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Effects of Center of Gravity Position on Rollover Based Upon Detection of Three-Dimensional Center of Gravity

Üç Boyutlu Ağırlık Merkezinin Tespitine Dayanarak Ağırlık Merkezi Konumunun Devrilme Üzerindeki Etkileri

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ABSTRACT

Preventing truck rollover accidents is of great importance to ensure traffic safety, which is United Nations Sustainable Development Goal (SDG) Number 9. It is a misunderstanding of rollover accidents that trucks with heavier loads are more likely to roll over. In fact, when a truck passes through a curve, the truck will tend to roll over if the centrifugal force moment is greater than the gravitational moment. Even if the truck's speed is low and the load is not heavy, if the center of gravity (COG) is high, then the centrifugal torque will be strong. Therefore, finding the COG position is important.

Trucks usually carry multiple types of cargo simultaneously. Each type of cargo has different quantity and volume. Considering the time and economic costs, it is almost impossible to find the position of COG of the entire truck through piece-by-piece calculation. But Detection of the Three-Dimensional Center of Gravity (D3DCG) can indicate the COG position in a short time when a truck is moving.

This paper first introduces the principle of truck rollover, showing that whether a truck rolls over is related to the curve radius, speed, COG height, and the distance between the wheels on both sides. Secondly, results of this study demonstrate the theory of D3DCG which can calculate the COG position based upon the natural frequency of the moving truck. Then, after the authors use a truck scale model to verify the D3DCG accuracy, they conduct a controlled experiment to prove that even if the load remains the same, a truck with higher COG rolls over more easily. The achievement of this study presents new possibilities to prevent rollover accidents. Fruits of this study can also contribute to sustainable development of transportation industries.

Keywords: D3DCG, Natural frequency, Rollover accident, Traffic safety

ÖZ

Kamyon devrilme kazalarının önlenmesi, Birleşmiş Milletler Sürdürülebilir Kalkınma hedefi (SDG) numarası 9 olan trafik güvenliğini sağlamak için büyük önem taşımaktadır. Daha ağır yüklere sahip kamyonların devrilme olasılığının daha yüksek olduğu düşüncesi, devrilme kazalarına ilişkin bir yanlış anlaşılmadır. Aslında, kamyon bir eğimden geçtiğinde, merkezkaç kuvveti momenti yerçekimi momentinden daha büyükse, kamyon devrilme eğiliminde olacaktır. Kamyonun hızı düşük olsa ve yük ağır olmasa bile, ağırlık merkezi (COG) yüksekse, merkezkaç momenti güçlü olacaktır. Bu nedenle, ağırlık merkezinin konumunu bulmak çok önemlidir. Kamyonlar genellikle aynı anda birden fazla tür yük taşır. Her kargo türü farklı miktar ve hacme sahiptir. Zaman ve ekonomik maliyetler göz önüne alındığında, parça parça hesaplama ile tüm kamyonun ağırlık merkezi konumunu bulmak neredeyse imkansızdır. Ancak üç boyutlu ağırlık merkezinin (D3DCG) tespiti, bir kamyon hareket ederken ağırlık merkezinin konumunu kısa sürede gösterebilir. Bu makale ilk olarak, bir kamyonun devrilip devrilmediğinin yatay kurp, hız, ağırlık merkezi yüksekliği ve her iki taraftaki tekerlekler arasındaki mesafe ile ilgili olduğunu gösteren kamyon devrilme prensibini tanıtmaktadır. İkinci olarak, bu çalışmanın sonuçları, hareket eden kamyonun doğal frekansı temel alınarak ağırlık merkezi konumunu hesaplayabilen Üç Boyutlu Ağırlık Merkezinin Tespiti teorisini göstermektedir. Daha sonra, yazarlar üç boyutlu ağırlık merkezinin doğruluğunu tespit etmek için

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bir kamyon ölçekli model kullandıktan sonra, yük aynı kalsa bile, daha yüksek ağırlık merkezine sahip bir kamyonun daha kolay yuvarlandığını kanıtlamak için kontrollü bir deney yaparlar. Bu çalışmanın başarısı, devrilme kazalarını önlemek için yeni olanaklar sunmaktadır. Bu çalışma, ulaştırma endüstrilerinin sürdürülebilir kalkınmasına da katkıda bulunabilir.

Anahtar Kelimeler: D3DCG, Doğal frekans, Devrilme kazası, Trafik güvenliği.

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1. INTRODUCTION

Since vehicles were first invented, they have provided great convenience for people's daily traffic and the transportation of goods, but with inherent benefits and shortcomings. As the utilization rate of vehicles increases year by year, vehicles have caused numerous and severe social difficulties such as environmental pollution, oil resource shortage, and serious road traffic hazards. With needs for urban construction and continuously increasing speeds, the numbers of trucks are increasing. Because of trucks' high centers of gravity (COGs) and large freight vehicle volume, traffic accidents are more likely to occur at special areas of roadways, such as curves. Once an accident occurs, high mortality seriously threatens the safety of people's life and property.

A rollover accident is one by which two wheels on the same side or all wheels of a vehicle are suspended off the ground. Subsequently, the vehicle body touches the ground. Reasons for rollover accidents include the following: (1) Road factors, such as the curve radius through which a vehicle passes is too small, the super-elevation design is unreasonable, or an overly low friction coefficient. (2) Excessive vehicle speeds cause excessive centrifugal force. The vehicle's overturning moment increases gradually and exceeds the limit, leading to sideslip or rollover. (3) Improper driver operation such as sudden braking and slamming direction are caused by tension. (4) The COG position of the vehicle is too high, causing the vehicle to roll over.

According to an annual report of traffic accident statistics of Japan's Ministry of Land Infrastructure, Transport and Tourism in 2019, 191 rollover accidents occurred, of which 176 were truck rollover accidents, thereby accounting for 92.147% of all rollover accidents. The truck rollover accidents account for the vast majority of rollover accidents. Trucks usually carry various goods, including flammable, explosive, toxic and corrosive goods. Once a truck rolls over, risk of further damage is high. Preventing the occurrence of truck rollover accidents is important to ensure traffic safety, which is a United Nations Sustainable Development Goal (SDG No. 9).

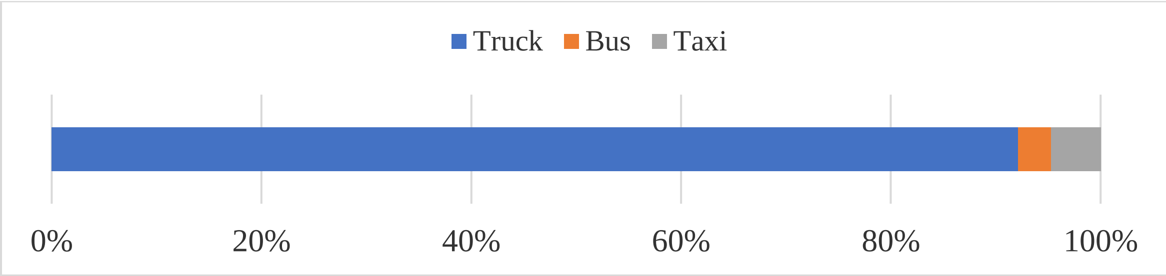


Figure 1. Rollover Accidents of Vehicles İn Japan İn 2019.

Data source: Annual report on automobile accident statistics for automobile transportation business from Ministry of Land, Infrastructure, Transport and Tourism

2. THEORY OF ROLLOVER AND DETECTION OF THREE-DIMENSIONAL CENTER OF GRAVİTY (D3DCG)

This chapter describes that, through force analysis of a vehicle passing through a curve, factors affecting vehicle rollover include the vehicle speed, the distance between the wheels on two sides, the curve radius, and the vehicle COG height. When the curve radius and the distance between the wheels are fixed, one must find the COG height of the vehicle to ascertain the safe speed for passing through the curve. The conventional method for finding the COG requires calculation using the target object volume, shape, and weight. The cost of using a truck scale is too high. Therefore, that method is not suitable for detecting the COG position of the truck. The low-cost and accurate method introduced herein to ascertain the position of the truck's COG using D3DCG imposes no requirements on the vehicle.

2.1 Principle of Rollover

Trucks usually carry more weight and have a higher COG than ordinary cars have. Therefore, when a truck is turning, if its speed is too high, then the body will roll over to the outside of the curve, usually leading to catastrophe. Therefore, analyzing the forces acting upon the vehicles when passing through a curve is very important. One must then find the main factors affecting traffic safety for that critical state of the vehicle in the curve section.

When a truck turns, it is subjected to centrifugal force (Yang and Qiu, 2019: 393). Centrifugal force is not a real force, but a virtual force, a manifestation of inertia, which keeps a rotating object away from its center of rotation. At the same time, the ground imposes frictional forces on the wheels pointing to the curvature center of the curve, which is used to provide the centripetal force which acts when the truck turns. When the centripetal force and centrifugal force are balanced, the truck can pass the curve steadily, but if the centrifugal force is greater than the centripetal force, the truck will start to roll outward. To maintain the torque balance of the vehicle, the support force received by the outer wheels must be greater than that received by the inner wheels. When the truck speed is too high, the inner wheels will lift from the ground; the vehicle might then roll over.

This report describes the study following idealized assumptions about the vehicle and its movement: (1) Suspension structure deformation of the vehicle is not considered. (2) Tire deformation is not considered. (3) Tire width is not considered. (4) The front and rear wheels on the same side are probably subjected to the same force when turning, which can be equivalent to one wheel. (5) Super-elevation of the road surface on the curved section is not considered.

The vehicle movement when turning is rotation along a fixed axis. The rotation axis passes through the center of curvature of the curve. For this study, it is assumed that the vehicle is subjected to a traction inertia force (centrifugal force). Figure 2 is a force diagram of a vehicle turning left through a curve.

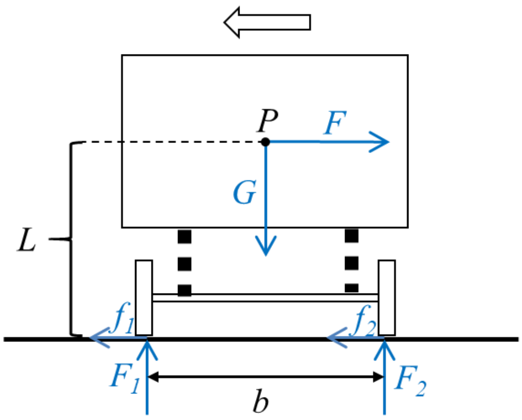


Figure 2. Force Diagram When a Vehicle Turns Left Through A Curve.

Note: *P* is the COG position. *G* represents gravity. *F* represents traction inertia force (centrifugal force).

F_1 and F_2 respectively represent the vertical forces on the outer and inner wheels provided by the ground. f_1 and f_2 respectively represent the lateral forces (frictional forces) on the outer and inner wheels.

To keep the body moment balance when the vehicle passes through the curve, F_2 will be greater than F_1. The difference between them will increase with increased vehicle speed. When the vehicle speed reaches a certain value, F_1 decreases to 0. The inner wheel starts to leave the ground. This speed is designated as the critical speed of rollover.

According to Figure 2, the torque equation of the contact point between the outer wheel and the ground is given as

$$G \cdot \frac{b}{2} = F \cdot L \quad (1)$$

where *b* represents the distance between two wheels and *L* denotes the COG height. Also, *G* and *F* can be expressed by the following equations.

$$G = mg \quad (2)$$

$$F = m\frac{v^2}{R} \quad (3)$$

Therein *m* signifies the vehicle mass, *v* stands for the velocity, *R* denotes the turning radius of curve, *g* expresses the gravitational acceleration, and π is the circular constant.

By substituting equations (2) and (3) into equation (1), the expression of the critical rollover speed of the vehicle during passage through a curve can be obtained as shown below.

$$v = \sqrt{\frac{gRb}{2L}} \quad (4)$$

According to the equation presented above, when *R* and *b* increase, *v* increases monotonously; when *L* increases, *v* decreases monotonously. Therefore, if the distance between the wheels and the curve radius is fixed, then a higher COG position and lower critical speed will be reached when the vehicle rolls over. Ascertaining the COG position can enable the driver to adjust the speed in time before passing through the curve. Thereby, a driver can avoid the occurrence of rollover accidents.

2.2. Theory of D3DCG

The conventional and easiest method of finding the COG position of multiple objects is to find the COG position of each object first, then to calculate the combined position of two objects based on the weight and the distance between their COG, and then to add the objects one by one (Watanabe, 2017: 11). Nevertheless, this computation procedure presents some difficulties. This method can be used on the premise that the COG, weight, shape, and other information of each component are known, but trucks are often loaded with goods of different weights and shapes. In fact, the truck itself is composed of numerous parts. Therefore, it is almost impossible to ascertain the truck COG in this way. Even if this method were feasible, the errors caused by the calculation would be large. In addition, the operation of trucks must consume gasoline or diesel. With fuel consumption and refueling operations, the COG position of the truck would also change. This method is not flexible. It is not available.

Reportedly, a truck's COG can be detected using a truck scale (Mikata, Yamanaka, et al., 2011: 405). A truck scale is a fixture. Therefore, this method can only be implemented if the driver has sufficient time to drive the truck to a place with a truck scale. Additional costs of measurements and fuel are not considered. Actually, it is not realistic to neglect the time and economic costs. Therefore, the only means of low-cost, accurate, and flexible detection of the COG position of a truck is D3DCG.

The theory of D3DCG can be derived from the floating behavior of ships. It is applied to prevent the rollover of railway cars (Kawashima and Watanabe, 2016: 8). D3DCG finds the COG position based upon the natural frequency of a moving vehicle. It works by inverse operation of the period of the vertical simple harmonic oscillation in the vertical direction and rolling in the transverse direction of the body of a vehicle. Figure 3 presents a schematic drawing of free oscillation of a vehicle during motion.

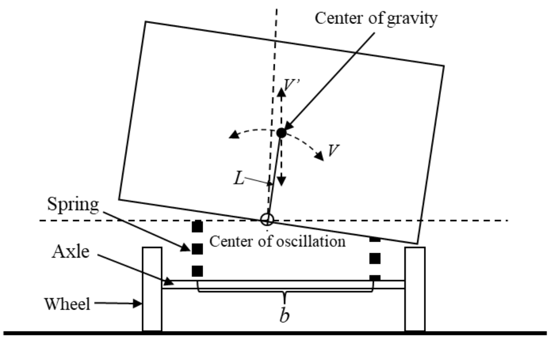


Figure 3. Concept of D3DCG.

The road surface disturbs a moving vehicle so that some elastic structures such as springs and tires generate vertical acceleration. This simple harmonic motion can be formulated as the following equation.

$$V' = \frac{1}{2\pi}\sqrt{\frac{2k}{m}} \qquad (5)$$

Therein, *V'* denotes the frequency of vertical simple harmonic oscillation of the body, *k* represents the spring constant on each side, and *m* expresses the vehicle mass. Also, π is the circular constant.

Heaving has a tendency to alleviate itself by horizontal movement so that rolling occurs. Rolling is a circular motion around the center of oscillation as in the following equation.

$$V = \frac{\sqrt{\frac{kb^2}{2m} - gL}}{2\pi L} \tag{6}$$

In that equation, *V* stands for horizontal shaking (rolling) frequency, *L* denotes the COG height from the axis of center of oscillation, *g* represents the gravitational acceleration, and *b* expresses the width of a portion that supports the vehicle weight.

In equations (5) and (6), *k/m* can be regarded as one variable. After eliminating it, the D3DCG theory can be expressed as shown below.

$$L^2 + \frac{g}{4\pi^2 V^2} L - \frac{b^2 V'^2}{4V^2} = 0 \tag{7}$$

In the equation above, the values of g and π are fixed; b can be measured. The values of V and V' can be ascertained with a motion sensor and a computer. For that reason, L can be calculated if the values of other variables are substituted into equation (7).

3. ACCURACY OF D3DCG

In the preceding chapter, the relation between rollover and the COG position of the vehicle in a curved section is introduced. A method of using D3DCG to measure the COG position is also proposed. This chapter introduces the truck model as the experiment object, through the conventional hanging method and the method of D3DCG to detect the position of its COG. Then results are compared to demonstrate the accuracy of D3DCG.

3.2. **Measurement Of COG by Hanging A Truck Model**

A static object is subject to balancing forces. If a hung object is static, it will only be subject to two forces: gravity and tension. If the two forces are balanced, then they must be equal and opposite and in a straight line (to ensure the balance of torque). Therefore, the extension line of the tension must pass through the COG. The authors hang the empty truck model from three directions by a rope, as Figure 4 shows. Extension lines of the rope intersect in the same point. Therefore, this point represents the COG position, the height of which is 9.5 cm.

However, the hanging method is inapplicable for detection of the COG position of a truck because, on one hand, the truck is too heavy to hang. It is very dangerous. On the other hand, the internal structures of the truck and the loading cargoes are not completely fixed. Therefore, if it is hung, then the COG position will change. The result will not be accurate.

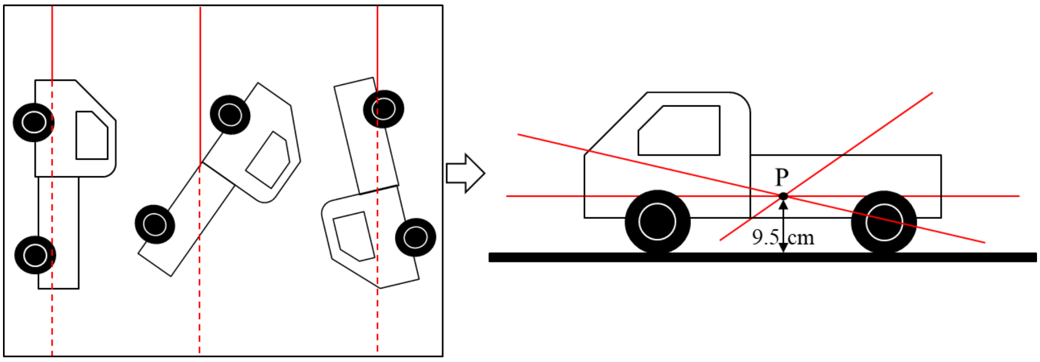


Figure 4. Measurement of COG by hanging.

3.3. Detecting The COG of A Moving Truck Model Using D3DCG

D3DCG can find the COG position of a moving object based upon its natural frequency. Authors install a motion sensor on the truck model carriage, as shown in Figure 5(a). Figure 5(b) portrays sensor details, where *x* is made to be consistent with the direction of movement. Therefore, *y* represents the horizontal direction; *z* represents the vertical direction. The sensor records the displacement changes in these three directions every 0.005 s. It then sends the collected data to the PC through a Bluetooth connection.

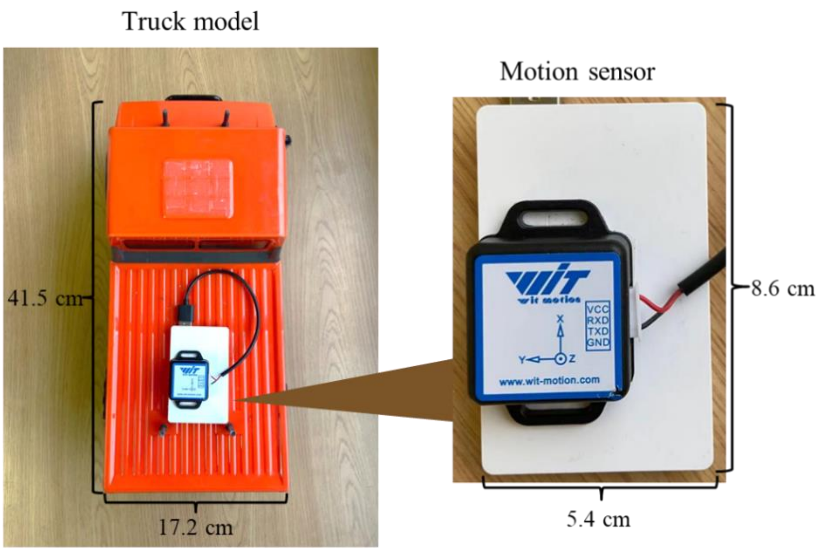


Figure 5. Truck model and Motion Sensor.

The model is controlled to move straight along the road for about 1 min. The collected data are processed by Fast Fourier Transformation (FFT), which processes 2048 data as a group. FFT is done continually, shifting the starting point to next. For example, the first group includes the 1st data to the 2048th data. The second group includes the 2nd data to the 2049th data, etc. When the ending point of FFT reaches the end of the whole data set, the average of FFT results is calculated to divide the accumulation by the number of FFT done. The truck model is so small that the road conditions strongly influence on its motion state. The average frequency can reduce the disturbance from the road surface. Thereby the time-based displacement change is converted to frequency-based displacement change. Figure 6 depicts FFT results obtained for one set of data. In the figure, the peak amplitude in a specific range is regarded as the natural frequency of the moving object in a certain direction. Therefore, the frequency of heaving and rolling of the empty truck model can be ascertained.

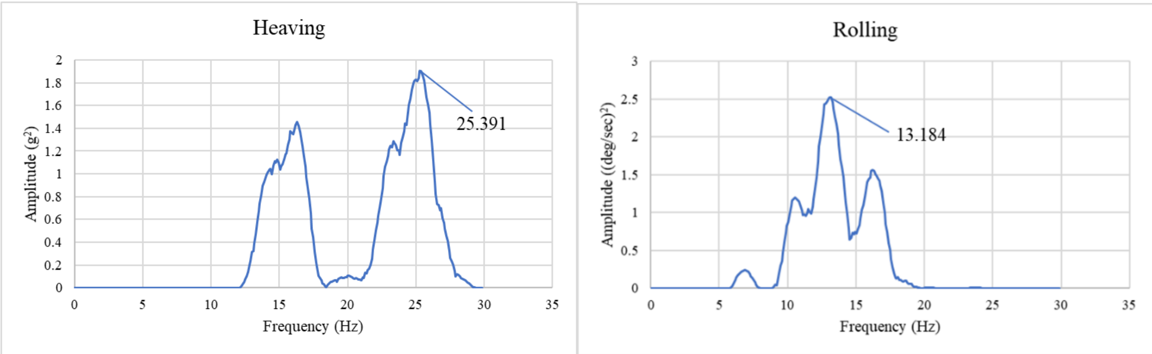


Figure 6. Frequency Image from the FFT Analyzer.

Two elastic structures cause heaving and rolling: springs and tires. When the truck model is empty, springs play the main role. Therefore, in this case, the width of a portion that supports the vehicle weight is the distance between two springs, denoted as b_s.

Table 1. COG Of An Empty Moving Model Detected Using D3DCG

	V' (Hz)	*V* (Hz)	b_s (m)	*L* (m)
	Vertical simple harmonic oscillation	Horizontal rolling frequency	Width of a portion supporting the weight	Height of COG
Exp. 1	25.391	13.184		0.096
Exp. 2	24.805	12.793		0.096
Exp. 3	25.977	12.988	0.100	0.099
Exp. 4	24.707	12.500		0.098
Exp. 5	25.293	12.695		0.098
Average	25.234	12.832	-	0.098
Standard deviation	0.456	0.234	-	0.001

The experiment is repeated five times. The results are presented in Table 1. The average FFT results are applied to equation (7). Therefore, the COG position of the empty moving model is detected. It is 0.098m.

Compared to the position measured by hanging, the result detected using D3DCG is about 0.3 cm higher. Some disturbances, such as the condition of road surface and the remote control of adjusting direction, cause errors. The result detected using D3DCG shows the COG position of both the truck model and the sensor. The sensor is not much lighter than the model. Therefore, it might raise the COG height. The result detected by hanging only shows the position of the empty truck model. If the volume and mass of the model are sufficiently large, then some error can be ignored.

Hanging method is a precise method to measure the COG position for objects that are small and light. It will not change the internal structure because of the change of the position of the hanging point. For objects that are heavy and bulky and which have an internal structure is not fixed, the hanging method is difficult to practice. In this case, D3DCG can work. Moreover, D3DCG does not cost a lot. It can find the COG accurately and quickly.

4. CONTROLLED EXPERIMENTS BETWEEN MODELS WITH HIGHER AND LOWER COG

The rollover principle is introduced in chapter 2. The following conclusions were drawn: when other variable values are fixed, a truck with higher COG rolls over more easily. Nevertheless, this supposition is not proved by experiments. Therefore, in this chapter, controlled experiments were conducted to verify the relation between rollover and the COG height. The experiments were designed to produce models with different heights of COG to pass through the same curve at the same speed. Then, based on the motion states of two models with different heights of COG, the rollover theory can be proved.

4.2. Center of Gravity of Objects in The Controlled Experiments

For the controlled experiments, values of all other variables except the height of COG remain unchanged. And the change in the overall COG height is realized by changing the position of the load carried by the truck model, shown as Figure 7. Devices used for the controlled experiments are shown in Figure 8, including the remote control truck model, motion sensor, plastic foam and a load with 1 kg weight. Unlike the empty truck model, the sensor is installed on the cab instead of the carriage. When the load is put on the upper side of the plastic foam, the overall COG position is higher. When it is put under the plastic foam, the position is lower.

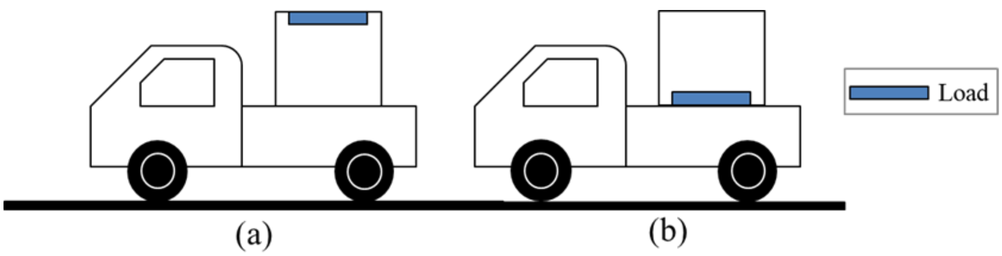


Figure 7. Model with a higher COG (a) and model with a lower COG (b).

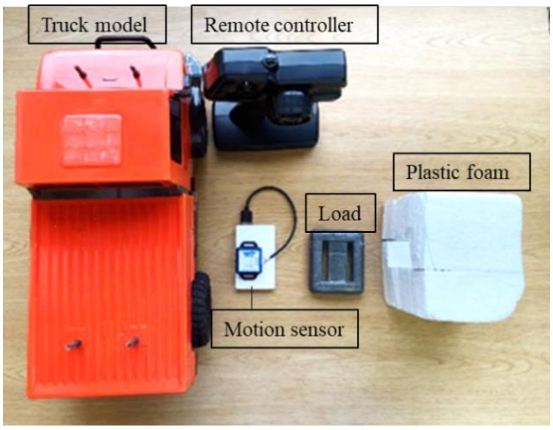


Figure 8. Experiment devices used for controlled experiments.

The COG positions of different models detected using D3DCG and the results are shown in Table 2 and Table 3. Both springs and tires are elastic structures that can cause heaving and rolling. In the loaded condition, heaving and rolling mainly occurs on tires. Therefore, the width of a portion that supports the weight of the vehicle is the distance between two tires, denoted as b_l. The higher COG position is 0.153 m. The lower one is 0.117 m.

Table 2. Results of Model with Higher COG Detected by D3DCG

	V' (Hz)	*V* (Hz)	b_l (m)	*L* (m)
	Vertical simple harmonic oscillation	Horizontal rolling frequency	Width of a portion supporting the weight	Height of COG
Exp. 1	8.398	3.906	0.150	0.153
Exp. 2	8.398	4.004		0.150
Exp. 3	7.910	3.711		0.151
Exp. 4	8.510	3.809		0.159
Exp. 5	8.308	3.906		0.152
Average	8.305	3.867	-	0.153
Standard deviation	0.208	0.096	-	0.003

Table 3. Results of Model with Lower COG detected by D3DCG

	V' (Hz)	*V* (Hz)	b_l (m)	*L* (m)
	Vertical simple harmonic oscillation	Horizontal rolling frequency	Width of a portion supporting the weight	Height of COG
Exp. 1	11.914	7.422	0.150	0.118
Exp. 2	12.012	7.520		0.118
Exp. 3	11.719	7.324		0.118
Exp. 4	12.598	7.813		0.119
Exp. 5	11.700	7.520		0.113
Average	11.953	7.520	-	0.117
Standard deviation	0.363	0.163	-	0.002

4.3. Velocity Detection Process and Results of The Loading Truck Model

Because of constraints of the model itself, adjusting the speed by remote control as needed is impossible, but its maximum speed can be regarded as uniform. The truck model speed is influenced only by the loading weight, instead of the COG position. Therefore, models with both higher and lower positions of the COG have the same maximum speed. According to the formula of uniform rectilinear motion $v = s / t$, where v represents the velocity, s stands for the displacement, and t denotes the time that the object takes to pass through displacement s at speed v, the model velocity is calculated by measuring the duration of model passage through 10 m distance at its maximum speed. As Figure 9 shows, the timing starts when the front of the truck model passes the starting point. It ends when the front of the model reaches the ending point. The elapsed time is the time at which the model passes the 10 m mark at maximum speed. The truck model accelerates for some distance before the starting point. Thereby, we ensured that the model reached its maximum speed at the starting point. The average velocity of the loading truck model was 5.119 m/s, as shown in Table 4.

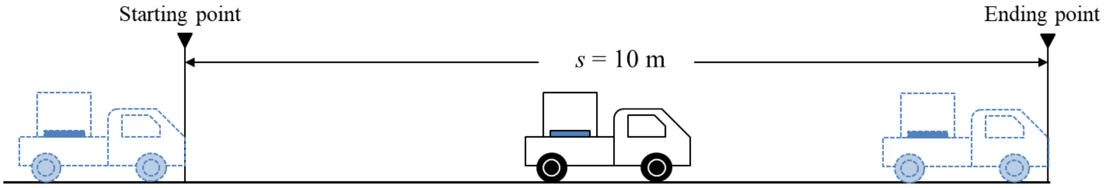


Figure 9. Velocity Detection Process of The Loading Truck Model.

Table 4. Average Maximum Velocity of The Loading Truck Model

	s (m)	*t* (s)	*v* (m/s)
	Displacement	Time	Velocity
Exp. 1	10.0	1.960	5.102
Exp. 2		1.850	5.405
Exp. 3		2.020	4.950
Exp. 4		2.040	4.902
Exp. 5		1.910	5.236
Average	-	1.956	5.119
Standard deviation	-	0.078	0.207

4.4. Process and results of controlled experiments

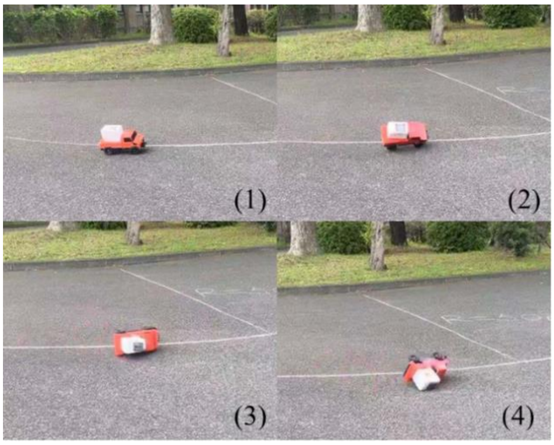
To ascertain the rollover critical radius of the curve, equation (4) can be converted as shown below.

$$R = \frac{2Lv^2}{gb} \quad (8)$$

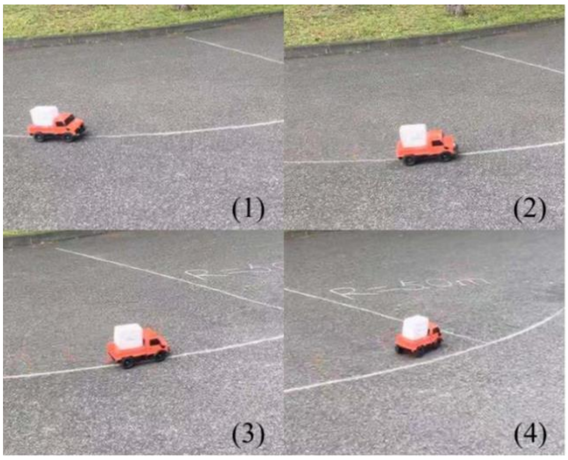
When the velocity and COG height of the two models are put in the equation (8), the rollover critical radii of the curves can be calculated. The critical radius for the model with lower COG was 4.171 m. That for the model with higher position was 5.455 m. Drawing a curve with the rollover critical radii of the two models that have different positions of COG will cause errors. It is also difficult to make the truck model move completely along the drawn curve. Therefore, the curve radius in the experiment is taken as 5.000 m (between 4.171 m and 5.455 m). The motion states of the models are portrayed in Figure 10, in which the moving direction and the speed remain unchanged.

When the truck model with higher COG enters the curve, the whole body tilted outwards, its outer wheels are compressed. Then its inner wheels start to leave the ground. If the speed is reduced in time, the truck model might not roll over. If the speed is not lowered and the direction of movement is not changed, the model will eventually roll over. If the moving direction is changed to avoid rollover, the body of the truck model will shake violently and rush out of the curve. The model with lower COG passes through the curve steadily, but only with the outer wheels undergoing a slight compression deformation.

Results obtained from controlled experiments verify that when a truck model has a constant load and a constant speed, a truck with higher COG rolls over more easily. Similarly, to avoid rollover, the higher a vehicle's COG becomes, the lower its speed should be when passing through a curve of a given radius.



(a) Rollover process of model with higher COG



(b) Passing of a model with lower COG

(c)

Figure 10. Motion States of Models with Different Heights of COG When Passing Through a Curve.

5. CONCLUSION

This report first describes causes of vehicle rollover accidents and data of Japanese truck rollover accidents from 2019. Subsequently, it explains the importance of research on preventing truck rollovers.

Then the study described herein elucidated the rollover mechanism, with results suggesting that the critical speed of rollover decreases with the increase of the COG height and increases with the increase of the curve turning radius. Among the factors affecting rollover, the curve turning radius is fixed. Therefore, only the height of COG should be detected. D3DCG finds the COG position based on the natural frequency of the moving truck. This method requires only a motion sensor and a PC. The motion sensor transmits data to a PC. Then the PC converts it into frequency-based data through Fast Fourier Transformation, subsequently outputting the conversion results and image. According to the image, the frequency corresponding to the peak amplitude in a certain range is regarded as its natural frequency. It is substituted into the equation to calculate the COG position of the truck.

To prove the accuracy of D3DCG for detecting the COG position, a truck model is taken as the experimental object. The COG is first detected using the hanging method. Then it is detected by D3DCG. By comparing the results obtained using these two methods, it was found that the COG found by D3DCG is close to the figure found through detection by hanging the vehicle.

Controlled experiments prove that when trucks with the same load but with different heights of COGs pass through the same curve at the same speed, the truck with a higher COG position is more likely to roll over.

The theory of D3DCG can be used not only to avoid truck rollover accidents. It can also be applied to other vehicles such as buses and trains. With further development of science and technology, research into intelligent automobiles is becoming increasingly popular. Application of D3DCG can contribute to safe driving. Trucks carry various cargoes, including dangerous goods. The study presented herein is of great importance for the safeguarding of life and property, in addition to sustainable development of transportation industries.

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