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DEVELOPMENT OF ROLLOVER CRITERIA BASED ON SIMPLE PHYSICAL MODEL OF ROLLOVER EVENT

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ABSTRACT−The high potential for injury involved in rollover accidents warrants the development of a system to protect passengers against such events. To effectively implement such a protection system, it is first necessary to determine rollover criteria (i.e., real time states which indicate the occurrence of rollover events). In this paper, several rollover criteria have been developed based on simplified physical models. Such accidents are first classified into two types, untripped and tripped, according to the main cause that initiates the rollover. Characteristics of these rollover situations are identified by applying appropriate principles of dynamics to corresponding simplified physical models. Two main rollover criteria, Rotational Kinetic Energy (RKE) and Initial Kinetic Energy (IKE), are then introduced based on these characteristics. ADAMS/View simulations have been performed to verify the feasibility of the introduced rollover criteria. ADAMS/Car simulations have also been conducted to get more realistic rollover data with a complete vehicle model. Results of these experiments reveal that our established criteria prove useful for predicting whether actual rollover occurs or not.

KEY WORDS : Rollover, Physical modeling, Rollover criteria, Simulation

1. INTRODUCTION

Today's passenger cars are well protected against frontal and side impact by appropriate restraint systems. However, the importance of occupant protection in rollover situation has been relatively underestimated up to the present. According to the traffic accident statistics shown in Figure 1 (Missouri department of transportation, 2002), even though the proportion of rollover accidents are relatively small compared to other accidents, it usually causes fatal injuries to the occupant. The severe injuries and fatalities are mainly caused by head contact with the vehicle interior or ejection of the occupant during the rollover situation. Therefore, it is necessary to provide appropriate safety devices such as seat-belt pretensioner, inflatable curtain airbag, etc. in case of a rollover accident.

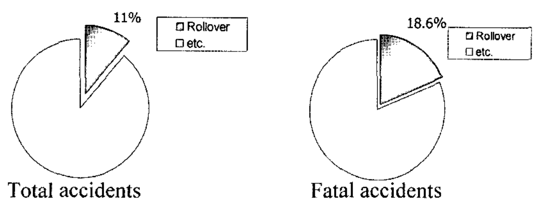

Figure 1. Traffic accident statistics (Missouri department of transportation, 2002).

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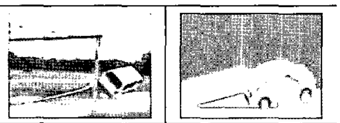
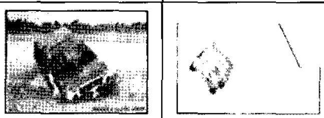
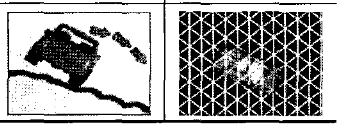
Extensive studies have shown that it is necessary to activate the safety devices before the actual rollover begins. While all four wheels are still in contact with the ground, the occupant starts moving towards the side of the vehicle (Saczalski *et al.*, 1999). Hence, a rollover criterion for timely activation of the safety devices has to be studied. To study the criteria, first, we should have a good knowledge of rollover characteristics. Accident statistics shows that 34% of all rollover accidents happen after a collision with an object. It means that rollovers are mostly concatenated events and occur due to the first contact with an object. Field accident analysis also shows that 82% occur in the countryside. Among the rollover accidents, 66% occur during driving situations, such as braking maneuvers or vehicle skidding. The main influence comes from vehicle velocity, road pavement, and friction change. In addition, 60% occur by driving on an embankment (Frimberger *et al.*, 2000).

There are many different rollover situations in the field such as corkscrew (ramp obstacle), embankment, curb trip, soil trip, cliff, and so on (Frimberger *et al.*, 2000; Steiner *et al.*, 1997; Bardini and Hiller, 1999). Those

Table 1. Rollover types and example (Viano and Parenteau, 2003).

Rollover type	Ex.	Situation
Untripped rollover	Ramp	
	Ditch	
Tripped rollover	Curb trip	
	Soil trip	

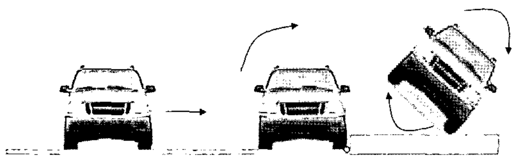


Figure 2. Delta-m case example - curb trip (Steiner *et al.*, 1997).

situations can be largely classified into two types according to the main cause for initiating the rollover - untripped and tripped rollover (Viano and Parenteau, 2003).

The untripped rollover is caused by a one-sided vertical car movement. In other words, vehicle rolls when its CG (center of gravity) exceeds the stable point. Ramp and embankment (or ditch) events are typical example for this type of rollover.

The tripped rollover occurs by lateral hit against an obstacle (e.g., a curb), or a lateral slipping on a surface with variable friction. The tripped rollover occurs mainly due to a rapid change of the friction coefficient, m (Steiner *et al.*, 1997), which is sometimes called "delta-m case". The car gets out of control due to a rapid decrease of the friction (ex. Ice load, $\mu << 1$). Next, the car laterally slides off the road. If the car is rapidly decelerated by barrier ($\mu >> 1$), then it can be called "curb trip". Alternatively, if the car is digging itself with its tires into the field ($\mu > 1$), then it can be expressed as "soil trip". In summary, the rapid change of the friction coefficient (delta-m) causes a high torque of the CG of the car at a pivot point on the tires (Steiner *et al.*, 1997).

Numeric simulation of a vehicle is very useful for the development of a rollover physical model because it allows watching a complete and detailed vehicle behavior and it is also important in terms of cost and time (Frimberger *et al.*, 2000; Bardini and Hiller, 1999; Saczalski *et al.*, 1999; Fay and Scott, 1999; Ungoren and Peng, 2004). In addition, numerical simulation offers the possibility to reconstruct the rollover situation, in comparison with real vehicle tests (Frimberger *et al.*, 2000; Bardini and Hiller, 1999; Fay and Scott, 1999).

It is known that ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is a helpful simulation package for solving dynamics problem (Frimberger *et al.*, 2000). ADAMS/View has feature to build a virtual prototype of a mechanical system. ADAMS/Car has feature providing a virtual prototype of a complete vehicle, combining accurate mathematical models of the chassis subsystems, engine and driveline subsystems, steering subsystems, controls, and the body; therefore full vehicle performance can be simulated on a virtual test track or in a virtual test lab to simulate and refine real-world behavior.

The main concern of this study is to investigate the characteristics of rollover event and develop the rollover criterion based on physical model. ADAMS/View and / Car simulation will be intensively used for the development. Of course, it will be a very difficult task to validate the ADAMS simulation result without the real test data. However, the ADAMS simulation will still provide very useful information to understand the physics of rollover event. Therefore, making physical modeling and criterion will be performed with simulation.

2. PHYSICAL MODELING

In order to understand the physics of rollover event, a simplified rollover modeling under several assumptions will be considered. We will use a simple box shaped model which has the following vehicle parameters:

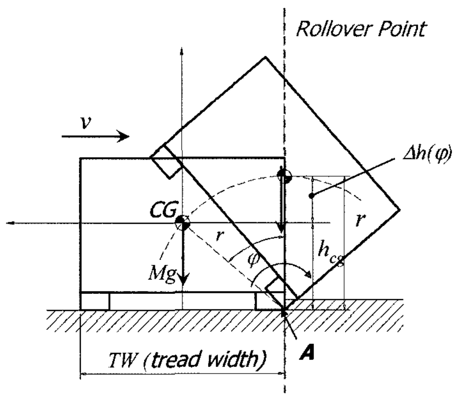
- CG Height
- Vehicle Weight
- Thread Width
- Roll Moment of Inertia

Generally speaking, as shown Figure 3, rollover occurs if rotational kinetic energy generated by an external cause is able to exceed the potential energy necessary to lift the CG of the vehicle to the rollover point. The rollover point means that CG is lying on the perpendicular line passing the rotation point, A.

The rollover condition can be described as follows:

Rollover will occur when roll angle, φ reaches a critical roll angle, φ_c corresponding to rollover point.

The critical roll angle is determined by the following equation



φ : Roll Angle of vehicle ω : Angular rate CG : Center of gravity hcg : CG Height TW : Tread Width

Figure 3. Rollover point.

Table 2. Classification for typical rollover situations.

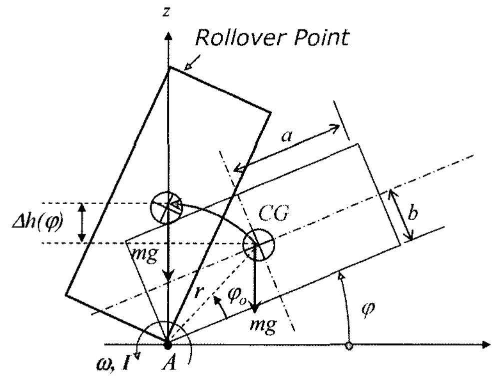
Rollover type	Cause of rollover	Governing rule
Untripped (Ramp or Ditch)	Asymmetric vertical acceleration	Principle of mechanical energy conservation T + V = const (T: Kinetic energy, V: Potential Energy)
Tripped (Soil or Curb trip)	Rapid change of friction coefficient (High lateral acceleration)	Principle of conservation of angular momentum H = Iω = const (I: Moment of inertia, ω: Angular velocity)

$$\varphi_c = 90° - \varphi_o, \text{ where } \varphi_o = \tan^{-1}\left(\frac{h_{cg}}{TW/2}\right) \tag{1}$$

Table 2 shows a summary of rollover situation in terms of rollover type, energy source for rollover, and governing rule. As already mentioned in the previous chapter, the rollover situations can be largely classified into two types, untripped and tripped rollover, according to the main cause for initiating the rollover.

3. ROLLOVER CRITERION

As mentioned above, to develop criterion, it is necessary to do physical modeling under assumptions and simplications. Under those circumstances, two basic rollover criteria are established.



φ : Roll Angle of vehicle ω : Angular rate CG : Center of gravity I : Moment of Inertia

Figure 4. Physical model of untripped rollover.

3.1. Rotational Kinetic Energy (RKE) Criterion

For untripped rollover situation, the energy source of rollover is asymmetrical upward or downward movement of vehicle due to an obstacle. Ramp and ditch (descending embankment) situations belong to this type. In this case, we can see small peak of the vertical and lateral acceleration signals in the beginning of event. However, there is no remarkable high peak much greater than 1g or 2g depending on vehicle and rollover situation. A simplified physical model of untripped rollover situation is described in Figure 4.

If we assume that there is no non-conservative force such as friction force, the principle of mechanical energy conservation can be applied to this model as follows.

$$T + V = const. \tag{2}$$

Where, T denotes kinetic energy and V means potential energy

The rotational kinetic energy with respect to point A is expressed by:

$$T = \frac{1}{2} I_A \omega^2 \tag{3}$$

The potential energy required to life CG to the rollover point is

$$V = mg \cdot \Delta h(\varphi) \tag{4}$$

According to the rollover condition mentioned in the previous section, rollover will occur if the following condition is satisfied.

$$T \geq V \tag{5}$$

By combining the above equations, we can obtain a critical angular velocity to meet the rollover condition.

$$\omega_c(\varphi) = \sqrt{\frac{2mg}{I_A}\Delta h(\varphi)} \tag{6}$$

Here, we can obtain the moment of inertia w.r.t. point A from the parallel-axis theorem:

$$I_A = I_{CG} + mr^2 \tag{7}$$

In addition, the other parameters can be obtained from the geometry:

$$\Delta h(\varphi) = r(1 - \sin(\varphi + \varphi_0)) \tag{8}$$

$$r = \sqrt{\frac{TW^2}{4} + h_{cg}^2} \tag{9}$$

$$\varphi_0 = \tan^{-1}\left(\frac{h_{cg}}{TW/2}\right) \tag{10}$$

Therefore, rollover criterion for untripped rollover situation can be expressed by:

$$\omega(t) \geq \omega_c(\varphi(t)) \tag{11}$$

Namely, if the measured angular velocity exceeds the critical angular velocity, we can expect a rollover event will occur.

We call this relationship "Rotational Kinetic Energy (RKE) criterion" which gives us a good indication if current rotational kinetic energy is sufficient to exceed the potential energy necessary to lift the CG of the vehicle to the rollover point.

3.2. Initial Kinetic Energy (IKE) Criterion

For tripped rollover situation, the main cause of rollover is due to an impact force caused by a rapid change of friction coefficient. Curb trip and soil trip are the typical examples of this type. In this case, an initial kinetic energy is an important factor to determine whether rollover will occur or not. The translational kinetic energy generated by a lateral sliding of vehicle will be suddenly transformed to rotational kinetic energy due to an impact force.

Due to the contact of vehicle tire with curb or mound of soil, relatively high lateral acceleration signal is detected. The acceleration signal characteristics look like a kind of side crash event. It has been known that the occupant movement of tripped rollover is much faster compared to the untripped rollover. Therefore, the decision for activation of restraint system has to be made at small roll angle and the required activation time is generally much faster than 1 second. A simplified physical model of this type of rollover is shown in Figure 5.

In this model, we assume that all of the kinetic energy is transformed to potential energy, raising the CG to the rollover point. It is also supposed that energy dissipation from wheel contact with ground, energy storage or dissipation in the tires and suspensions are neglected.

With these assumptions, we apply the principle of angular momentum conservation w.r.t. point A in order to get the angular velocity after impact.

$$H_{A,b} = H_{A,a} \tag{12}$$

Where, $H_{A,b}$ denotes angular momentum before impact, and $H_{A,a}$ represents angular momentum after impact. Therefore, the angular velocity after impact can be obtained by:

$$\omega = \frac{Mvh_{cg}}{I_A} \tag{13}$$

Once we obtain the initial angular velocity for rollover, we can use RKE criterion.

The critical angular velocity is given by:

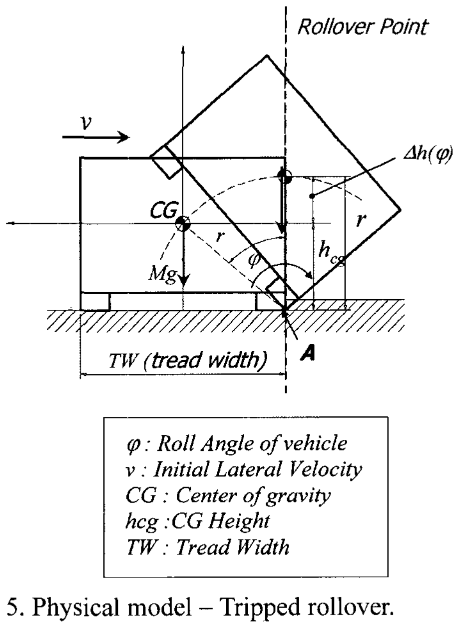


Figure 5. Physical model – Tripped rollover.

Table 3. Summary of introduced rollover criteria.

Criterion name	Rollover type	Condition for selecting criteria	Rollover criteria
RKE	Ramp or Ditch	$\Delta\omega$ is monitored without detecting high acceleration.	$\lvert\omega\rvert > \lvert\omega_c(\varphi)\rvert$
IKE	Curb or Soil trip	High vertical acceleration is detected @ nearly zero roll angle and angular velocity	$\lvert v_y\rvert > \lvert v_c\rvert$ & $\lvert\omega\rvert > \lvert\omega_c(\varphi)\rvert$

$$\omega_c(t) = \sqrt{\frac{2mg}{I_A}r(1-\sin\varphi_0)} \quad (14)$$

By combining the equation (13) and (14), the critical sliding velocity (csv) for rollover is obtained as follows:

$$v_{CSV} = \sqrt{\frac{2gI_A}{Mh_{CG}^2}\left(\sqrt{\frac{TW^2}{4}+h_{CG}^2}-h_{CG}\right)} \quad (15)$$

This equation implies that the initial kinetic energy determined by the sliding velocity is the most important factor to predict if rollover occurs or not. Actually, we can estimate the initial kinetic energy by evaluating the lateral and vertical acceleration signal since the vehicle speed signal is supposed to be not available. Thus, we call it "Initial Kinetic Energy (IKE) criterion".

The IKE criterion can be summarized as follows:

When a high lateral acceleration is detected at a nearly zero roll angle, IKE criterion will be started to evaluate. If a sudden change in angular velocity is monitored in succession to the high lateral acceleration, tripper rollover situation can be identified. Otherwise, the high lateral acceleration may be caused by a side crash. The final decision of rollover will be made by comparing both angular velocity and lateral acceleration with a predefined threshold.

Table 3 shows the summary of rollover criteria introduced in this chapter.

4. ROLLOVER SIMULATION

ADAMS/Car simulation will be used to verify the feasibility of the simplified modeling. Through the simplified modeling and ADAMS/View simulation, important criteria to predict the propensity of rollover will be investigated.

4.1. Modeling Parameter

In real world, the important vehicle parameters for rollover is tread width, CG height, mass, and roll moment of inertia (Gillespie, 1992). In addition, it is known that spring and damper is not affected much, when suspension is determined (Frimberger *et al.*, 2000). Therefore, in my model, tread width, CG height, mass, and roll moment of inertia are taken into account. Table 4 is comparison with my simulation model and commercial vehicle (Heydinger *et al.*, 1999), to verify reality of my model.

Table 4. Modeling parameter.

Model	Simulation model	Hyundai excel	Ford festiva
Tread width (m)	1.52	1.362	1.403
Height of center of mass (m)	0.53	0.539	0.52
Roll moment ($kg\text{-}m^2$)	320	383	340

4.2. ADAMS/View Simulation

In ADAMS/View, Simplified box-shaped model was used with several assumptions as the same as physical modeling. The two main assumptions are that a box-shaped model is a rigid body model (no deformation) and a box-shape model has no tires or suspension. Hence, important vehicle factors are tread width, CG height, roll moment of inertia, and mass, as described above. The objectives to do ADAMS/View simulation are to verify propensity of the simplified physical model and rollover criteria, and to investigate rollover behavior.

Then, the preliminary criteria will be used to study rollover algorithm.

4.2.1. ADAMS/View simulation – RKE criterion

To verify untripped rollover physical model and RKE criterion, the ramp case is supposed and simulated. The important factors for external geometry are ramp shape, because it gives an external upward force to roll. After simulation, result graph is analyzed and compared with theoretical value.

Figure 6 is the ramp model used in ADAMS/View simulation. In Ramp model, to apply asymmetric force, point A is pivoted and force is applied at CG point. Figure 7 and Figure 8 are the ADAMS/View simulation results. In Figure 8, in the beginning of event, a small peak of vertical and lateral acceleration signals is detected that does not exceed 1g. The acceleration is a source of roll kinetic energy. To verify the concept of RKE criteria and simulation results, the point when time is 0.51 second, which right after force is applied, is selected and critical angular velocity is calculated.

The result is shown in Table 5.

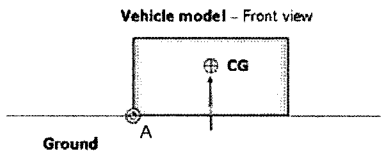


Figure 6. Ramp case ADAMS/View model.

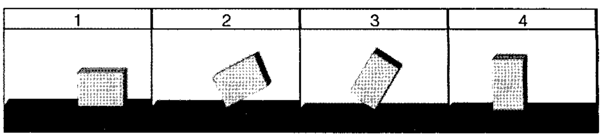


Figure 7. Ramp case ADMAS/View simulation.

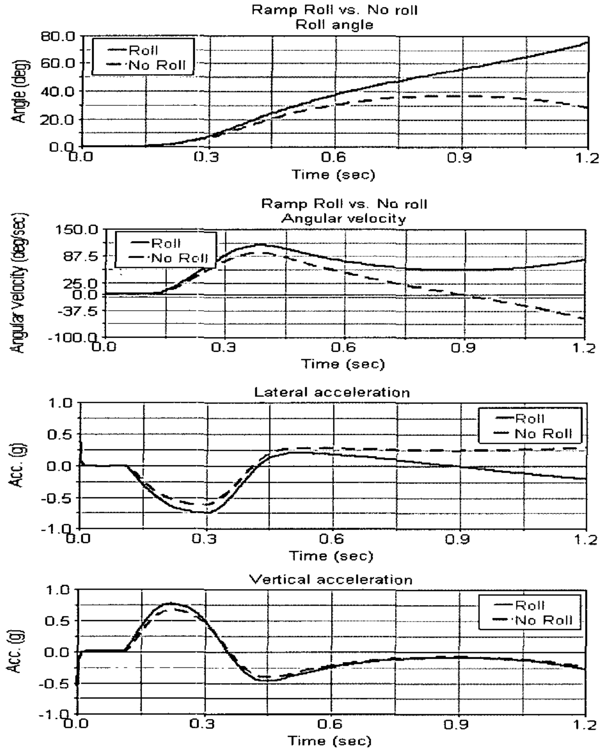


Figure 8. Ramp case ADAMS/View simulation result graph.

Table 5. Ramp case result analyses.

	φ	ω	ω_c	Check	Result
Roll	30	91.8	77.5	$\omega_c < \omega$	Roll
No-Roll	20	70.1	114.5	$\omega_c > \omega$	No-roll

(φ: Measured Roll Angle (deg)
ω : Angular Velocity (deg/sec)
ω_c : Critical Angular Velocity (deg/sec))

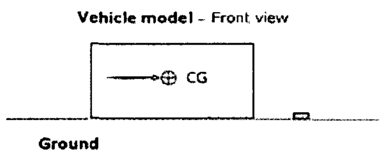


Figure 9. Curb case ADAMS/View model.

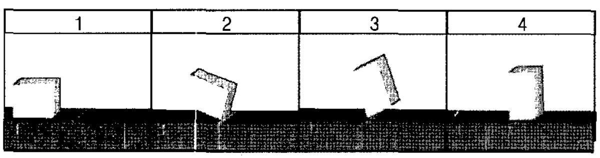


Figure 10. Curb case ADAMS/View simulation.

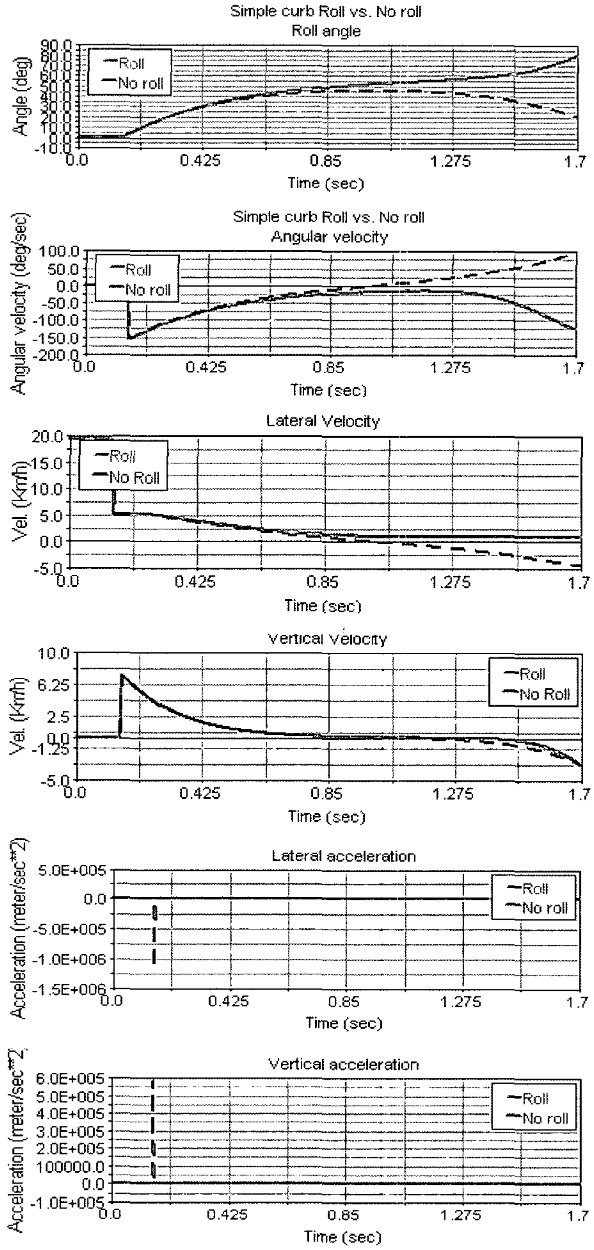


Figure 11. Curb case ADAMS/View result graph.

4.2.2. ADMAS/View simulation – IKE criterion

Curb trip is a kind of Tripped rollover. Therefore, in ADAMS/View, curb trip is used to verify physical model of tripped rollover and IKE criteria. As shown in Equation (15) one of the important factors of external environment is lateral sliding velocity. In addition, from the property of curb trip, friction change is also an important factor. Therefore, in ADAMS/View simulation is done with lateral velocity variation. The result sets are analyzed afterwards.

Figure 9 is the curb trip case ADAMS model. Initial lateral velocity is applied at CG point. Critical rollover velocity obtained from simulation was 19.66 KPH. For comparison, roll case was simulated 10% higher than critical rollover velocity, 19.80 KPH and no-roll was simulated 10% lower than critical rollover sliding velocity, 19.44 KPH. Figure 10 and Figure 11 are ADAMS/View simulation result.

In Figure 11, acceleration peaks are detected due to impact, and rapid angular rate increase can be found, right after impact, as expected. Hence, it is showed that impact energy is transformed to rotational kinetic energy. After impact, the curb trip graph is similar to the graph of untripped rollover without impact. It means that the general rollover model is correct. In addition, comparison to theoretical value 19.58 KPH, the simulated value has only 0.36% deviation. Therefore, the simulation result is acceptable and the model and simulation are verified and IKE criterion can be used to predict rollover.

4.3. ADAMS/Car Simulation

To perform ADAMS/Car simulation, several conditions to describe a desired rollover test mode have been also specified as follows.

- Vehicle Velocity
- Steering Angle
- Obstacle Geometry
- Friction coefficient of road and obstacle

Through ADAMS/Car simulation, the following results can be obtained

- Roll/No-roll condition
- Output Data (Angular Velocity, Lateral & Vertical Acceleration)

Objectives for ADAMS/Car Simulation are follows.

- Investigate critical factors for each rollover type.
- Find roll/No-roll criteria for each rollover type.
- Investigate vehicle behavior during rollover.
- Analyze sensing data (ω, a_y, a_z) to check plausibility.
- Investigate and interpret any particular signals.
- Interpret signals connecting with vehicle behavior.
- Find signal characteristics to identify each rollover type.

Furthermore, simulation output data will be used later for criterion simulation.

In ADAMS/Car simulation, important factors of vehicle also tread width, CG height, roll moment of inertia, vehicle mass, as mentioned above.

4.3.1. ADMAS/Car simulation – RKE criterion

In ADAMS/Car, ramp case is simulated as a kind of untripped rollover. In ramp case, external environment important factors are ramp height, ramp angle, and vehicle velocity. In ADAMS/Car, several simulations are done with variation of the factors and the results are analyzed. Figure 12 is the ramp road, used in simulation. Figure 13 and Figure 14 are ADAMS/Car simulation results. As expected, ramp test has characteristic of untripped rollover. Angle increases continuously before ground contact and in small angle, angular velocity difference are detected. In addition, small peak of lateral and vertical acceleration detected initially, which give an initial angle

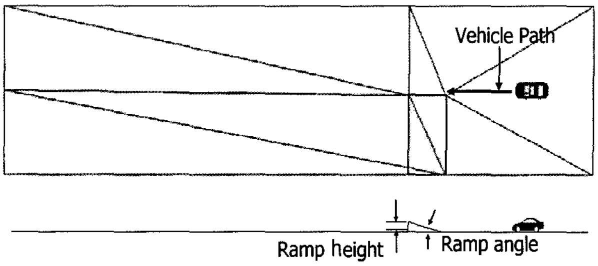


Figure 12. Ramp case ADAMS/Car road model.

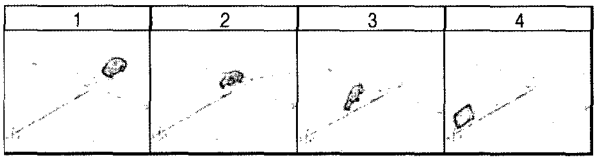


Figure 13. Ramp case ADAMS/Car simulation.

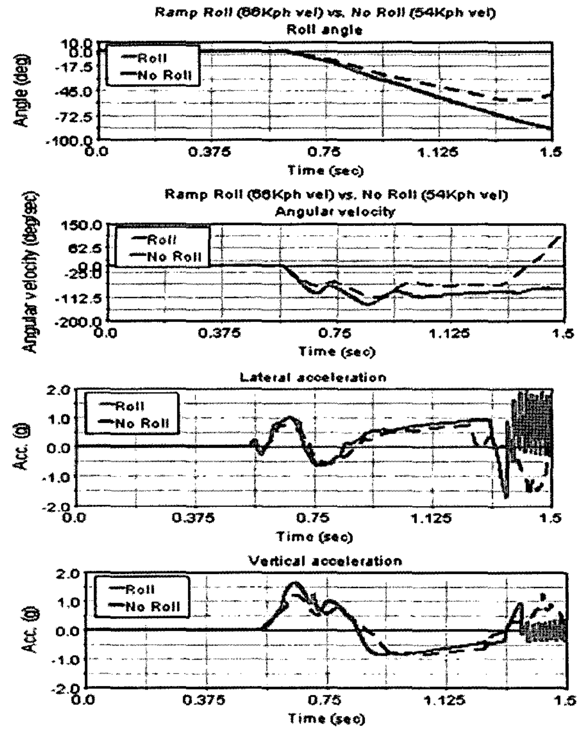


Figure 14. Ramp case ADAMS/Car simulation result graph.

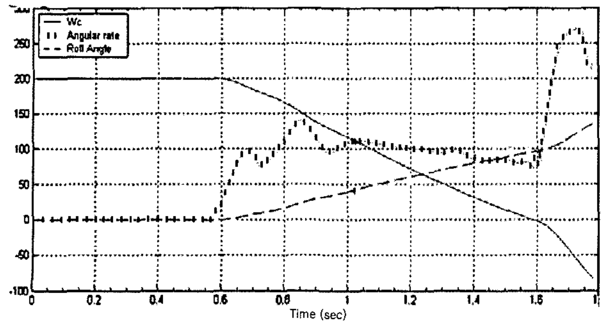


Figure 15. Ramp case – Roll.

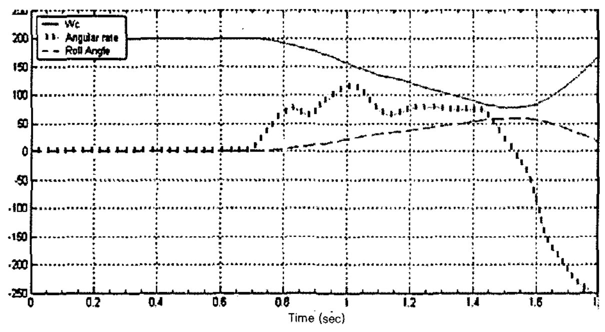


Figure 16. Ramp case – No roll.

and angular velocity, but it does not exceed 1g. Therefore, angular velocity can be used as criteria, and physical model and simulation results are well matched.

Figure 15 and Figure 16 show the validation of criterion. In Figure 15, angular rate exceeds critical angular rate, but in Figure 16, it does not exceed critical angular rate. Therefore, it verifies that critical angular velocity calculated from simple physical modeling is appropriate to use in criterion.

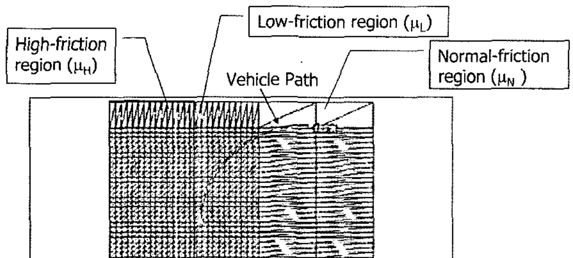


Figure 17. Soil trip case ADAMS/Car road model.

Figure 18. Soil trip case ADAMS/Car simulation.

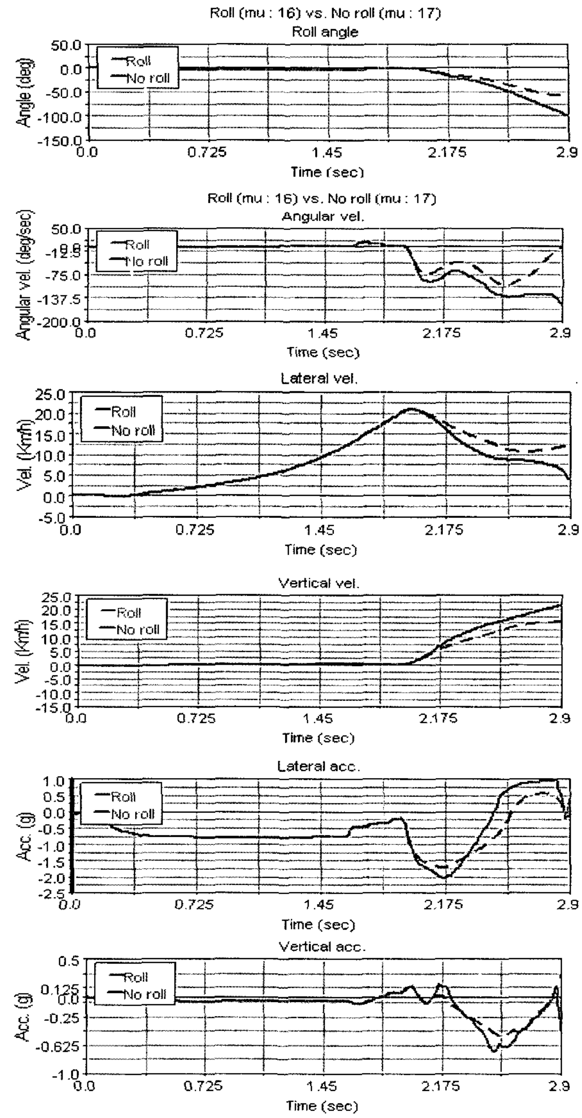


Figure 19. Soil trip case ADAMS/Car simulation result graph.

4.3.2. ADMAS/Car simulation – IKE criterion

To verify the effect of friction change of tripped rollover, soil trip case is simulated. In this case, important environment parameters are friction change and lateral velocity. Appropriate lateral sliding velocity was set first, and then the critical friction coefficient for rollover was found. Next to that, vehicle behavior and sensing data are analyzed.

Figure 17 is the road model to simulate soil trip. The road condition and driving condition is the same as curb trip case except that there is no curb in soil trip model. Figure 18 and Figure 19 are simulation results.

In Figure 19, acceleration peaks, which are higher than 1g, are detected. According to the first acceleration peaks, angular velocity increases in both cases. The

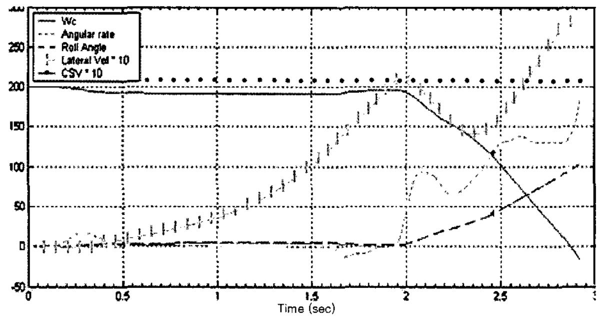


Figure 20. Tripped rollover – Roll.

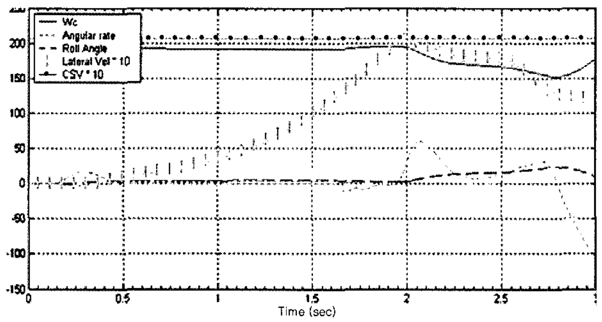


Figure 21. Tripped rollover – No roll events.

propensity is well known with physical model concept. From the results, it can be found that a rapid change of the friction coefficient ($\Delta\mu$) can lead to rollover. $\Delta\mu$ causes a high torque of the CG of the vehicle at a pivot point on the tires. Hence, $\Delta\mu$ generates a peak signal of lateral acceleration. The peak value of lateral acceleration will decide if a rollover occurs or not. Overall, lateral acceleration signal as well as angular velocity can be used to discriminate roll and no-roll.

Figure 20 and Figure 21 show the feasibility of the criterion. In Figure 20, it is seen that velocity is over the critical velocity and angular rate is also over the critical angular rate. It shows that in tripped rollover case, both of velocity and angular rate are important factors. However in Figure 21, both of them are not over the critical values. Both situations show that criterion from simple physical modeling is suitable to predict rollover.

5. CONCLUSION

In this research, several rollover criteria have been developed based on simplified physical models. First, the rollover situations have been largely classified into two types – untripped and tripped rollover – according to the main cause for initiating the rollover. Applying an appropriate principle of dynamics to each simplified physical model, characteristics for each rollover situation has been identified. Two main rollover criteria – RKE and IKE criterion – have been introduced by investigating the characteristics. ADAMS/View simulation has been conducted to verify the feasibility of the introduced rollover criteria. In order to get a more realistic rollover data with a complete vehicle model, ADAMS/Car simulation has been also carried out. More detailed analysis has been done for the simulation results of various rollover situations. Through the series of ADAMS simulation, the proposed rollover criteria has been turned out to be very useful to explain the various rollover situation and predict whether actual rollover occurs or not.

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