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Research on Rollover Stability and an Anti-Rollover Warning System for the Vibroseis Truck

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Abstract: Vibroseis trucks are in danger of rollover during the steering process, which severely threatens the safety of the drivers and the equipment. Therefore, it is important to examine approaches to increase the anti-rollover ability of vibroseis trucks. According to the structural characteristics and working field of the vibroseis truck, an analysis of the influence of different factors on its rollover stability was carried out. Then, a rollover warning index and an anti-rollover warning system were established, which can achieve four levels of judgment of different driving states. A simulation analysis of the anti-rollover warning system was conducted with MATLAB/Simulink software. The results showed that this warning system could accurately determine the driving state on a flat road and a sloping road and produce four types of sound–light alarm according to different rollover states. At the same time, the vibroseis truck showed poor roll stability in the slope steering process which is more prone to rollover accidents. This study establishes a foundation for further research on the design of warning systems not only for vibroseis trucks but also for other articulated trucks.

Keywords: vibroseis truck; rollover stability; warning index; anti-rollover; warning system

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1. Introduction

As special vehicles in oil and gas exploration, vibroseis trucks are widely used in seismic exploration, having the advantages of high efficiency, environmental protection, and low cost [1]. With the developments in oil and gas exploration, vibroseis trucks can be easily used in the desert, such as the Gobi, and other harsh terrains [2]. The vibroseis truck is a heavy, low-speed special vehicle with a weight of 30 tons. Its engine is Cummins KT19-C450 with a rated power of 450 HP. The vibroseis truck is propelled by a hydraulic motor, which limits its maximum speed to 30 km/h. As a low-speed vehicle of this type, the vibroseis truck does not have any suspension system installed. With high centroid height and low stability, even though its top speed is 30 km/h, the truck still undergo rollover when it steers on a slope, which threatens severely the safety of the driver and the equipment. It is urgent to carry out research on the rollover stability and anti-rollover systems for vibroseis truck. Therefore, the comprehensive analysis of the vibroseis truck rollover stability and the development of a rollover warning system represent a significant step forward. The results of these investigations will provide vital theoretical support for designing vibroseis trucks that are safer and more stable, thus reducing the potential for rollover accidents.

Research about vehicle stability and dynamics mainly focuses on cars, SUVs, and trucks. Jin et al. [3] established a linear vehicle model to study vehicle rollover stability due to critical driving maneuvers. They suggested that a vehicle rollover stability can be improved by optimizing the parameters affecting the dynamic stability factor (DSF) in the design phase of a vehicle. Yao et al. [4] developed a dynamic model for simulating the rollover stability performances of articulated loaders, and their research showed that the proposed model was reasonable and could be used instead of field experiments. Qi

et al. [5] proposed a new roll-plane hydraulically interconnected suspension (HIS) system to enhance both the roll and the lateral dynamics of a two-axle bus. In both simulation and measurement, they proposed some basic suspension tuning rules for buses. To improve the overall rollover stability, Sree Ram et al. [6] modified the suspension design by improving the roll stiffness and optimizing the motion ratio, thereby increasing the overall rollover stability. A six-degree-of-freedom rollover model of the triaxle bus was developed by Jin et al. [7], and their results showed that the new method can precisely describe the rollover dynamics of the studied bus. To determine the rollover index, Shin et al. developed [8] a simplified lateral and vertical vehicle dynamic model. The simulation studies showed that the proposed estimation method reduced the parameter uncertainties.

To enhance vehicle steerability, lateral stability, or roll stability, Jo et al. [9] developed a vehicle stability control system whose satisfactory performance was verified with simulation. Considering chassis key subsystems, Lu et al. [10] presented an integrated control strategy to improve the rollover ability of a vehicle. The results indicated that their method could greatly improve the anti-rollover ability and lateral stability. To improve the roll stability of an articulated vehicle carrying a liquid, Saeedi et al. [11] developed an active roll control system with two different control methods. The simulation results showed that this roll control system was more successful in achieving target control and reducing the lateral load transfer ratio than the classical sliding-mode control.

The above literature illustrates that many achievements have been made in the research on driving stability and anti-rollover systems of traditional vehicles. However, few works have been carried out on the rollover stability of and anti-rollover warning systems for vibroseis trucks. The vibroseis truck is a specialized vehicle used for oil and gas exploration and, as such, plays a crucial role in the efficiency and accuracy of seismic surveys. Despite major research efforts focused on enhancing the performance of the vibrator, including investigations into its dynamic response [12], ground-coupled vibration [13], and fatigue life [14], relative little attention has been given to rollover stability and anti-rollover warning systems. It is imperative to address these aspects of the vibroseis truck technology, as they impact not only the safety of personnel and equipment but also the quality of the seismic data produced. It is necessary to develop an anti-rollover warning system for vibroseis trucks to accurately judge the driving states and avoid rollover accidents.

Based on the structural characteristics and working field of the vibroseis truck, this paper carried out an analysis of the influence of different factors on the rollover stability of a vibroseis truck. Treating speed as a monitoring value and in comparison with the critical steering speed, a rollover warning index and an anti-rollover warning system were established, which can achieve a multi-level judgment of different driving conditions. A simulation analysis of the anti-rollover warning system by MATLAB/Simulink software 2016b was conducted, and results showed that this system can provide an effective stability analysis and alarms for the vibroseis truck.

2. Rollover Stability Analysis for Vibroseis Truck

2.1. Structure of the Vibroseis Truck

As shown in Figure 1, the vibroseis truck is composed of a front body, a rear body, and an articulated steering mechanism. The articulated steering mechanism has the advantages of low energy consumption, large traction force, and simple structure. In the steering process, the stroke difference and arm difference of the hydraulic cylinders of the articulated steering mechanism make the rear body and front body generate a relative deflection and angle for steering.

2.2. Analysis of the Rollover Stability Mechanism of the Vibroseis Truck

Based on the structural characteristics and the working conditions of the vibroseis truck, slope stability, flat road steering stability, and slope steering stability were analyzed to understand the rollover stability of the vibroseis truck.

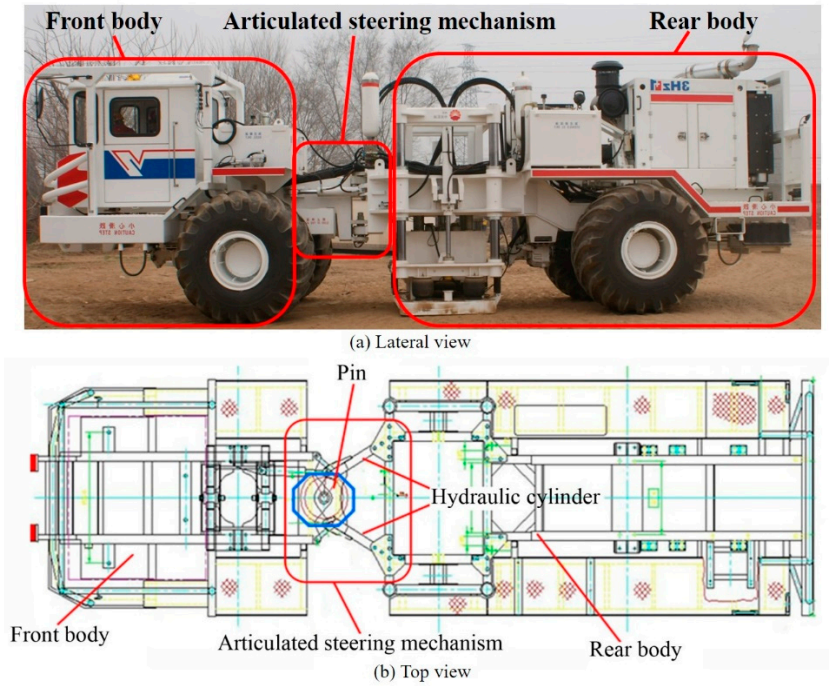


Figure 1. Vibroseis truck: (**a**) lateral view, (**b**) top view.

2.2.1. Slope Straight-Driving Stability

The basic condition for a vehicle's stability is that the gravity of the vehicle and the supporting force of the ground reach a balance. When the vibroseis truck drives straight on a certain slope with a slope angle φ, this balance will be broken if the centroid center G crosses the flip axis. The flip axis is the connection line between the load points of the front wheel and the rear wheel on the rollover side of the vibroseis truck. The critical rollover state is shown in Figure 2, where the wheel track is B, the centroid height is H, the mass of the vibroseis is M, and the acceleration of gravity is g. The critical roll angle θ can be calculated.

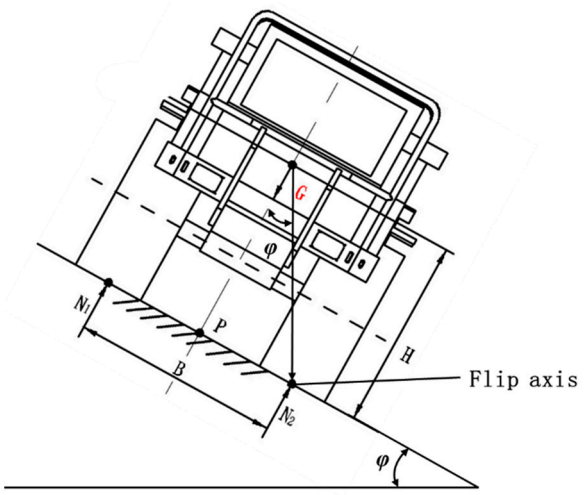


Figure 2. Critical rollover state of the vibroseis truck driving straight on a slope.

According to the principle of moment balance, the equilibrium equation is

$$Mg \cdot \sin\varphi \cdot H - Mg \cdot \cos\varphi \cdot \frac{B}{2} = 0 \quad (1)$$

$$\tan \varphi = \frac{B}{2H} \tag{2}$$

Therefore, we can obtain the critical rollover angle at the rollover critical state:

$$\theta = \varphi = \arctan \frac{B}{2H} \tag{3}$$

As the curve in Figure 3 shows, the critical rollover angle θ is the inherent characteristic of a vibroseis truck, and its value increases with the increase of the wheel track B and the centroid height H. A larger wheel track and a smaller centroid height are conducive to improving the stability of the vibroseis truck. For the vibroseis truck, the wheel track B is 3.65 m and centroid height H is 1.83 m; therefore, the critical rollover angle θ is 44.9°. If the critical value is exceeded, the truck will lose its balance, and a rollover accident occurs on the slope, as Equation (3) shows. Therefore, driving on a slope with a slope angle of less than 44.9° is crucial to prevent vibroseis trucks from undergoing rollover accidents on a slope.

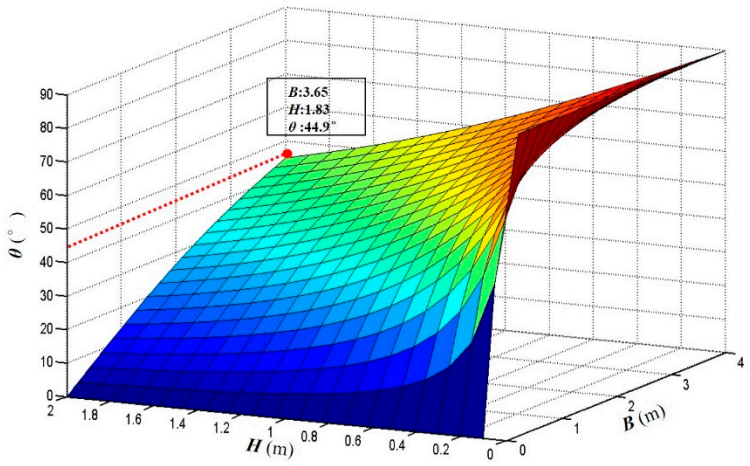


Figure 3. Relationship between critical rollover angle, tread, and centroid height for the vibroseis truck during slope straight driving.

2.2.2. Flat-Road Steering Stability

In Figure 4, the vibroseis truck is shown during the steering process on a flat road. Th centrifugal force is F, the critical steering speed is u_1, the steering angle is β, the steering radius is R, the distance between the front axle and the hinged joint is K, the wheelbase is L, the ground support force on the left side is N_1, and the ground support force on the right side is N_2. According to the principle of force balance, the formula derivation of flat-road steering stability is

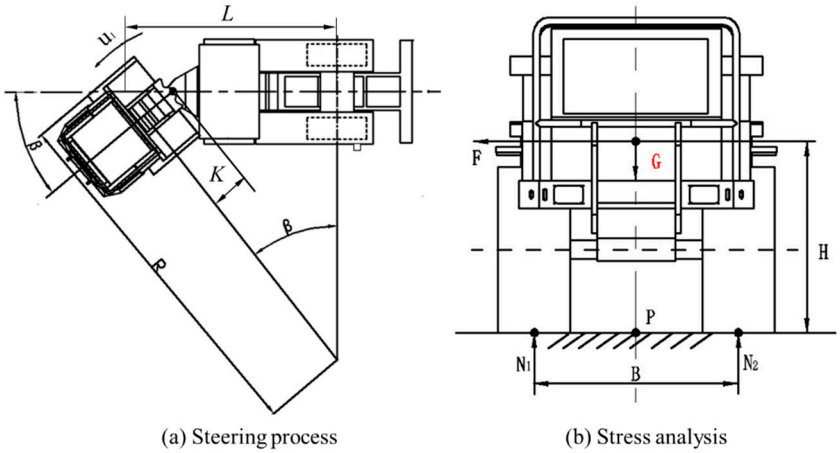
$$N_2 B - \frac{1}{2} MgB + FH = 0 \tag{4}$$

$$R = \frac{K \cos \beta + L - K}{\sin \beta} + \frac{B}{2} \tag{5}$$

$$F = M \frac{u_1^2}{R} \tag{6}$$

So, we can obtain the critical steering speed u_1:

$$u_1 = \sqrt{\frac{gBR}{2H}} \tag{7}$$



(a) Steering process (b) Stress analysis

Figure 4. Steering process analysis for the vibroseis truck on a flat road.

As shown in Figure 5, with the increase of the steering angle β, the critical steering speed u_1 tends to decrease and then to gradually stabilize. The critical steering speed is 10.5 km/h while the steering angle reaches 30°. The side-friction force provided by the ground cannot reach the centripetal force needed for the steering when the actual steering speed is beyond the critical speed, and this will cause a rollover accident.

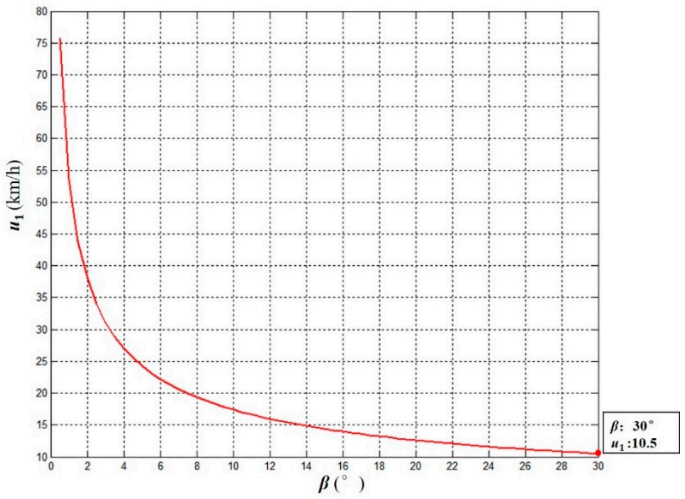


Figure 5. Relationship between critical steering speed and steering angle for a vibroseis truck steering on a flat road.

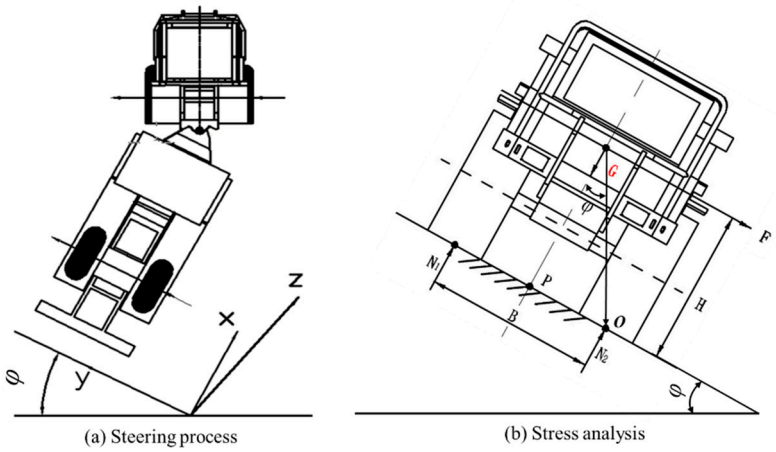
2.2.3. Slope Steering Stability

During the steering process on a slope, the resultant force along the slope cannot provide the centripetal force needed for the steering because of influencing factors such as roll angle, self-structure, and gravity, which leads to a rollover accident. The steering process on the slope is shown in Figure 6. When the vibroseis truck is in a rollover critical state, the support force N_1 is equal to zero. By calculating the moment for point O, the following equilibrium equations can be obtained:

$$(G\sin\varphi + F)H = G\cos\varphi \cdot \frac{B}{2} \tag{8}$$

$$R = \frac{K\cos\beta + L - K}{\sin\beta} + \frac{B}{2} \tag{9}$$

$$F = M\frac{u_2^2}{R} \tag{10}$$



(a) Steering process (b) Stress analysis

Figure 6. Steering process analysis of the vibroseis truck on a slope.

So, we can obtain the critical steering speed of the vibroseis truck:

$$u_2 = \sqrt{\left(\frac{\cos\varphi \cdot B}{2H} - \sin\varphi\right)gR} \tag{11}$$

Figure 7 demonstrates that with the increase of the steering angle β and the slope angle φ during the steering process on a slope, the critical steering speed u_2 tends to decrease. The critical steering speed is reduced to 3.7 km/h, while the steering angle β is 30° and the slope angle is 40°, which is much lower than the critical steering speed of 10.5 km/h during the flat-road steering process. Therefore, for the vibroseis truck, steering on a slope is more dangerous than steering on a flat road. The research on the influence of different parameters on the rollover stability provides directions and guidance to establish a warning system suitable for vibroseis trucks.

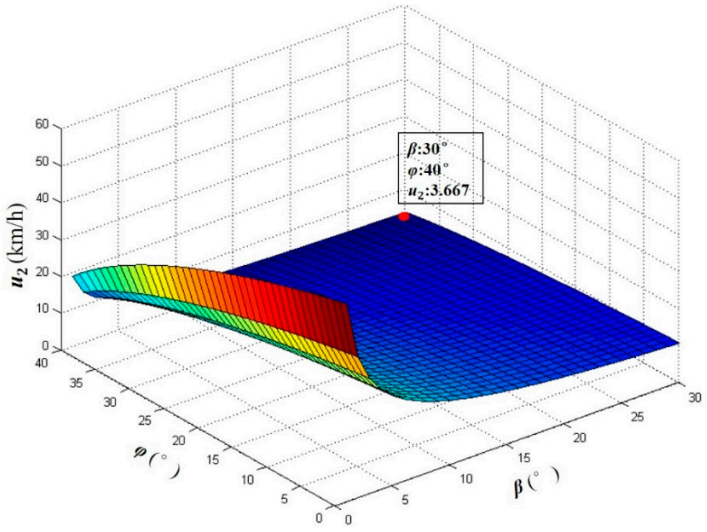


Figure 7. Relationship between critical steering speed, steering angle, and slope angle for the vibroseis truck during slope steering.

2.3. Stability of the Vibroseis Truck on a Sloping Road

To analyze the driving process of the vibroseis truck on a sloping road, a simulation analysis model, a lateral slope road upward turning analysis, and a sloping road downward turning analysis were established, as shown in Figure 8a–c, respectively. As shown in Figure 8b, the process of turning upwards on a sloping road involves driving on a horizontal road to a sloping road (stage one), going straight on the slope and turning to the right (stage two), going straight up the slope and turning upwards (stage three), and turning up the slope and going straight (stage four). As shown in Figure 8c, the downward turning process on the sloping road involves driving on the horizontal road to the slope road stage (stage one), going straight up the slope and turning to the right (stage two), turning straight on the slope and turning downward (stage three), and going straight down the slope (stage four). In the simulation, the driving speed was 7 m/s (25.2 km/h), the maximum steering angle was 25°, and the slope angle was 15°.

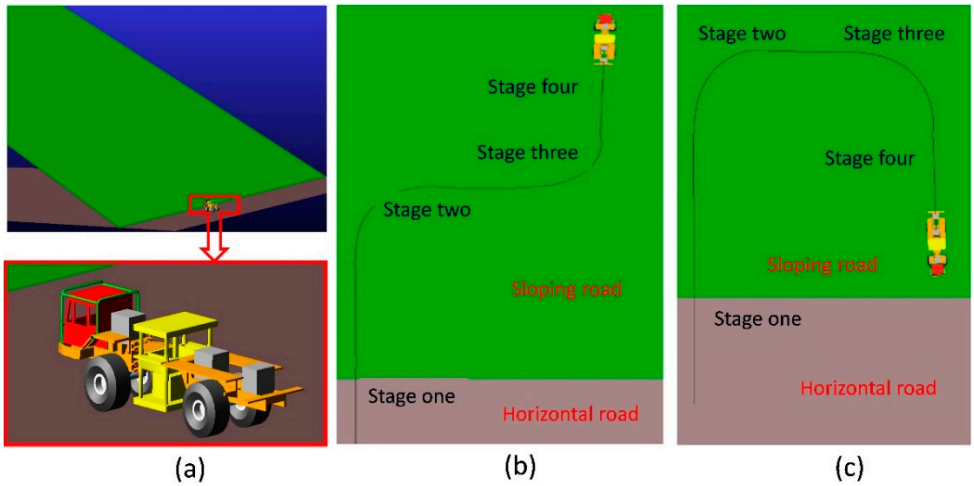


Figure 8. (**a**) Simulation analysis model, (**b**) sloping-road upward turning, and (**c**) sloping-road downward turning.

A comparative analysis of the speed changes of the front and rear bodies of the vibroseis truck during the upward and the downward steering on the lateral slope was carried out to determine the changes in the speed of the vibroseis truck during the turning process. The speed comparison curve of the front and rear car bodies is shown in Figure 9.

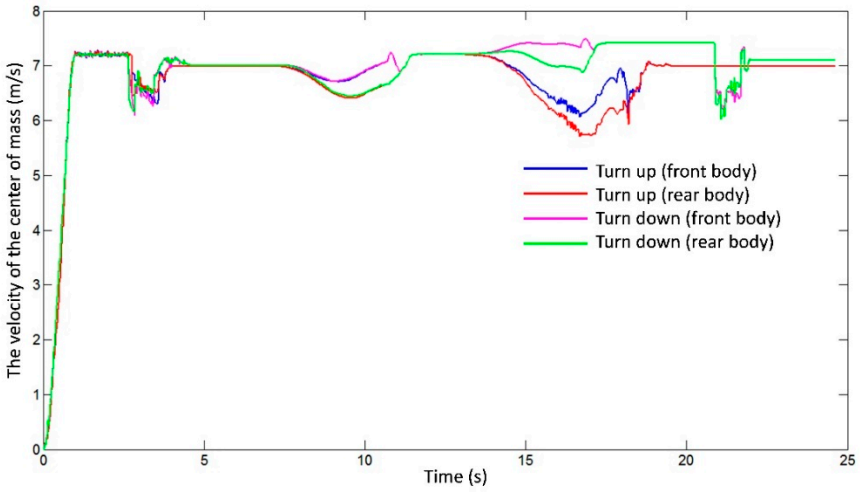


Figure 9. The speed comparison curve of the front and rear car bodies.

It can be seen in Figure 9 that in 3~4 s, the vibroseis truck reached the longitudinal slope from the horizontal road. During this process, the speed decreased significantly. The reason is that when the front and rear wheels leave the horizontal road, an impact is generated at the boundary between the slope and the horizontal road, resulting in a decrease in speed. The vibroseis truck required 7~11 s to turn right on the longitudinal slope. During this process, the speed of the front and rear car bodies decreased first and then increased with the continuous increase of the steering angle, and the speed of the rear car body was lower than that of the front car body. At t = 13 s, the vibroseis truck began to turn from the lateral slope. During the upward and downward steering, the speed of the front body was greater than the speed of the rear body. When turning downward, the speed of the front and rear car bodies was greater than the speed when turning upward. The reason is that the distance between the front and rear axles and the hinge point was not equal, and the front body was equipped with a swing bridge structure, which caused the speed of the front body to be slightly higher than that of the rear body. At the same time, during the upward turning process of the source vehicle, the gravity component along the slope was opposite to the direction of the speed. This produced a negative work, which reduced the speed of the vehicle. When turning downward, the component of gravity along the slope was the same as the speed direction; this produced a positive work and accelerated the speed of the vehicle.

Based on the above analysis, during the longitudinal and lateral turning of the vibroseis truck on the examined slope, the speed of the front body was greater than the speed of the rear body, and the lateral downward turning had a higher driving speed than the upward turning, which indicated the steering angle and slope angle. They have a certain influence on the speed of the vibroseis truck's turning process and have a greater influence on the speed when turning laterally upwards.

3. Study on the Warning Index of Rollover for the Vibroseis Truck

The rollover warning index is the precondition and key technology to develop an anti-rollover system for vibroseis trucks. Therefore, by analyzing the vehicle rollover warning index and combining it with the principles determining the rollover stability of vibroseis trucks in relation to different parameters, a rollover warning index suitable for vibroseis trucks could be developed.

3.1. Analysis of the Vehicle Rollover Warning Index

The conventional rollover warning index uses the lateral load transfer ratio (LTR) as the dynamic warning index for judging the risk of a vehicle rollover. The LTR refers to the absolute ratio of the difference between the sum of the loads of the left-side tires and of the right-side tires to the sum of normal loads of all tires [15,16]. The range of LTR is [0, 1]. When the LTR = 0, the normal loads of both sides of the vehicle are nearly equal. The vehicle is in a balanced state. When the LTR approaches 1, one side of the wheels is off the ground, and rollover occurs. This index is easy to calculate in real time. However, it does not cover structural parameters and motion parameters and easily produces false positives.

The time to rollover (TTR) is a kind of dynamic rollover warning index [17–21]. A vehicle can adopt different forewarning measures depending on the value of TTR. The TTR refers to the time from the moment to motion until rollover. With good real-time performance, the TTR is a dynamic index and avoids the influence of parameters such as the gravity center. For vehicles with large changes in load and center of mass, it is difficult to determine the parameters' threshold with this method.

The change of the gravity center of the f vehice generates an angle (roll angle) which is between the gravity direction and the vertical slope direction. The roll angle is selected as the warning index to judge whether the vehicle will roll or not [22,23]. When the roll angle is greater than the critical value θ_{max}, the vehicle undergoes rollover, according to the formula $\theta > \theta_{max}$. This index is simple and easy to be measured. However, its warning performance is poor, and it cannot accurately predict a dangerous situation in real time.

The lateral acceleration a_y is produced by the centrifugal force of the vehicle during the steering process, and its value represents the rollover stability of the vehicle [24]. If the lateral acceleration exceeds the critical value amax, the vehicle is undergoes rollover, according to the formula $a_y > a_{max}$. This index is simple, intuitive, and easy to determine in the basis of the vehicle's turning speed. The disadvantage of this method is that this index requires many measurements, and its warning ability is poor, with a low precision.

Therefore, the commonly used vehicle rollover warning indexes have some disadvantages such as poor measuring reliability, low accuracy, and no real-time performance. Some indexes also do not consider the effect of vehicle load and the gravity center position on critical values. Therefore, exploring a new type of warning index for vibroseis trucks is important for the development of a warning system for vibroseis trucks.

3.2. Rollover Warning Index for Vibroseis Truck

Through the analysis of rollover stability for vibroseis trucks, some parameters such as steering speed and steering angle appeared to have a decisive influence on the stability of vibroseis trucks. Therefore, based on the existing vehicle warning index and the rollover stability of the vibroseis truck analyzed before, a new warning index for the vibroseis truck was established, based on the absolute value of the quotient of the vehicle speed v and the critical steering speed u_2 in the slope steering process. It can allow a multistage evaluation of dangerous situations involving the vehicle.

$$A = \left| \frac{v}{u_2} \right| = \left| \frac{v}{\sqrt{\left(\frac{\cos\varphi \cdot B}{2H} - \sin\varphi \right) gR}} \right| \tag{12}$$

As shown in Figure 10, this multistage warning index range is divided into 4 levels. The evaluation index is named A, and with an increase in its value, the rollover stability of the vibroseis truck gradually decreases. When the index ranges from 0 to 0.6, the alarm level is defined as level 1, called the safe level. The sound–light alarm wave for this level is green. The system sets off a blue sound wave in the range from 0.6 to 0.9 to produce a primary alert to the driver, and this alarming level is defined as level 2. In the range from 0.9 to 1, the third alarm level is activated. The system issues a yellow sound–light alarm to further alert the driver. Finally, when the value of the index A is beyond 1, the fourth alarm level is defined, and a red sound–light alarm wave is issued, which shows that the vehicle is undergoing a rollover accident.

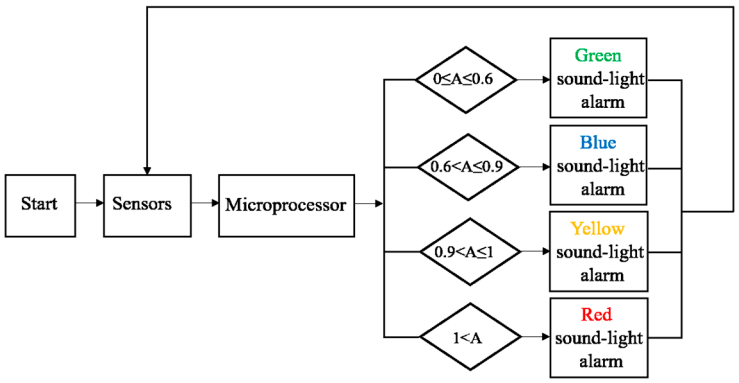


Figure 10. Schematic diagram of the anti-rollover warning system.

This warning index for the vibroseis truck uses a multistage contrast judgment method of vehicle speed v and critical steering speed u_2 and can issue different types of sound–light alarm according to the different levels of security. At the same time, the index can not only

accurately judge the dangerous state in the slope steering process in real time, but also judge the stability of the flat road steering process.

4. Working Principle of the Anti-Rollover Warning System for the Vibroseis Truck

Based on the vibroseis truck rollover warning index A, an anti-rollover warning system for the vibroseis truck was established. It consists of a microprocessor, a speed sensor, an angle displacement sensor, an inertial measurement unit (IMU), a slope meter, and an alarm device. Among them, the microprocessor is used to receive and analyze signals from the sensor. The angle displacement sensor mainly monitors the steering angle between the front body and the rear body. The inertial measurement unit is used to monitor parameters such as the roll angle and the lateral acceleration of the vehicle. The slope meter is used to monitor the slope angle.

The microprocessor calculates the vehicle rollover warning index A and runs the rollover warning algorithm. The warning index A is compared with the multi-grade warning scope, and the system judges the degree of danger based on the vibroseis truck warning level and emits a sound–light alarm to remind the driver to take reasonable measures to prevent a rollover accident.

5. Simulation Analysis of the Anti-Rollover Warning System for Vibroseis Truck

To validate the warning system, we established an anti-rollover warning system for the vibroseis truck and carried out a simulation analysis by using MATLAB/Simulink software for the flat road steering process and the slope steering process. The warning system simulation platform is shown in Figure 11. The input simulation speed v and the simulation steering angle β are shown in Figure 12. The slope angle φ was 0° and 15° to simulate the flat-road steering process and the slope steering process, respectively.

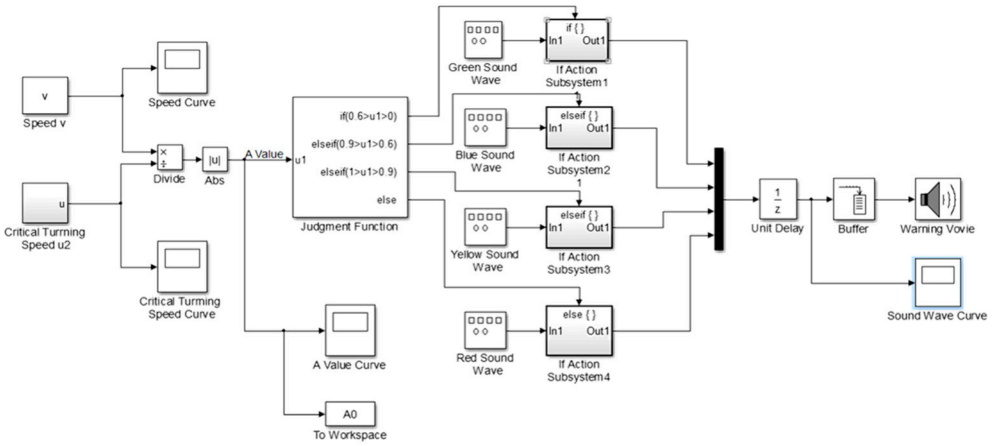


Figure 11. Simulation platform for the anti-rollover warning system for the vibroseis truck.

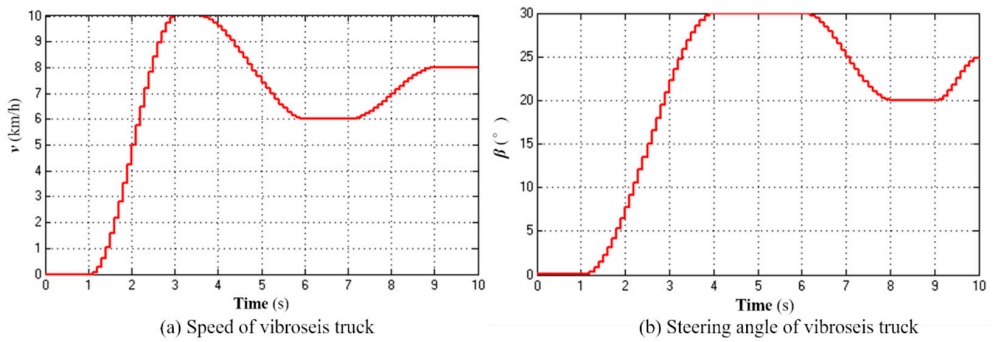


Figure 12. Simulation signal of the vibroseis truck. (**a**) Speed, (**b**) steering angle.

5.1. Warning Analysis for the Vibroseis Truck in the Flat-Road Steering Process

The warning index A and the sound–light alarm for the vibroseis truck in the flat-road steering process are shown in Figures 13 and 14, respectively. The warning index A showed a rapid increase within the range of 0~3.3 s, causing the warning system to set off different levels of sound–light alarms. In the range of 3.3~4.2 s, the warning index A was beyond 1. The speed of the vibroseis truck was beyond the critical steering speed, eventually causing the warning system to set off a red sound–light alarm, which indicated the vibroseis truck had already undergone a rollover accident. After a time of 4.2 s, with the decrease of the velocity, the A value appeared to decrease, and the warning system set off a lower sound–light alarm. The warning system could accurately evaluate the stability of the vibroseis truck in the flat-road steering process.

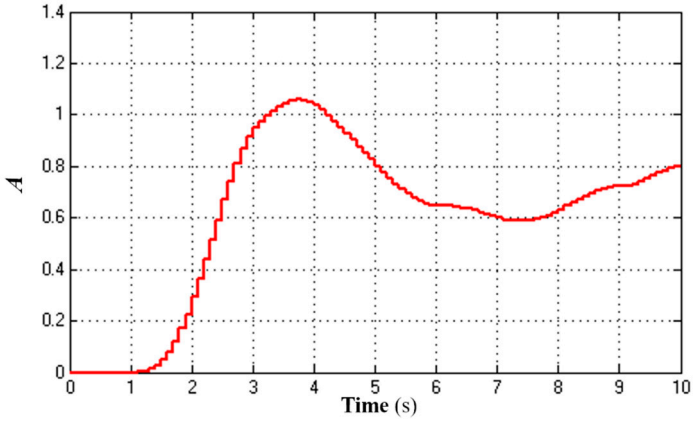


Figure 13. The time–amplitude curve of the warning index A in the flat-road steering process.

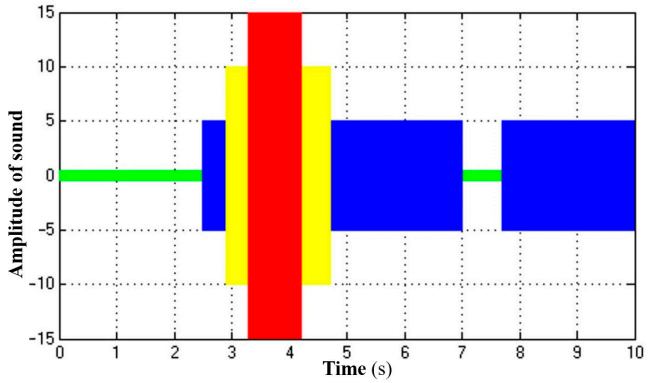


Figure 14. Sound–light alarm of the vibroseis truck in the flat-road steering process.

5.2. Warning Analysis of the Vibroseis Truck in the Slope Steering Process

Figures 15 and 16 indicate that the proposed warning system for the vibroseis truck can also provide accurate and real-time alarms in the slope steering process. The warning index A tended to increase with the increase of time in the range of 0~2.7 s, and the warning system set off different levels of sound–light alarm. The warning index A was greater than 1 within the range of 2.7~5.1 s, reaching the maximum value of 1.4. In this case, the actual speed of the vibroseis truck was beyond the critical steering speed, eventually causing the warning system to set off a long red sound–light alarm alert, which indicated that the vibroseis truck had already undergone a rollover accident. With the decrease of the vehicle speed v, the A value also appeared to decrease significantly after 5.1~9.9 s, and the vibroseis truck set off different levels of the sound–light alarm alert. Within 9.9~10 s, the warning index A is higher than 1, and the warning system emitted a red alert again.

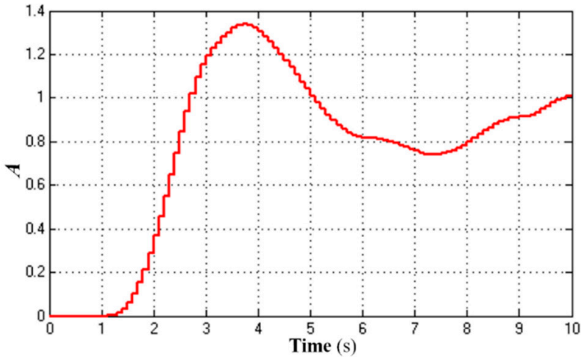


Figure 15. Time–amplitude curve of the warning index *A* in the slope steering process.

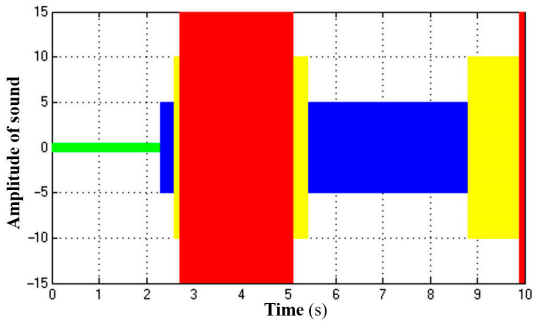


Figure 16. Sound–light alarm of the vibroseis truck in the slope steering process.

5.3. Comparative Analysis between Flat-Road Steering and Slope Steering Process for the Vibroseis Truck

The contrasting curves of critical steering speed and warning index between flat road steering and slope steering are shown in Figures 17 and 18, respectively. The values of the two critical steering speeds gradually decreased with the increase of time, tending to finally stabilize. If the speed and steering angle were the same, and the slope angle was different, the flat road and the slope angle were 0° and 15°, respectively, causing the critical steering speed on the slope to be greater than the critical steering speed on the flat road. The warning index *A* behaved as the speed. The index *A* for the slope was the first to reach its critical value of 1, which indicated that the rollover stability and security in the slope steering process were low; in other words, the slope steering process was prone to rollover accidents. Therefore, in the driving process on the slope, the driver should pay more attention to the control of speed and steering angle to improve the stability and safety of the vibroseis truck.

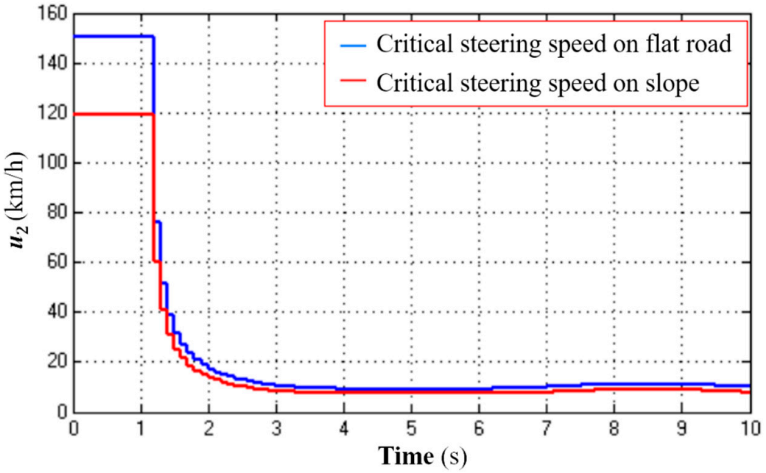


Figure 17. Comparison of the critical steering speed between flat-road steering and slope steering.

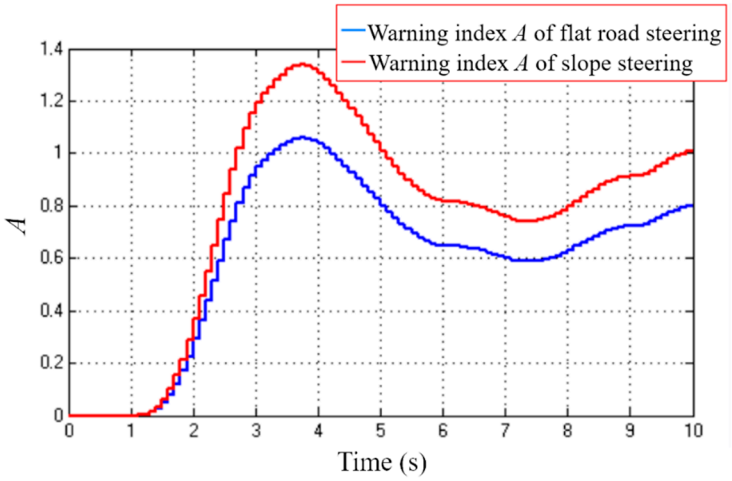


Figure 18. Comparison of the warning index A between flat-road steering and slope steering.

6. Conclusions

The vibroseis truck is in danger of rollover during the steering process, which severely threatens the safety of the drivers and the equipment. This paper researched the rollover stability of and anti-rollover warning systems for vibroseis trucks. The main findings are as follows.

(1) According to the structure characteristics and working conditions of the vibroseis truck, the analysis of the influence of different factors on the rollover stability of the vibroseis truck was carried out. The results indicated that the rollover stability of the vibroseis truck tends to decrease when the roll angle, steering angle, slope angle, and steering velocity increase. This study lays the foundation for establishing a valid anti-rollover warning system for vibroseis trucks.

(2) Based on the analysis of a vehicle warning indexes, a new warning index delivering four levels of alert was developed. The warning index considers the absolute quotient of vehicle speed to critical steering speed in the slope steering process as an evaluation index.

(3) A warning system simulation analysis of the vibroseis truck was carried out by using MATLAB/Simulink software for the flat-road steering process and the slope steering process. It was concluded that the warning index A can realize an accurate evaluation of the driving state in the two conditions, activating the warning system, which sets off the corresponding level of sound–light alarm. Meanwhile, the result indicated that the vibroseis truck had lower roll stability in the slope steering process. Maintaining a reasonable vehicle speed and steering angle is the most effective way to ensure the stability and safety of a vibroseis truck. This warning system can lay the foundation for developing anti-rollover warning systems for vibroseis trucks and other articulated trucks.

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