ISSN: 2147-8414

RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Rollover Prevention By Maximum Lateral Force Based On The Detection of Three-Dimensional Center of Gravity

Üç Boyutlu Ağırlık Merkezi Tespitine Dayalı Maksimum Yanal Kuvvetle Devrilme Önleme

Kailun YU[1] Yutaka WATANABE[2]

ABSTRACT

The center of gravity (COG) height is an important factor affecting rollover. Earlier studies by the authors assessed the theory of Detection of Three-Dimensional Center of Gravity (D3DCG), which provides an innovative and accurate method for COG height detection. This report describes development of D3DCG, which can be used to prevent rollover accidents by calculating the maximum height of COG and the maximum lateral force that can exist without causing rollover. For a fixed total weight of a vehicle, the COG height has an upper limit. Based on the law of energy conservation, if the COG height is lower than that upper limit, then the vehicle has potential energy against rollover. When the vehicle is running, road disturbances make its body shake. Some potential energy transfers to the spring energy to provide a restorative force and to make the COG return to its original position. Therefore, when the COG height reaches its maximum value, the potential energy disappears, causing rollover. The highest COG can be expressed according to the principle of the balance of rotational torque. To verify this theory, a COG adjustable experiment is designed with a table-top D3DCG device and a tower object. The total object weight does not change, but its COG height increases until the object cannot maintain stability on the device anymore. Comparison of the real COG and the highest COG confirmed that only when the COG is lower than the highest COG, the object will not roll over. If a lateral force is acting on a moving object such as a vehicle, then the object will tilt. At the same time, the restoring moment will resist the rolling moment. According to the theory of D3DCG, the lateral force has relation with the rolling angle. When the vehicle starts to roll over, based on the physical structure of moving vehicle, the critical lateral force can be represented by the rolling angle. Therefore, by eliminating the rolling angle as an unknown variable, the maximum lateral force can be expressed by two known variables: the actual COG height and the maximum height of COG. To verify this theory, a remotely controlled truck is made to rotate in a random rotation radius. Then its speed increases gradually until it rolls over. The real-time lateral force is recorded and compared with the calculated maximum lateral force. Results indicate that rollover occurs when the real-time lateral force reaches the maximum lateral force. This study examines a novel method of rollover prevention without knowing either the total weight, the vehicle speed or turning radius. The accuracy of this theory was well confirmed by comparing the real-time lateral force and the calculated maximum lateral force based on D3DCG.

Keywords: Accident prevention, D3DCG, motions of moving objects, safety of vehicles.

ÖZ

Ağırlık merkezi (COG) yüksekliği devrilmeyi etkileyen önemli bir faktördür. Yazarların daha önceki çalışmaları, COG yükseklik tespiti için yenilikçi ve doğru bir yöntem sağlayan Üç Boyutlu Ağırlık Merkezinin (D3DCG) Tespiti teorisini değerlendirdi. Bu rapor, maksimum COG yüksekliğini ve devrilmeye neden olmadan var olabilecek maksimum yanal kuvveti hesaplayarak devrilme kazalarını önlemek için kullanılabilecek D3DCG'nin gelişimini açıklamaktadır. Bir aracın sabit toplam ağırlığı için COG yüksekliğinin bir üst sınırı vardır. Enerji korunumu yasasına göre, eğer COG yüksekliği bu üst sınırdan daha düşükse, o zaman aracın devrilmeye karşı potansiyel enerjisi vardır. Araç çalışırken yoldaki bozulmalar vücudunu sallar. Bazı potansiyel enerjiler, onarıcı bir kuvvet sağlamak ve COG'nin orijinal konumuna geri dönmesini sağlamak için yay enerjisine aktarılır. Bu nedenle, COG yüksekliği maksimum değerine ulaştığında, potansiyel enerji kaybolur ve devrilmeye neden olur. En yüksek COG, dönme torku dengesi ilkesine göre ifade edilebilir. Bu teoriyi doğrulamak için, bir masa üstü D3DCG cihazı ve bir kule nesnesi ile COG ayarlanabilir bir deney tasarlanmıştır. Toplam nesne ağırlığı değişmez, ancak COG yüksekliği, nesne artık cihaz üzerinde dengeyi koruyamayacak duruma gelene kadar artar. Gerçek COG ve en yüksek COG'nin karşılaştırılması, yalnızca COG en yüksek COG'den düşük olduğunda nesnenin devrilmeyeceğini doğruladı. Taşıt gibi

[1] Graduate School of Tokyo University of Marine Science and Technology, d202012@edu.kaiyodai.ac.jp, ORCID: 0000-0002-0742-5445

[2] Corresponding author: Tokyo University of Marine Science and Technology, ywatana@kaiyodai.ac.jp, ORCID: 0000-0002-1308-9855

hareketli bir nesneye yanal bir kuvvet etki ediyorsa, nesne eğilir. Aynı zamanda, geri yükleme momenti, yuvarlanma momentine direnecektir. D3DCG teorisine göre, yanal kuvvet yuvarlanma açısı ile ilişkilidir. Araç devrilmeye başladığında, hareket eden aracın fiziksel yapısına bağlı olarak kritik yanal kuvvet, yuvarlanma açısı ile temsil edilebilir. Bu nedenle, yuvarlanma açısını bilinmeyen bir değişken olarak ortadan kaldırarak, maksimum yanal kuvvet bilinen iki değişkenle ifade edilebilir: gerçek COG yüksekliği ve maksimum COG yüksekliği. Bu teoriyi doğrulamak için, uzaktan kumandalı bir kamyon rastgele bir dönüş yarıçapında dönecek şekilde yapılır. Sonra devrilene kadar hızı kademeli olarak artar. Gerçek zamanlı yanal kuvvet kaydedilir ve hesaplanan maksimum yanal kuvvet ile karşılaştırılır. Sonuçlar, gerçek zamanlı yanal kuvvet maksimum yanal kuvvete ulaştığında devrilmenin gerçekleştiğini göstermektedir. Bu çalışma, toplam ağırlığı, araç hızını veya dönüş yarıçapını bilmeden yeni bir devrilmeyi önleme yöntemini incelemektedir. Bu teorinin doğruluğu, gerçek zamanlı yanal kuvvet ve D3DCG'ye dayalı hesaplanan maksimum yanal kuvvet karşılaştırılarak iyi bir şekilde doğrulandı.

Atıf (to cite): *Yu, K. & Watanabe, Y. (2022).* Rollover Prevention By Maximum Lateral Force Based On The Detection of Three-Dimensional Center of Gravity. *Toros University FEASS Journal of Social Sciences, 9(Special Issue),26:38. doi:* 10.54709/iisbf.1169500

Received Date (Makale Geliş Tarihi): 01.09.2022 Accepted Date (Makale Kabul Tarihi): 03.10.2022

1. INTRODUCTION

Road traffic is the most common and widely used mode of transportation. Therefore, road safety should attract more attention. Based upon data from the US National Highway Traffic Safety Administration (NHTSA, USA), rollover accidents have become the second most dangerous road traffic accident type, after crash accidents. Figure 1 shows that the number of occupants killed in all road traffic accidents and rollover accidents declined from 2007, but the percentage of rolloveraccidents in all road accidents showed no marked decrease. Consequently, preventing rollover accidents is necessary for promoting road traffic safety.

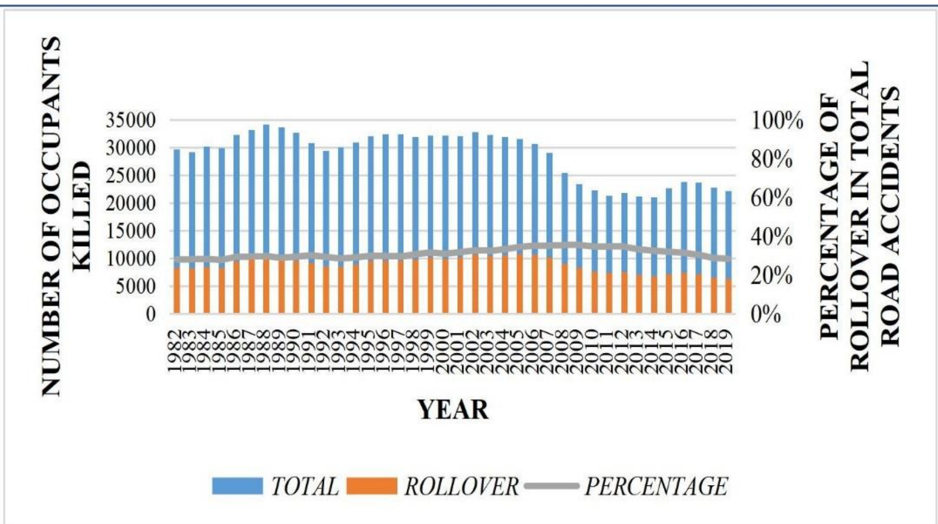


Figure 1. *Statistics data of death in road accidents and rollover accidents in the USA during 1982–2019.* ***Data source****: Traffic Safety Facts Annual Report Tables from National Highway Traffic Safety Administration (NHTSA,USA)*

Rollover accidents invariably occur on curved sections of roads because they are caused by external horizontal force. In this case, the most important factors that affect rollovers include the curve radius, velocity, and the center of gravity (COG) height. Vehicles are loaded with a wide variety of goods. Also, the COG changes before and after loading and unloading.For that reasons, detecting the COG height, let alone the real-time COG height, is difficult.

Some researchers have reported effective methods for detecting the COG height of objects that have large mass. Watanabe created the theory of Detection of Three-Dimensional Center of Gravity (D3DCG) by applying the principle of ship buoyancy to moving vehicles. The buoyancy supports a ship as it stays on the water surface in a vertical direction, although no definite force acts in the horizontal direction. Even a breeze or a ripple can make a ship shake. Such a shaking process is permanent. The shaking frequency depends on the ship's COG height. Watanabe found that, when avehicle moves, road surface disturbances will make the vehicle body shake. This phenomenon is similar to that for a ship. Later, Watanabe combined the equations of vertical and horizontal oscillation to obtain an expression of COG height. The theory provides an innovative means of detecting the COG height without the need to ascertain the object's mass.

Dang and Watanabe conducted experiments to verify the D3DCG theory accuracy. They first designed an experiment that incorporates a truck model. The model was hung from three directionsby a line. The intersection of the lines' extensions showed the COG position. Compared to the intersection height, the D3DCG calculation result was verified accurately. Then they detected the COG height of an actual truck. The results were also satisfactory.

Yu and Watanabe conducted controlled experiments to prove, based upon D3DCG, the COG height effect on rollover. They detected the COG heights of truck models that had the same load but different COG heights by D3DCG. Then they calculated the critical rollover radii with the full speed.

The experiment radius was chosen between the larger one and the smaller one. The model withlower COG passed through the curve safely, although model with higher COG rolled over. Theexperiments demonstrated that an object with higher COG rolls over easily.

Merely knowing the COG height of a moving object is insufficient to avoid rollover. This study is a development of D3DCG theory. It proposes the maximum lateral force of rollover by combining the dynamic rolling angle in a shaking process and a moving vehicle's geometric structure of critical rollover state. The study can produce a means of preventing rollover by comparison of the maximum lateral force with the real-time lateral force.

2. MAXIMUM HEIGHT OF COG DETECTED USING D3DCG

2.1. Theory of the maximum height of COG

Every object's COG height has an upper limitation. Even though it is in a static state, the object cannot remain steady if its COG height is beyond the upper limitation. Actually, D3DCG theory can detect the real-time COG height; it can also be used to detect the maximum height of the COG of a moving object.

When a vehicle is moving, disturbances from the road surface make the vehicle' s body shake around the oscillation center. Figure 2 presents an oscillation diagram of a moving vehicle at a certain point during shaking.

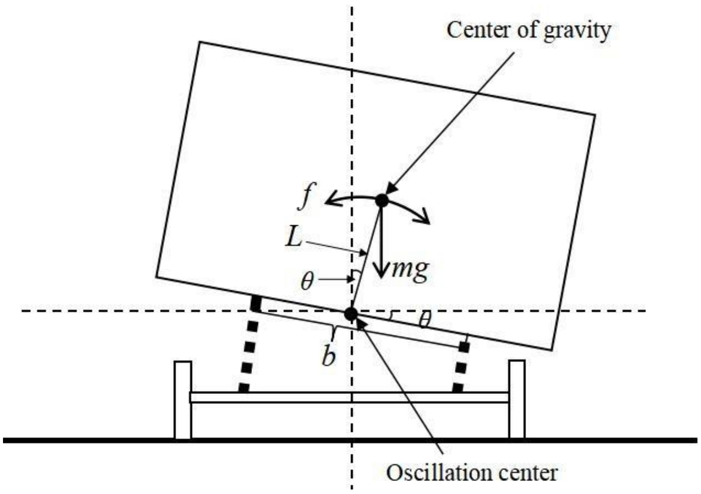


Figure 2. *Oscillation diagram of a moving vehicle*

When the vehicle body tilts to one side, springs on this side are squeezed, whereas the springs on the other side are stretched. Therefore, the direction of elastic moment is in the opposite direction of rolling. However, because of the inertia, the direction of gravity moment is consistent with the rolling direction.

The elastic moment and gravity moment are not equal. Therefore, the balance of the rotational moment is expressed as

$$Lf = -k\left(\frac{b}{2}\sin\theta\right)\frac{b}{2} + mgL\sin\theta - k\left(\frac{b}{2}\sin\theta\right)\frac{b}{2}\ , \qquad (1)$$

which equals

$$f = \left(-\frac{kb^2}{2L} + mg\right)\sin\theta, \qquad (2)$$

where L denotes the COG height from the oscillation center, f represents the force perpendicularto the connecting line between COG and oscillation center, k denotes elastic coefficient of spring, b represents the width of the portion that supports the whole weight, θ stands for the rolling angle,

m denotes the whole mass of the vehicle, and g signifies the gravitational acceleration which is 9.8 m/s^2.

The direction of force f depends on the gravity moment and elastic moment. In this case, if the gravity moment is dominant, then f will have a positive value; the vehicle will roll over. However, if elastic moment is dominant, then f will have a negative value. Here f can be regarded as restoring force to return the COG to its original position.

When rollover does not happen, the restoring moment direction reverses the gravity moment. In other words, the value of f should be no more than 0, so Equation (3) exists as

$$-\frac{kb^2}{2L} + mg \le 0, \qquad (3)$$

When f becomes 0, in a static condition, L becomes the maximum height of COG denoted as L_{max}, which can be expressed as shown below.

$$L_{max} = \frac{kb^2}{2L}, \qquad (4)$$

It can be found from Equation (4) that because the spring constant and the width of supportingpart does not change, the maximum height of COG depends only on the total mass. In other words, if the total weight does not change, then the maximum height of the object is constant.

Based on the basic equations of D3DCG, the COG height can be detected through the natural frequencies of simple harmonic oscillation of a moving object caused by elastic structures. The formula of vertical simple harmonic motion is therefore

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

where V' denotes the frequency of vertical simple harmonic oscillation of the vehicle body. Therefore, k/m can be expressed by V' as

$$\frac{k}{m} = 2\pi^2 V'^2, \quad (6)$$

If Equation (6) is put into the Equation (4), then Equation (4), then the expression of themaximum height becomes

$$L_{max} = \frac{\pi^2 V'^2 b^2}{g}, \quad (7)$$

2.2. Verification of the maximum height of COG by experimentation

The experiment uses a table-top device shown in Figure 3 to simulate the vehicle structure. The device comprises two plates and four springs. Springs represent the elastic structures of a vehicle. When the disturbances act on the wheels, the vehicle body starts shaking. Similarly, when an external force is given from the vertical direction to the table-top device, the object on the upper plate starts shaking. Furthermore, the shaking frequency depends on the COG height. The experiment object is a tape tower consisting of nine tapes with a metal component. The metal mass is much greater than that of the tape. Therefore, the COG height of the tape tower changesas the position of the metal changes. The tapes are numbered from the bottom to the top. First, themetal is put under Tape 1; then it is lifted one tape height to the position between Tape 1 and Tape 2. This process is repeated until the metal reaches the top of tape tower. At every different position, the tape tower is provided with a vertical force to make it shake. At the same time, the motion sensor records the motion data. The tape top device and the COG height changing processare shown in Figure 3.

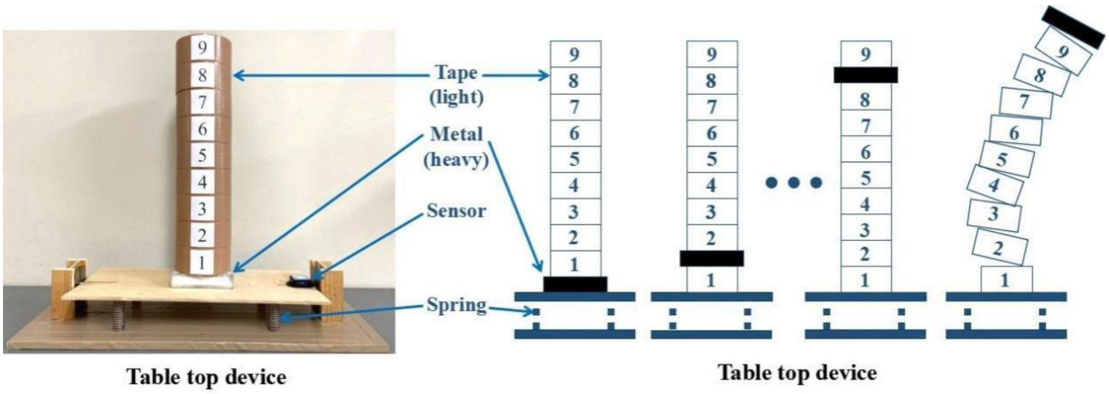


Figure 3. *Picture and diagram of table-top device and tape tower.*

The sensor can record the motion data including acceleration, angular velocity and angle from three directions, front and back, up and down, and left and right. Eight sets of data were collected when the metal is settled on one position. Table 1 presents the average of heaving frequency, rolling frequency, COG height and the maximum height of COG with the metal settled on different positions. Appendix 1 presents the specific data of each stage.

Table 1. Results of tape tower experiments with the table-top device

	Number of tapes under the metal								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
***V'* (hz)**	3.614	3.593	3.591	3.560	3.565	3.551	3.572	3.520	3.553
***V* (hz)**	0.870	0.850	0.773	0.681	0.583	0.486	0.390	0.264	0.165
***b* (m)**	0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160
***L* (m)**	0.206	0.207	0.218	0.229	0.245	0.261	0.281	0.295	0.315
SD of *L*	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.002
L_{max} (m)	0.337	0.333	0.332	0.327	0.328	0.325	0.329	0.320	0.325
SD of L_{max}	0.002	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.002

To eliminate the effects of errors, both L and $Lmax$ are calculated with the average values of heaving frequency and rolling frequency on different stages. The standard deviations of L and $Lmax$ are no more than 0.002, which means that the results are not discrete. Therefore, these datasets are accurate. Figure 4 intuitively shows the change of L and $Lmax$ and the relation between$L$ and $Lmax$ as the metal position rises.

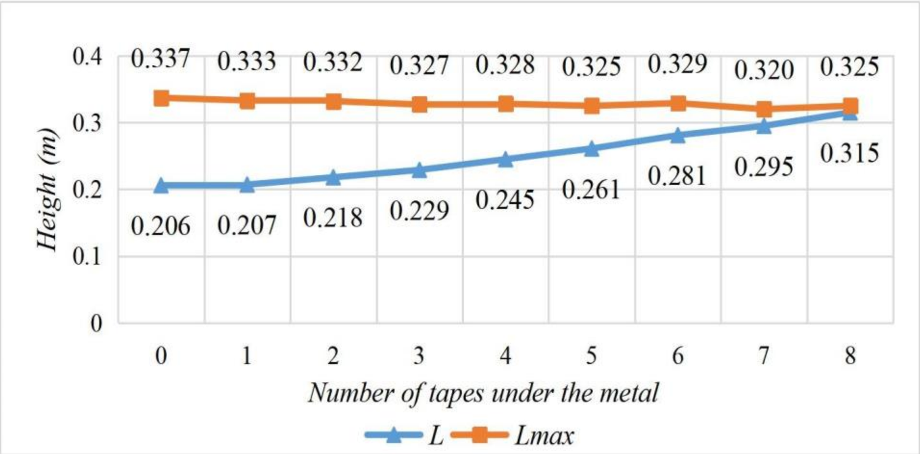


Figure 4. *Height of COG and maximum height of COG.*

The total weight of the object is fixed. Therefore, the maximum height of COG should be constant. Because of the errors, the calculated values of $Lmax$ are not absolutely the same, but they do not change a lot. It is statistically satisfactory. As the metal position rises gradually, the COG height increases. The object becomes increasingly difficult to keep steady. When there are eight tapes under the metal, the COG height is very close to the maximum height of COG. In this case, if the object is given an external force, then it is very easy for a rollover to occur. Furthermore, even if there is no existing external force, it is impossible to lift the weight to the top of the tape tower (nine tapes under the metal).

This experiment proves that an upper limitation of COG height exists. Objects with lower COG height are easier to keep steady than the higher ones. As the COG height increases, the stability lessens. In addition, the COG height cannot be greater than the maximum height of COG without rollover. The closer the COG height is to the maximum height of COG, the easier the object is to roll over.

3. MAXIMUM LATERAL FORCE OF ROLLOVER

3.1. Equation of rotational moment

Based on Figure 5 and Equation (2), the gravity moment and elastic moment are not always the same. Therefore, a force that can make COG keep rolling or return it to the original position exists. This force is presumed to be perpendicular to the contact line between COG and the oscillation center and is presumed to have a relation with gravity, which is expressed as

$$f = qmg \cos\theta, \tag{8}$$

where q stands for the multiple of lateral force relative to gravity in horizontal direction. Because the force is perpendicular to L, q should be multiplied by $cos\theta$.

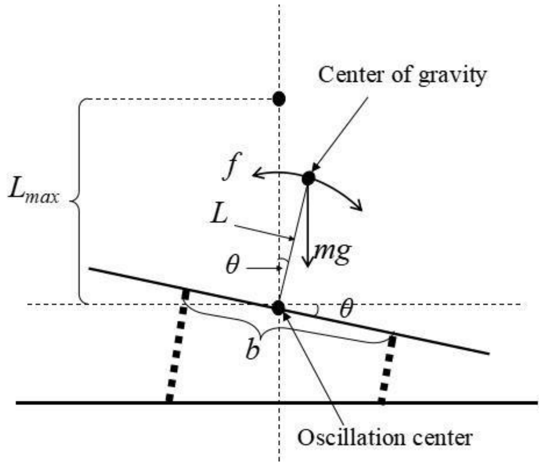


Figure 5. *Simplified sketch of oscillation*

If this force is replaced by its expression, then Equation (2) will become

$$qmg\cos\theta = \left(-\frac{kb^2}{2L} + mg\right)\sin\theta, \tag{9}$$

or

$$q = \left(-\frac{kb^2}{2Lmg} + 1\right)\tan\theta, \tag{10}$$

If unknown variables m and k are eliminated by the expression of L_{max} in Equation (4), then the relation between rolling angle θ and the multiple of lateral force q becomes

$$\theta = tan^{-1}\left(\frac{Lq}{L-L_{max}}\right), \tag{11}$$

3.2. Maximum lateral force without rollover

When a vehicle moves steadily along a road, the vehicle body is able to maintain a simple harmonic motion; the COG shakes around the oscillation center, which is located on the supporting portion. The line connecting it and the COG is perpendicular to the support.

When a moving vehicle is given an external force from lateral direction, for example, when a vehicle is affected by the centrifugal force when passing through a curve, the vehicle body willtilt to the opposite direction.

If the lateral force is sufficiently strong, then the vehicle will roll over. Figure 6 shows the criticalstate of the start of rollover.

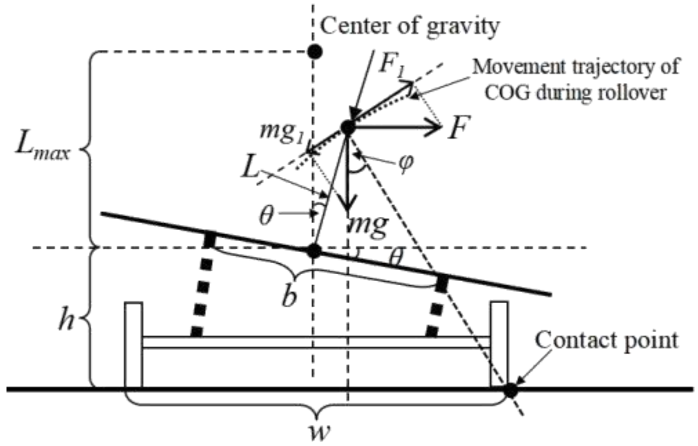


Figure 6. *Diagram of the start of the rollover critical state.*

According to the geometric structure of vehicle, when rollover starts, the rolling center is the contact point between the outer wheel and the road surface.

The lateral force is presumed as *F*. Its expression is

$$\boldsymbol{F = q_{\varphi} mg}, \quad (12)$$

where q represents the multiple of lateral force relative to gravity.

As Figure 6 shows, $F1$ is the component of lateral force on the tangent line of COG's movement trajectory. To prevent rollover occurrence, $F1$ should not be greater than the component of gravity denoted as $mg1$ in Figure 6. That is

$$mgsin\varphi \geq q_{\varphi} mgcos\varphi, \quad (13)$$

which is also written as

$$tan\varphi \geq q_{\varphi}, \quad (14)$$

where φ stands for the angle between the vertical direction and the connecting line of COG andthe contact point between the outer wheel and the road surface.

Therefore, at the critical state of rollover, the maximum value of $q\varphi$ equals the minimum value of

$tan\varphi$, which is expressed as

$$q_{\varphi max} = tan\varphi_{min}, \quad (15)$$

where $q\varphi max$ is the maximum multiple of lateral force relative to gravity, and φmin is the minimum angle between the vertical direction and the connecting line of COG and the contact point.

According to the geometric structure shown in Figure 6, $tan\varphi$ is expressed as

$$tan\varphi = \left|\frac{\frac{w}{2}-Lsin\theta}{Lcos\theta+h}\right., \quad (16)$$

where w denotes the distance between the outer sides of the wheels on both sides, and where h represents the oscillation center height.

In Equation (15), $tan\varphi$ decreases as θ increases. Therefore, when θ reaches θmax, $tan\varphi$ becomes $tan\varphi min$ so that the multiple of lateral force becomes maximum. By combining Equation (15) and Equation (16), the maximum multiple of lateral force becomes

$$q_{\varphi max} = \frac{\frac{b}{2} - Lsin\theta_{max}}{Lcos\theta_{max} + h}, \quad (17)$$

Based on Equation (11), the only unknown variable θmax can be replaced. Thereby, Equation (17) becomes

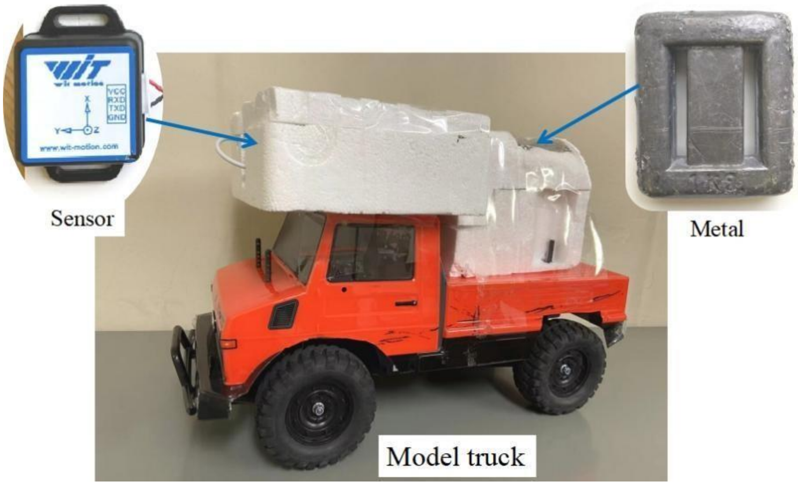
$$q_{\varphi max} = \frac{\frac{w}{2} - Lsin\left[tan^{-1}\left(\frac{Lq\varphi max}{L - L_{max}}\right)\right]}{Lcos\left[tan^{-1}\left(\frac{Lq\varphi max}{L - L_{max}}\right)\right] + h}, \quad (18)$$

Therefore, the expression of the maximum lateral force without rollover has been found.

3.3. Rollover experiment verification

To verify the theory of the maximum lateral force, a rollover experiment is conducted. The experiment object is a model truck on which a motion sensor is settled, as Figure 7 shows.

Figure 7. *Object of rollover experiment.*



The model truck runs straight for a while so that the COG height and the maximum height of COG can be detected according to D3DCG. The detection process is repeated 10 times. The results are presented below.

Table 2. *Detected results of model truck by D3DCG*

Experiment number	*V'* (hz)	*V* (hz)	*b* (m)	*w* (m)	*L* (m)	L_{max} (m)
Exp. 1	9.473	3.516	0.150	0.170	0.192	2.033
Exp. 2	8.203	3.516			0.165	1.525
Exp. 3	8.398	3.516			0.169	1.598
Exp. 4	8.008	3.613			0.157	1.453
Exp. 5	9.668	3.516			0.196	2.118
Exp. 6	9.863	3.809			0.186	2.204
Exp. 7	8.301	3.613			0.163	1.561
Exp. 8	8.594	3.906			0.157	1.673
Exp. 9	9.473	3.809			0.178	2.033
Exp. 10	9.961	3.613			0.197	2.248
Average	8.994	3.643	-	-	0.176	1.845

As Table 2 shows, the COG height of the model truck is 0.176 m. The maximum height of the COG is 1.845 m. The distance between the outer sides of the wheels on both sides (w) ismeasured as 0.170 m. The oscillation center height (h) is 0.005 m. When these values are put into Equation (18), the maximum lateral force without rollover is found to be 0.481 g.

Based on the expression of maximum lateral force in Equation (18), neither the spring constant, total mass, speed nor curve radius is considered. Consequently, the experiment is designed to make the model truck continue turning with a random but fixed turning angle. Initially, the model truck speed is low. It speeds up gradually until the truck rolls over.

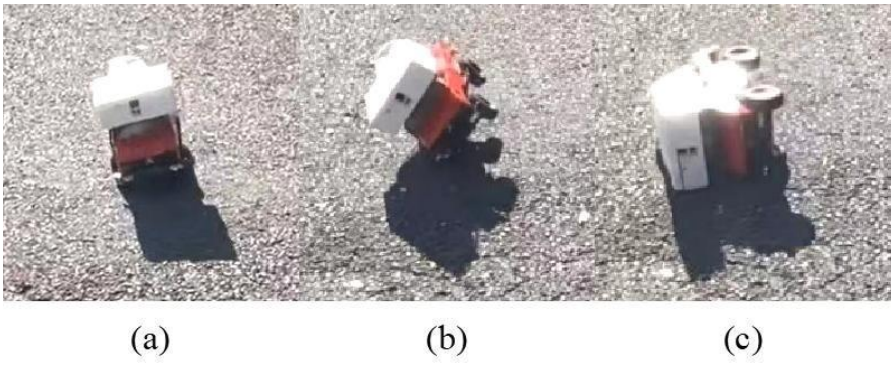
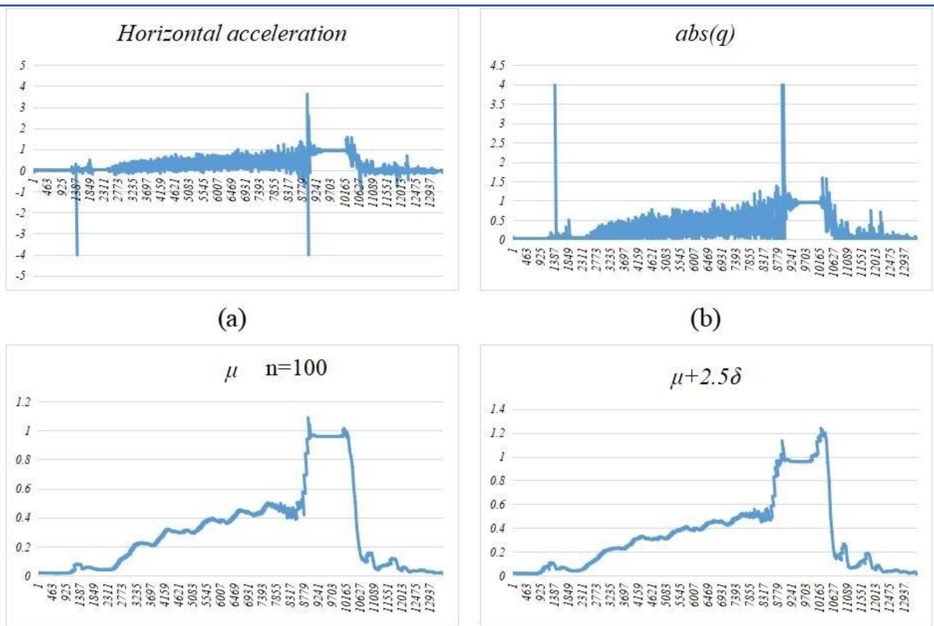


Figure 8. *Motion process of model truck.*

The motion process of the model truck is shown in Figure 8. First, the model truck speed is very low; the lateral force (centrifugal force herein) is weak. Therefore, the truck body merely tilts outward slightly. As the truck speeds up, the outward inclination of the truck body increases. Then, the truck body shakes dramatically. Finally, it rolls over.

During the experiment period, the motion sensor continues recording data. The original data are regarded as those for real-time lateral force after processing. The data processing process is shown in Figure 9. Panel (a) presents the original data, which have both positive and negative values. The plus and minus marks merely demonstrate the direction of the lateral force. This study does not take the marks into consideration. Consequently, the original data are transferred to their absolute value, as Panel (b) shows. The sampling frequency of the motion sensor is 200. To reduce the errors, the average value in a half second is chosen for this research. In other words,the data in Panel (c) are the average of every 100 data. To make the results more convincing, the real-time lateral force is the average absolute value of original data plus a 2.5 multiple of standard deviation, as Panel (d) shows.



(c) (d)

Figure 9. *Process of lateral force data processing.*

Both the real-time lateral force and the maximum lateral force without rollover are portrayed together in Figure 10. Two lines intersect on the red point, with rollover starting at the purple point. This phenomenon indicates that after the intersection the model truck loses control; it is at the critical state of rollover. In this condition, if the driver does not take some measure such as lowering the speed or turning the steering wheel, then the truck will roll over. The experiment is repeated seven times. Other results are presented in Appendix 2

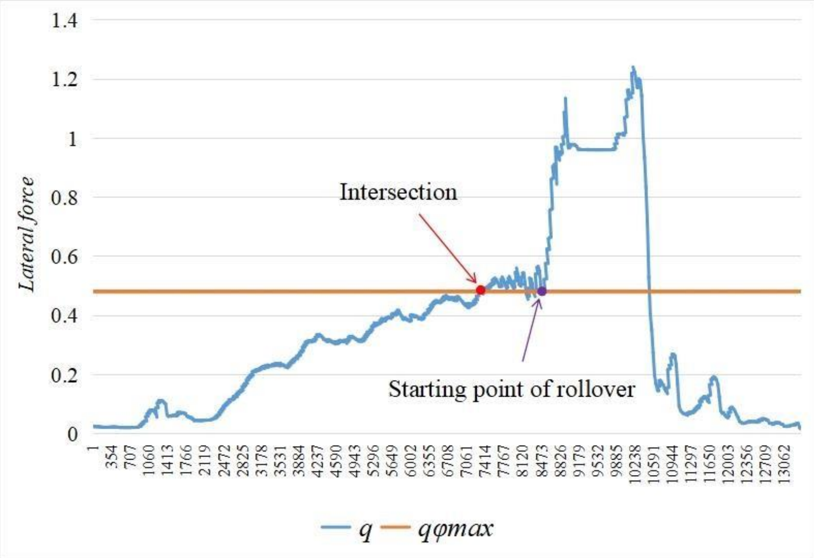


Figure 10. *Real-time lateral force and maximum lateral force without rollover*

4. CONCLUSION

This research first derives the equation of the maximum height of COG according to the basic equation of D3DCG. The tape tower experiment verifies the theory that the COG height closer to the maximum height of COG makes it more difficult for the object to remain stable and makes it easier to roll over. Furthermore, the object can not avoid rollover if the COG is higher than the maximum height of COG.

Based on the rotational moment of a moving vehicle, the lateral force has a relation with the rolling angle. Rollover often occurs in curved sections of a road because of lateral forces such as centrifugal force. When rollover starts, the rolling center changes from the oscillation center tothe contact point between the outer wheel and the road surface. At this critical state, according to vehicle ’ s geometric structure combined with the relation between the lateral force and rolling angle, the maximum lateral force which does not cause rollover is expressed by the COG height, the maximum height of COG and some basic parameters. The COG height and the maximum height of COG can be detected based on D3DCG. The basic parameters can be measured directly.Therefore, no unknown variable exists in the equation of the maximum lateral force without rollover.

The process of detection and calculation takes only a few seconds, therefore allowing real-time usability. Furthermore, when the lateral force acting on the vehicle reaches the maximum lateral force calculated, the vehicle will not roll over immediately. It just loses control. Nevertheless, some time remains for a driver to take some measures to avoid rollover accidents such as slowing the speed or adjusting the direction.

This research provides a method for vehicle rollover prevention while using simpler calculations and fewer errors. Because the sensor repeats collection of data, both the real-time lateral force andthe calculated maximum lateral force without rollover are renewed continuously. The results updated in real time can greatly reduce the influence of external factors. This research has great prospects for application to vehicles of all types, even trains and aircraft, and especially to vehicles for which the COG position changes frequently.

REFERENCES:

Dang, R., and Watanabe, Y. (2016). Three-Dimensional Center of Gravity for Trucks Hauling Marine Containers. Journal of Engineering Research and Applications, 6(1), 27-34.

He, J. L., Gong, B., Zhu, T., Yang, C. X., and Sun, Y. F. (2017). Critical safety speed model of corners based on road geometry parameters. Journal of Changsha University of Science and Technology (Natural Science), 14(4), 75-82.

National Highway Traffic Safety Administration. Passenger Car and Light-Truck Occupants Killed, by Vehicle Type and Rollover Occurrence, 1982-2020. available at: https://cdan.dot.gov/SASStoredProcess/guest

Kawashima, S., and Watanabe, Y. (2016). Center of gravity detection for railway cars. Open Journal of Mechanical Engineering (OJME), 1(1), 8-11.

Kawashima, S., and Watanabe, Y. (2016). Experiment on The Three Dimensional Detection of Center of Gravity for Detecting Deterioration of Automobile Tire. The Japan Society of Mechanical Engineers,2012-12.5–7, 161-164.

Rogers, S., and Zhang, W. (2003). Development and evaluation of a curve rollover warning system for trucks. Institute of Electrical and Electronics Engineers (IEEE), 294-297.

Watanabe, Y. (2017). Three-Dimensional Center of Gravity Detections for Preventing Rollover Accidents of Trailer Trucks Hauling Containers. Open Journal of Mechanical Engineering (OJME), 2(1), 11- 14.

Yu, K., and Watanabe, Y. (2021). Effects of Center of Gravity Position on Rollover Based Upon Detection of Three-Dimensional Center of Gravity. Toros University FEASS Journal of Social Sciences Special Issue on International Symposium of Sustainable Logistics, 70-84.