-z_{uij}+(-1)^{j+1}t_{wi}\phi+(-1)^{i+1}a_i\theta\right]+C_{ij}\left[\dot{z}_s-\dot{z}_{uij}+(-1)^{j+1}t_{wi}\dot{\phi}+(-1)^{i+1}a_i\dot{\theta}\right]\right) \tag{1}$$

$$\left(J_\phi+m_sh_\phi^2\right)\ddot{\phi}=\sum_{i,j=1}^{2}\left[(-1)^{j-1}\begin{pmatrix}K_{ij}\left[z_s-z_{uij}+(-1)^{j+1}t_{wi}\phi+(-1)^{i+1}a_i\theta\right]+\\ C_{ij}\left[\dot{z}_s-\dot{z}_{uij}+(-1)^{j+1}t_{wi}\dot{\phi}+(-1)^{i+1}a_i\dot{\theta}\right]\end{pmatrix}t_{wi}\right]$$
$$+\left\{gsin\phi+\left[\dot{v}_y+\left(\dot{\beta}+\dot{\psi}\right)v_x\right]cos\phi\right\}m_sh_\phi \tag{2}$$

$$\left(J_\theta+m_sh_\theta^2\right)\ddot{\theta}=\sum_{i,j=1}^{2}(-1)^{i-1}\begin{pmatrix}K_{ij}\left[z_s-z_{uij}+(-1)^{j+1}t_{wi}\phi+(-1)^{i+1}a_i\theta\right]\\ +C_{ij}\left[\dot{z}_s-\dot{z}_{uij}+(-1)^{j+1}t_{wi}\dot{\phi}+(-1)^{i+1}a_i\dot{\theta}\right]\end{pmatrix}a_i \tag{3}$$

$$m_{uij}\ddot{z}_{uij}=K_{Tij}\left(z_{rij}-z_{uij}\right)-K_{ij}\left[z_s-z_{uij}+(-1)^{j+1}t_{wi}\phi+(-1)^{i+1}a_i\theta\right]$$
$$-C_{ij}\left[\dot{z}_s-\dot{z}_{uij}+(-1)^{j+1}t_{wi}\dot{\phi}+(-1)^{i+1}a_i\dot{\theta}\right] \tag{4}$$

The v_x, v_y, and ψ are determined by the nonlinear double-track dynamics model (Figure 2) [14,17]. This model has 3 degrees of freedom, so it is necessary to establish three equations corresponding to the three directions of motion of the vehicle.

$$\left(m_s+\sum_{i,j=1}^{2}m_{uij}\right)\dot{v}_x=\sum_{i,j=1}^{2}\left(F_{xij}cos\delta_{ij}-F_{yij}sin\delta_{ij}\right)-F_1+\left(m_s+\sum_{i,j=1}^{2}m_{uij}\right)\left(\dot{\beta}+\dot{\psi}\right)v_y \tag{5}$$

$$\left(m_s+\sum_{i,j=1}^{2}m_{uij}\right)\dot{v}_y=\sum_{i,j=1}^{2}\left(F_{xij}sin\delta_{ij}+F_{yij}cos\delta_{ij}\right)-F_2-\left(m_s+\sum_{i,j=1}^{2}m_{uij}\right)\left(\dot{\beta}+\dot{\psi}\right)v_x \tag{6}$$

$$J_\psi\ddot{\psi}=\sum_{i,j=1}^{2}\left[\left(-1\right)^j\left(F_{xij}cos\delta_{ij}-F_{yij}sin\delta_{ij}\right)t_{wi}+\left(-1\right)^{i+1}\left(F_{xij}sin\delta_{ij}+F_{yij}cos\delta_{ij}\right)a_i+F_ic_i-M_{zij}\right] \tag{7}$$

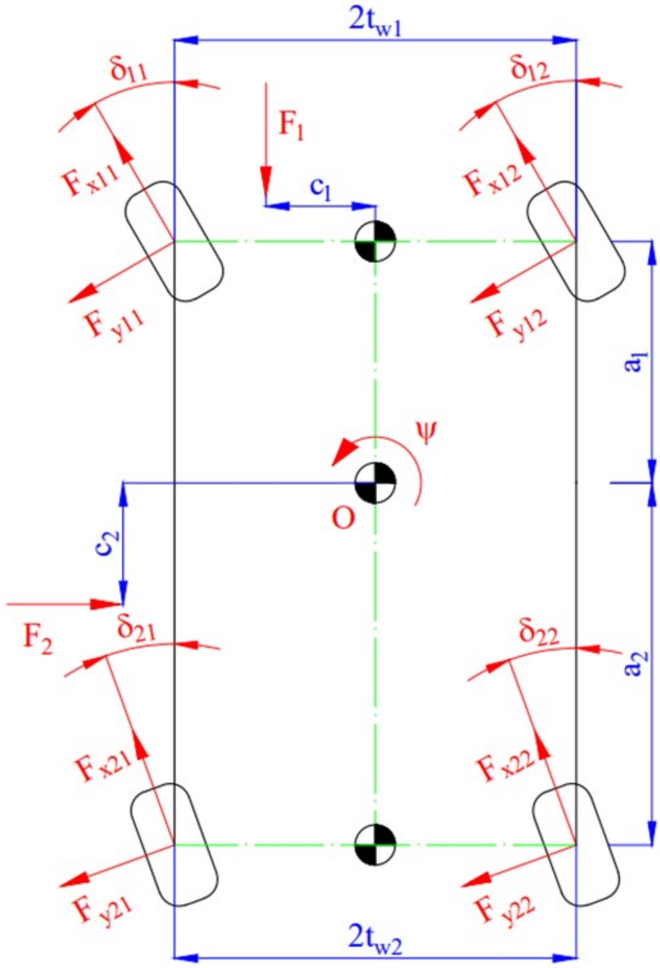

Fig. 2. Model of the nonlinear double-track dynamics.

The values of longitudinal force Fx, lateral force Fy, and aligning moment Mz at the wheel are determined by the tire model. In this study, the Pacejka tire model with experimental parameters was used.

$$F_x=D_xsin\left[C_xartan\left(B_x\kappa_x\right)\right] \tag{8}$$

$$F_y=D_ysin\left[C_yartan\left(B_y\kappa_y\right)\right]+S_{vy} \tag{9}$$

$$M_z=D_zsin\left[C_zartan\left(B_z\kappa_z\right)\right]+S_{vz} \tag{10}$$

After the dynamics model has been established, the simulation process will be carried out.

3. RESULTS

3.1. Simulation conditions

Three cases are used in the simulation, which is done in the MATLAB-Simulink system (Figure 3). The steering angle value will be modified in these instances. Table 1 lists the vehicle's specifications. The speed, steering angle, and distance from CG (center of the gravity) to RA (roll axis) are all inputs to the simulation problem. The value of RA can be referenced from the CARSIM software. Using this range of values helps to describe better the roll angle's dependence on the height of the center of gravity. The maximum roll angle and the minimum vertical force at the wheel are among the problem's outputs.

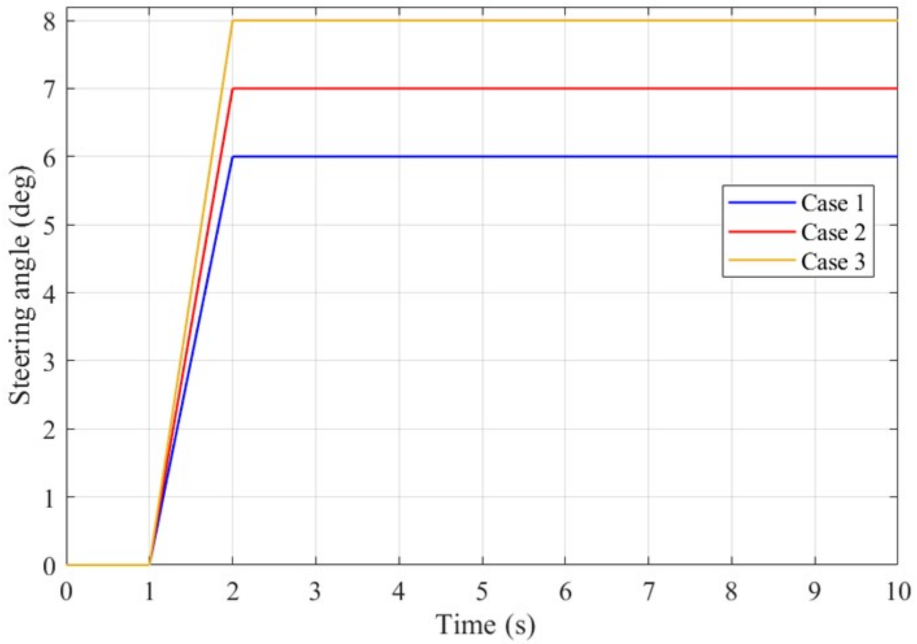

Fig. 3. Steering angle.

Table 1. Details about the simulation parameters.

Symbol	Description	Value	Unit
m_s	Sprung mass	1740	kg
m_{uij}	Unsprung mass	38	kg
t_{wi}	Half of the track width front/rear axle	730/725	mm
a_i	The distance between the center of gravity and the front or rear axle	1230/1620	mm
J_ϕ	Moment of inertia (longitudinal-axis)	725	kgm^2
J_θ	Moment of inertia (lateral-axis)	2750	kgm^2
J_ψ	Moment of inertia (vertical-axis)	2730	kgm^2

3.2. Simulation results

Figures 4, 5, and 6 depict the simulation's outcomes. The change in maximum roll angle and the lowest vertical force at the wheel is shown in Figure 4. According to this conclusion, the maximum roll angle rises as the distance between the CG and the RA increases. As a result, the vertical force at the wheel's minimal value is lowered. The maximum value of the roll angle increases as the vehicle's speed increases. The vertical force at the wheel is likewise reduced due to this. The vehicle may roll over if the vertical force at the wheel is lowered to zero. Therefore, the maximum roll angle of the vehicle will tend to decrease gradually, although the speed and distance from CG to RA will still increase.

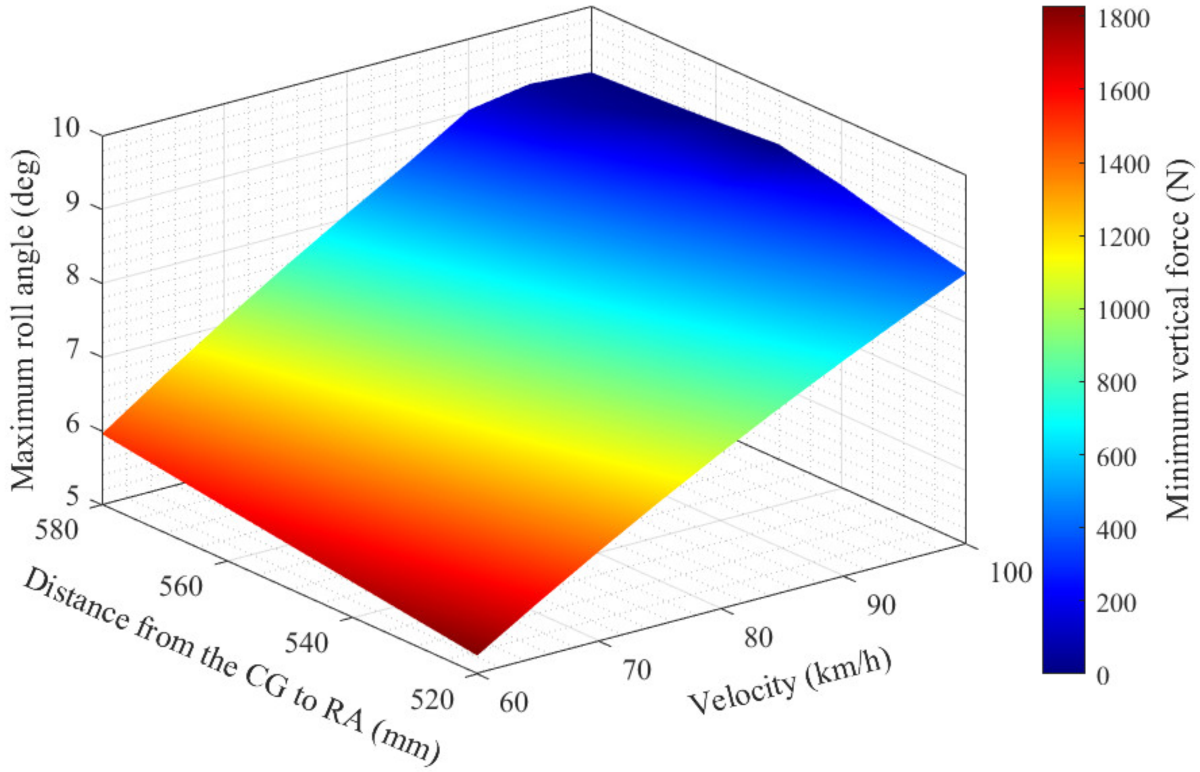

Fig. 4. Maximum roll angle (Case 1).

As the steering angle increases, the change in these values is also more considerable. The maximum roll angle of the vehicle will increase at the same speed and distance from CG to RA. At the same time, the minimum force at the wheel will also be smaller. This is shown in Figure 5. Because of the larger steering angle, the vehicle is at greater risk of rolling over sooner. If the velocity is greater or the height of the center of gravity is greater, the limited roll angle of the vehicle will decrease.

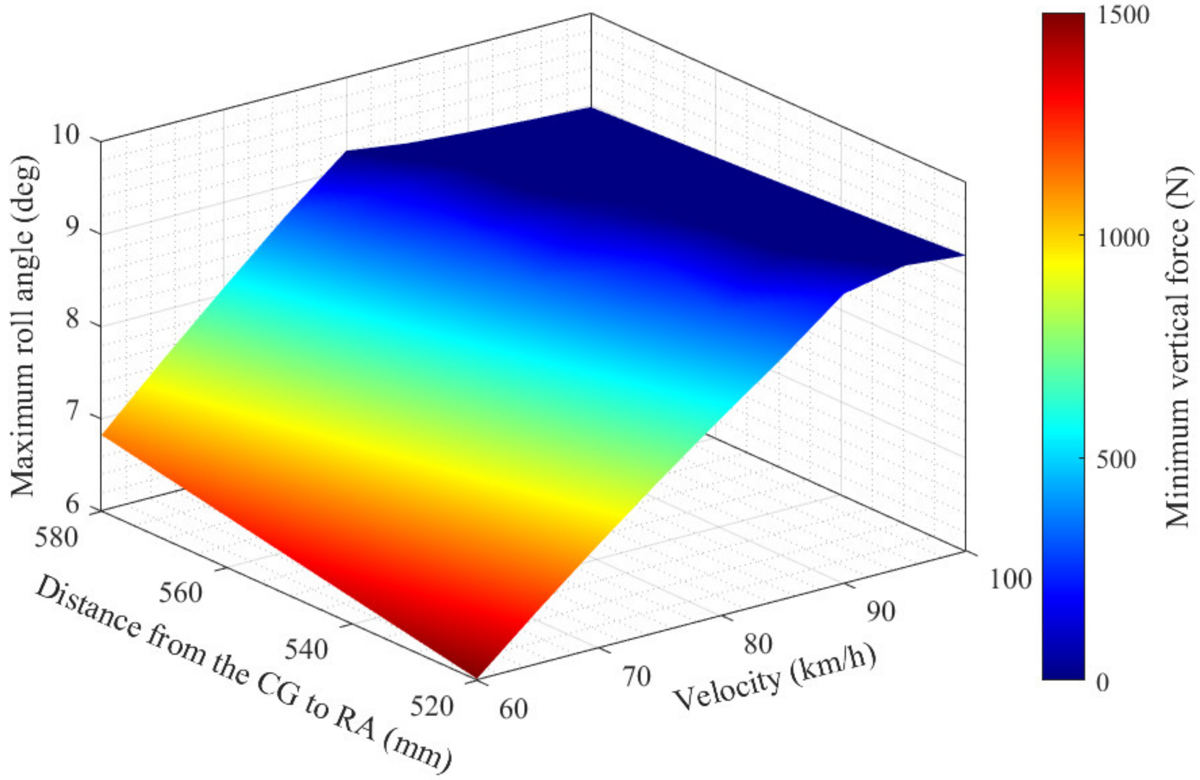

Fig. 5. Maximum roll angle (Case 2).

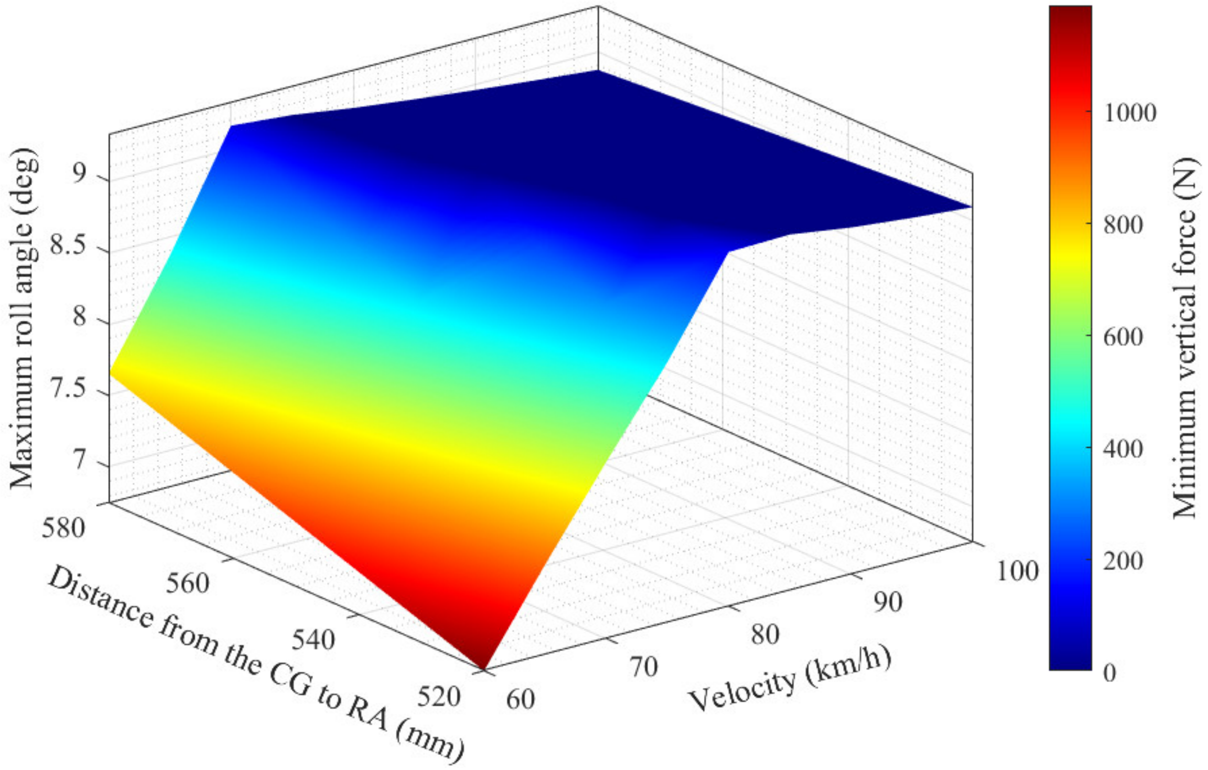

Fig. 6. Maximum roll angle (Case 3).

In the third case, this change is more pronounced (Figure 6). As a vehicle's speed rises, so does the chance of it rolling over. Besides, the distance from the object's gravitational center to the roll axis also increases the risk of rolling over. However, the effect of velocity is still more significant than size. The slope of the 4-dimensional graph demonstrates this.

4. CONCLUSION

The stability of the vehicle is a critical issue. It may affect the safety of passengers and cargo when the vehicle is on the road. There are many causes of instability, of which the rollover phenomenon is considered the most important. This phenomenon occurs when the wheel is lifted off the road, i.e., the vertical force at the wheel will approach zero. The consequences of rollover accidents are often very severe. This article studies the vehicle's rollover limitation when traveling on the road. A model of complex dynamics is used to simulate vehicle oscillations. This is a nonlinear model. It includes the influence of many factors. Therefore, its accuracy will be higher than that of other conventional models.

Simulation results are shown through 4-dimensional graphs. The parameters of the graph that show the relationship include velocity, distance from the CG to RA, maximum roll angle, and minimum vertical force. According to this result, if the speed or distance is increased, the maximum roll angle of the vehicle will also increase. This causes the minimum vertical force at the wheel to decrease. Once the value of the wheel's vertical force is reduced to zero, the risk of the vehicle rollover will appear, i.e., the maximum roll angle is reached. As the velocity or distance rises, the value of the restricted roll angle decreases. This indicates that the vehicle will be at risk of rollover sooner. If the value of the steering angle is increased, the change in the roll angle and the vertical force at the wheel will also be much larger. This is a warning signal for possible danger.

The results obtained from this study are the basis for determining the rollover limitation of the vehicle. It is necessary to provide a function representing the relationship between these parameters. It can help predict the vehicle's rollover limitation under different conditions. However, this is not very easy. In the subsequent studies, this content can be conducted.

NOMENCLATURE

ϕ	: Roll angle, rad
ψ	: Yaw angle, rad
θ	: Pitch angle, rad
δ	: Steering angle, rad
β	: Heading angle, rad
F_C	: Damping force, N
F_K	: Spring force, N
F_{KT}	: Tire force, N
F_x	: Longitudinal force, N
F_y	: Lateral force, N
F_z	: Vertical force, N
M_z	: Aligning moment, Nm
v_x	: Longitudinal velocity, m/s
v_y	: Lateral velocity, m/s
z_s	: Sprung mass displacement, m
z_u	: Unsprung mass displacement, m

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